

Quantifying soil carbon measurement for agricultural soils management: A consensus view from science

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Foreword

This concept paper provides an overview of the current state of soil organic carbon (SOC) quantification approaches in working soils. The summary is based on a set of longer-form white papers developed en suite by many of the experts included in this authorship team. Collectively, the papers provide a detailed consideration of key scientific, technical and policy issues pertinent to the goal of designing and building an operational program or system that dynamically, credibly and usefully reflects the condition of soil organic carbon in U.S. working soils. Expert stakeholders, practitioners and policy makers were convened in two workshops in 2016 and 2017 to rigorously establish a collective understanding of the state of the science in SOC measurement relevant to agricultural and other soil management decisions where the goal is to maximize SOC and soil health on working lands.

This concept note is advanced by a group of mutually committed stakeholders from diverse fields toward a consensus from the scientific and technical community regarding how SOC quantification could be included in a dynamic, decision-relevant soil information service. Any modern soil information system must place local and regional insights regarding soil and relevant water cycle attributes within continental and global contexts, aligned with and anchored to existing local, state, national and global efforts. Given the crucial roles that organic carbon plays in the function of soils and the potential of soil management approaches to mitigate climate change, a crucial goal must be to better understand and manage the roles and dynamics of SOC in the short, medium and longer term.

1. INTRODUCTION

Take Home messages:

- There is heightened interest in increasing soil organic carbon (SOC) stocks to improve performance of working soils especially under drought or other stressors, to increase agricultural resilience, fertility and reduce greenhouse gas emissions from agriculture.
- There are many improved management practices that can be and are currently being applied to cropland and grazing lands to increase SOC.
- Farmers and ranchers are decision-makers who operate in larger contexts that often determine or at least bound their agricultural and financial decisions (e.g., crop insurance, input subsidies, 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 provides expert consensus evaluation of currently accepted methods of quantifying SOC that could provide the basis for a modern soil information system.

In recent years, soils have garnered increased attention for their crucial role in food security, provisioning of ecosystem services (e.g., clean water) and their capability and potential to help mitigate climate change – against a backdrop of widespread soil degradation across much of the globe. Unquestionably, the role of soils as the foundation for the farms, ranches and forests that sustain human society and the stability of governments, and indeed all terrestrial ecosystems and systems, remains paramount. Soils contain one of the largest organic carbon (C) stocks on the planet, with ca. 1500 Pg C (Pg = 10^{15} g or a billion metric tonnes) to a depth of 1 m and 2400 Pg C to 2 m depth (Batjes 1996). Relatively small percentage changes in these stocks can therefore greatly affect the amount of carbon (as CO₂) in the atmosphere.

When reduction of SOC occurs, it is typically coincident with soil degradation. 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. Anecdotal observations, especially in the past 5-10 years, suggest that agricultural operations that have been managed to improve SOC levels (through reduced tillage, for example) also improve soil quality, e.g. tilth, and outperform more conventionally managed systems with respect to agricultural yields and yield stability, especially under drought stress. Further, several high-profile papers have highlighted the potential for increased emissions of greenhouse gases (GHG) from soils in association with climate change. Conversely, the potential to increase C sequestration in soils, whereby soils act as a global ‘carbon sink’ for CO₂ removed from the atmosphere, is one of the few options for actively removing CO₂ already in the atmosphere, while at the same time improving soil health. Along with CO₂ capture and storage and biomass C sequestration in forests and long-lived wood products, 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 (Paustian et al. 2016). In the most recent IPCC assessment (Ciais et al. 2013, Smith et al. 2014), many of the integrated assessment models for GHG reduction strategies suggest that aggressive fossil fuel reductions must be supplemented with negative emission / 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 Hansen et al.'s (2016) recent analysis on the need for carbon negative emissions, as well as Rockström et al.'s (2017) roadmap for decarbonization. Many observers feel that relative to other negative emission options, soil C sequestration may offer the cheapest and most readily implementable option, while also contributing to improvements in soil health and other positive environmental outcomes on managed lands. Hence the heightened interest in soils in the context of climate change mitigation, adaptation and resilience.

Soil organic carbon constitutes about 60% of soil organic matter (SOM). SOM is the decomposing remains of plants from vegetation, crop residues, root exudates, manures and other organic wastes returned to the field; so, the other 40% includes essential nutrients for new plant growth. Farmers have known for millennia that their crop and soil management activities influence the health and fertility of soils, including the organic matter content. Formal scientific studies have been carried out for nearly two centuries¹ to determine the impact of various crop and soil management practices on SOM and resultant crop responses. Prior to the late 1980s, studies of SOM dynamics were almost exclusively done in the context of how changes in SOM influence soil physical properties (e.g. infiltration, porosity) and nutrient availability that affect crop growth.

Early studies on how management might be used to increase SOM for the purpose of removing more CO₂ from the atmosphere (Barnwell et al. 1992) relied on field experiments (Paul et al. 1997) and models (Powlson 1996, Paustian 1994) 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 our core knowledge of SOC dynamics. More recently in the past 20-30 years however, there has been considerable new research focused more on 'soil C accounting'. Given the myriad factors that control C dynamics in soil, we are far from having full knowledge of SOC across the diversity of managed ecosystems. Nevertheless, it is fair to say that we understand the basic controls on SOC and know reasonably well which management practices can be used to increase SOC storage across a wide range of environments. This then leads to the more proximal question of how can society develop the infrastructure, value improvements in SOC profile systems and create policies and practices that can promote the regeneration, maintenance and increase of C storage in soils as a powerful agricultural risk management strategy? Further, how can these methods be developed to ensure positive and equitable outcomes across a range of other key factors?

The fact that many farmers and ranchers still don't employ practices that maximize C storage indicates the need to incentivize practices that do. 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 improving long-term soil health, thus boosting productivity even in times of relative drought. 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 for declines in yield. However, there are many mainly anecdotal reports from farmers who have adopted SOC rebuilding activities about the reduction in other inputs, including fertilizers (because

¹ Boussingault, J.B. (1841) Ann. Chim. Phys. (III), 1, 208. (Cited by E.J. Russell – *Soil Conditions and Plant Growth*. 8th Ed., Longmans, Green and Co Publisher, 1953.)

of the nutrients associated with SOC in SOM), fossil fuels (because soil tillage improves reducing plough draft and diverse no-till cropping systems use less fuel and inputs), irrigation (because SOC holds water in soils right next to plant roots), and animal health (because the nutrition of forage is improved). Thus, there are opportunities for monetary benefits to the farmer to balance the potential added costs and to drive widespread adoption of improved practices.

Currently, there are three ways by which the value of soil C sequestration can potentially be included in financial returns to farmers and ranchers.

First, government subsidies as direct payments or as cost sharing can incentivize farmers, such as with the USDA Natural Resource Conservation Services (NRCS) Environmental Quality Incentives Program (EQIP)² and Conservation Reserve Program (CRP)³ in the U.S. Although these programs were designed to support more general resource conservation objectives, the practices they promote are generally compatible with C sequestration and GHG emission reductions. Further, the USDA Climate Building Blocks for Climate Smart Agriculture and Forestry plan⁴, established in 2015, reflect the inclusion of GHG mitigation benefits through soil health in the program objectives.

Second, farmers and ranchers could be directly compensated for CO₂ removal and storage as SOC as a C offset, in which emission reductions are marketed as a commodity. Some offset projects that include soil C are ongoing with several registries operating in the voluntary market space. Currently, however, registries make up a relatively small proportion of the total project volumes in the voluntary market. Further, low C prices (averaging < \$5/tonne CO₂) have limited project development to date (Hamrick and Goldstein 2016).

Third, agricultural producers are increasingly recognizing that improved “soil health” delivers diverse benefits including resilience of crop yield to drought, improved nutrient supply, reduced fossil fuel use for field operations, lengthened grazing seasons and improved profitability. Further, there is interest within supply chains to account for and reduce their ‘carbon footprint’ to reduce various types of risk and in some cases, appeal to environmentally-conscious consumers willing to pay a premium for more sustainable products. Diverse practice-based “standards,” “tools” and certification schemes in addition to brand and company pledges have proliferated to meet this demand.

Regardless of what approach is pursued, reliable and cost-effective quantification methods are critical to designing and implementing improved management of soil organic matter including soil organic carbon, and C sequestration policies in the land use sector. However, depending on the policy instrument used, the accuracy required, the acceptable level of uncertainty, and the allowable costs for measurement and monitoring, the 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 other conservation benefits, rather than, or in addition to, SOC. Some soil C offset

² <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip/>

³ <https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/?cid=stelprdb1041269>

⁴ <https://www.usda.gov/sites/default/files/documents/building-blocks-implementation-plan-progress-report.pdf>

programs are based on changes in management practices to increase SOC, rather than direct measurement of SOC on individual parcels of land. Any such programs must be founded on research that has included careful measurements to validate linkages between management practices and SOC storage. In general, there is an inverse relationship between measurement certainty and cost, and thus designing the most appropriate quantification approaches will to some degree involve determining the acceptable tradeoff between accuracy/precision and cost.

In this paper, we provide a short overview of current methods and approaches for quantifying SOC stock changes and removals of CO₂ from the atmosphere and its incorporation into SOM. Our aim is to illustrate how these methods apply to the quantification of SOC, at field to national scales, and give examples of the application of these methods in programs in Australia and Canada. We then outline needs to fill knowledge gaps and improve methodologies for a public goods system that might better quantify, monitor and report SOC stock changes as part of an agricultural risk management strategy as well as representing a key attribute in tracking and improving soil health.

2. QUANTIFICATION METHODS

Associating CO₂ removals with soil C stock changes

For purposes of improving managed soils, the **net** amount of CO₂ that is removed from the atmosphere and incorporated into the soil such that it increases the soil's total C sink capacity is the metric that matters. However, this value is the difference between two large fluxes of CO₂: 1) the uptake of CO₂ by plants and 2) emissions of CO₂ via respiration from plants and the soil biota. Since the net flux of CO₂ 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 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 C held in plant biomass and soils, an increase in SOC stocks is a close proxy for the net uptake of C (as CO₂) from the atmosphere. Conversely, 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 CO₂ accounting approach. In agricultural systems that are non-forested (e.g. cropland and grassland), plant biomass stocks are relatively small and mostly ephemeral due to 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 net source or sink of C. As a result, most of our discussion of measurements and modeling as quantification approaches focuses on determining SOC stock changes over time. Historically however, scientists have used other rigorous methods to assess SOC changes.

a. Direct measurement – CO₂ fluxes

The most direct means to determine whether ecosystems are functioning as a net C sink and therefore acting to *reduce* atmospheric CO₂ concentrations is by directly measuring the net CO₂ exchange between 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 (Baldocchi 2003). The most widely used technique, “**eddy covariance**” (EC), relies on very frequent and highly accurate measurements of

CO₂ 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 (CO₂ uptake) and ecosystem respiration (CO₂ release). When combined with measurements of harvested exports, 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 (e.g., Ammann et al. 2007, Matsuura et al. 2014), in which grazers make other on-the-ground sensors difficult to maintain, particularly at the levels of replication needed to account for grazer influence on heterogeneity, and for systems on peat (i.e., organic) soils (Hirano et al. 2007, Nieven et al. 2005), which have varying density and depth of organic layers that make SOC stock changes difficult to estimate on a large scale with other technologies. 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 that require relatively homogenous study plots of very specific scales that are not always possible in manipulative field experiments. While these types of measurements are very useful for developing and validating ecosystem C models (see section c, below), they are not practical for routine deployment for C offset projects or in extensive farm/ranch based measurement and monitoring networks. Rather, in such systems soil sampling and SOC stock change measurement is typically the most feasible field measurement.

b. Direct measurement – soil C stock changes

Take Home messages:

- Calculation of SOC stocks requires volumetric soil samples (to estimate bulk density) which are more laborious to collect than soil samples often 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 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 over time relative to 'background' SOC stock.
- Efficient, fit-for-purpose sampling designs that employ georeferenced benchmark sites and that optimize the balance between sampling intensity and reduced uncertainty can lower the cost and improve accuracy of direct measurements.

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. Thus, determining the concentration of C in a soil sample is **not**

technologically challenging or especially difficult. However, large aggregated mitigation and 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 preferably an estimate of the temporal change 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 to design effective *sampling methods* and to contain the time and effort in *sample processing and analysis*.

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 five-fold or more (Robertson et al. 1997). Using conventional approaches with simple randomized and/or stratified sampling schemes, accurate estimation of the “average” SOC contents across fields of 10s of hectares might require 10-100s of samples (Garten and Wulfschleger 1999). 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 top soil layer. In some cropland soils, SOC content may be fairly homogenous from 0 to 20 or 30 cm due to mixing by tillage, but in unplowed soils (grassland, forest, and 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 exclude inorganic C, especially in sub-surface layers, are required in many regions. Thus, 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 depth intervals. The 0 to 30 cm soil layer specified by IPCC 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, and even the minor changes to subsoil SOC stocks that manifest under typical cropping systems have the potential to amount to nontrivial quantities of C at the farm scale (Collier et al. 2017). 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 less than $0.5\text{--}1\text{ Mg C ha}^{-1}\text{ yr}^{-1}$, whereas ‘background’ SOC stocks in many soils, just in the top 20-30 cm, can be in the range of $30\text{--}90\text{ Mg C ha}^{-1}$. 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*. Establishing precisely located benchmark sites (e.g. Ellert et al. 2002, Conant et al. 2003), that can be resampled over time, can reduce sample requirements by as much as 8-fold compared to simple random or stratified random sampling designs (Lark 2009). Because much of variability of soils occurs at fine spatial scales, per unit area sample size requirements decrease greatly as the area of inference increases in size. Accordingly, field measurement approaches will be more feasible for supporting regional and national scale assessments of SOC, whereas current technologies are likely too expensive to support smaller SOC projects. 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 (e.g. DeGrujter et al. 2016).

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 % of total soil mass, i.e., 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. Secondly, 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, e.g., 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 (Bellon-Maurel and McBratney 2011). Since the instrumentation consists of a light source and detectors, much faster throughput of samples is possible compared to wet or dry combustion methods, analysis costs are much cheaper and the smaller, less demanding equipment can potentially be deployed in field labs and in developing countries (Shepherd and Walsh 2007). 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 technologies that don’t use conventional combustion methods and thus might be more readily deployed in the field have been tested (e.g. Izaurralde et al. 2013) but none have 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 (e.g. Rossel et al. 2016). However, such technologies are still at an early stage of development and their utility for quantification in support of soil C offset projects is yet to be determined. However, these direct measures of SOC still require a measure of soil bulk density to calculate SOC stocks.

More information on soil sampling and SOC analysis methods can be found in the full white paper by Ellert.

c. Model-based estimation 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 of soil and climate variables, on SOC stock changes. 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 (as discussed above) are a primary source of the information upon which these models are based (Campbell and Paustian 2016).

Broadly speaking, there are two types of models used to predict SOC stock changes: i) empirical models, which are based on statistical relationships estimated directly from sets of field experiment observations, and ii) process-based models, in which the model algorithms are based on more general scientific understanding, laboratory and field experiments, as well as variety of field-based measurements. Most process-based models aim to achieve a more *general* understanding and predictive capacity, based on the biogeochemical processes that control SOC dynamics and 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.

1. Empirical models

The most well used and widely known empirical based model for predicting SOC stock changes is the model developed for the Intergovernmental Panel on Climate Change (IPCC) national GHG inventory guidelines. The so-called Tier 1 method was developed to provide an easy method for countries (especially developing countries) to estimate national-scale SOC stock changes as a function of changes in land use and management practices (Paustian et al. 1997, IPCC 2006). 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 (Batjes 1996). Then a set of scaling factors, estimated from statistical estimates of extensive field data sets (e.g. Ogle et al. 2004, 2005), are applied to represent management impacts on stocks (i.e., land use type, relative C input level, soil management). Soil organic C stock changes are then computed for the stratified (i.e., climate \times soil \times 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:

$$\Delta SC = (SC_0 - SC_{(0-T)})/D$$

$$SC_i = SC_R * F_{LU} * F_{MG} * F_I * A$$

Where:

ΔSC = annual soil carbon stock change, Mg C yr⁻¹;

SC_0 = soil organic carbon stock at time 0, Mg C ha⁻¹;

$SC_{(0-T)}$ = 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 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.

2. Process-based models

Process-based models are generally in the form of computer simulation models that employ sets of differential equations (which describe **rates** of change) to describe the time and space dynamics of soil organic matter. Most of the models that are currently used to support GHG inventory and/or field to project-scale quantification were originally developed for research purposes, to analyze the behavior of soil organic matter 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, tillage, fertilizer, irrigation, residue management). Thus, 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.

Table 1. Some widely-used process-based models that include soil carbon.

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	Citation class*
DNDC	http://www.dndc.sr.unh.edu/	Li et al. (1992)	Li et al. (1997)	Grant et al. (2004)	Smith et al. (1997)	Wattenbach et al. (2010)	IV
ROTHC	http://www.rothamsted.ac.uk/sustainable-soils-and-grassland-systems/rothamsted-carbon-model-rothc	Jenkinson (1990)	Coleman et al. (1997)	Cerri et al. (2007)	Smith et al. (1997)	Falloon and Smith (2002)	III
APSIM	www.apsim.info	Mccown et al. (1995)	Luo et al. (2011)	O’Leary et al. (2016)	Moore et al. (2014)		III
DAYCENT	http://www.nrel.colostate.edu/projects/daycent/	Del Grosso et al. (2001)		Nocentini et al. (2015)	Del Grosso et al. (2016)	Smith et al. (2012)	III
DSSAT	dssat.net	Jones et al. (2003)	Gijsman et al. (2002)	De Sanctis (2012)	Yang et al. (2013)		II
ECOSYS	http://ecosys.ualberta.ca/	Grant (1997)	Grant et al. (2001)	Mekonnen et al. (2016)	Lokupitiya et al. (2016)		I

EPIC	http://epicapex.tamu.edu/	Izaurrealde et al. (2006)	Apezteguia et al. (2009)	Zhang et al. (2015)	Lokupitiya et al. (2016)		II
SOCRATES	http://socrates.n2o.net.au/main	Grace et al. (2006a)	Grace et al. (2006b)				I

3. 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). We present these three systems 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.

a. 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 CO₂. The ERF is enacted through the *Carbon Credits (Carbon Farming Initiative) Act 2011* (CFI). Under the ERF, businesses, farmers and community groups can earn C credits by undertaking projects to reduce emissions or sequester carbon. A range of methods have been approved for all sectors of the economy. For the purposes of this paper, we will be focusing on methods that increase SOC stocks. Projects must comply with the Offsets Integrity Standards, which ensure emission reductions 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 one tonne of carbon dioxide equivalent (CO₂-e) and can be sold to the Australian government or in a secondary market to generate income.

Currently, two soil C sequestration quantification methods have been endorsed by the Emissions Reduction Assurance Committee and made 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 is based on the direct measurement of changes in SOC stocks obtained through collection and analysis over time, whereas the second method is based on the use of default rates of soil C change predicted using a process-based model (Richard and Evans 2004, Skjemstad and Spouncer 2003). Common to both soil C methods are the definitions of a project, a project area and carbon estimation areas (CEAs) (Figure 1).

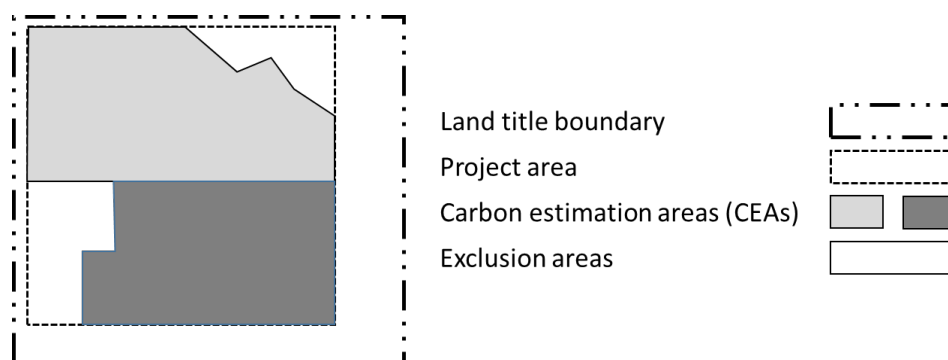


Figure 1. Schematic representation of the relationship between land title boundary, project area and carbon estimation areas.

“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 United Nations Framework Convention on Climate Change (UNFCCC). FullCAM model is process based and designed to be nationally applicable. The RothC soil carbon model (Table 1) is a constituent of FullCAM.

There are three defined classes of soil C sequestration rates: marginal benefit, some benefit, and more benefit. These rates are determined by a series of simulations and statistical tests to generate a histogram, which enables the three-class regionalization (Table 1; Fig. 2). More information on allowable activities and conditions can be found at (www.environment.gov.au/climate-change/emissions-reduction-fund/methods/sequestration-carbon-modelled-abatement-estimates).

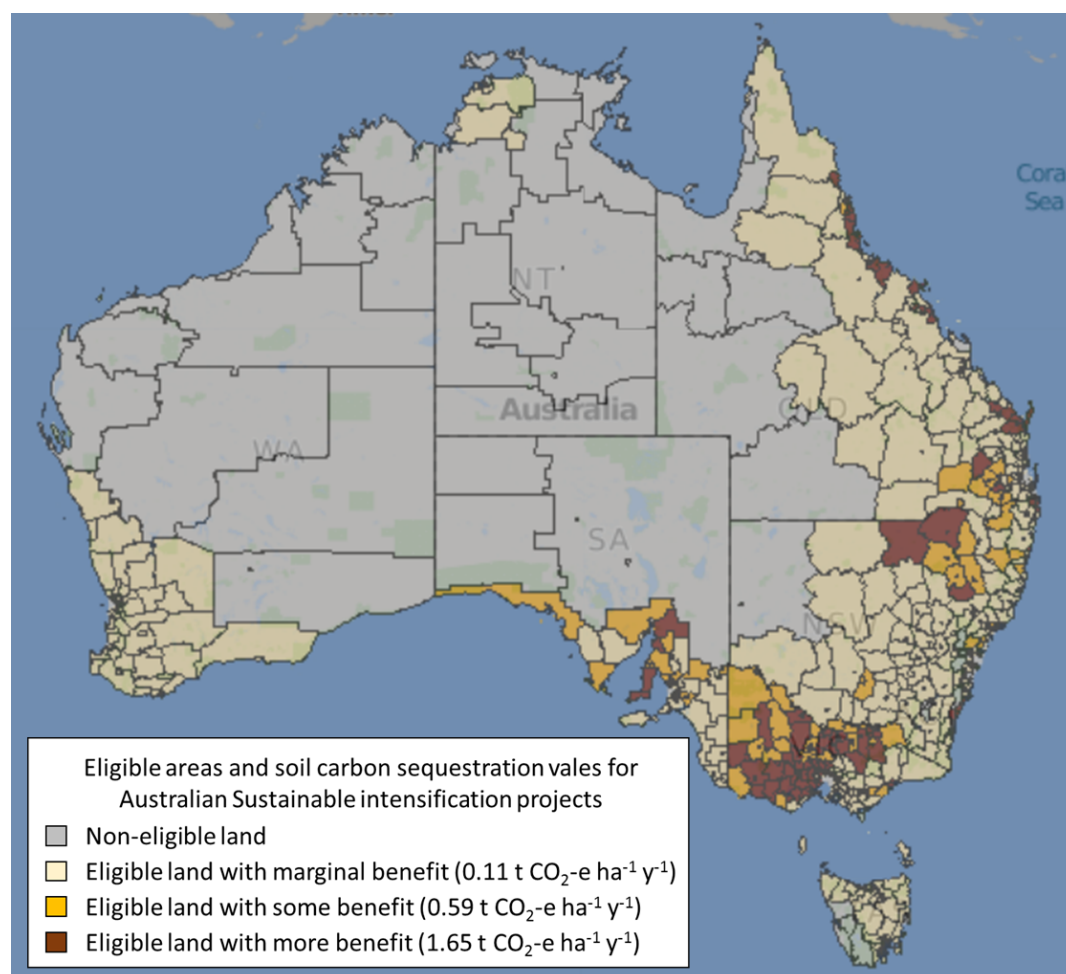


Figure 2. Delineation of non-eligible and eligible lands for Sustainable intensification projects and the areas associated with each of the three levels of soil C sequestration benefit predicted using the soil carbon component of the FullCAM simulation model.

Provided a project meets its reporting obligations and remains eligible, using the second methods based on default values, 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.

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

Project Type	Sequestration value ($\text{t CO}_2\text{-e ha}^{-1} \text{ year}^{-1}$)		
	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

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

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.

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 ₂ O 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. NGGI emission factors are to be used.
Synthetic fertilizer	CO ₂ N ₂ O	Include	Application of synthetic nitrogen fertilizers result in emissions of N ₂ O, and in the case of urea also CO ₂ . NGGI emission factors are to be used.
Non-synthetic organic based fertilizers	CO ₂ N ₂ O 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 CEA to which they have been applied would be no greater than 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 neutralise acidity. NGGI emission factors are to be used.
Irrigation energy	CO ₂ N ₂ O 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 ₂ O	Include	Retention of residues from crops will result in the emission of N ₂ O when they decompose. NGGI emission factors are to be used.

Residues burning	- CO ₂ N ₂ O CH ₄	Exclude CO ₂ Include N ₂ O 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 ₂ O and CH ₄ emissions due to the removal of burning in progressing from the baseline to project conditions need to be accounted for. NIR emission factors are to be used.
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More information is provided in the full white paper by Baldock (Paper pending).

b. Alberta, Canada

In 2007, the Government of Alberta amended the Climate Change and Emissions Management Act (CCEMA) to require industries with emissions (CO₂-e) exceeding 100,000 tonnes per year to report and reduce their emissions to established targets. Under the CCEMA “large emitters” are required to reduce their emissions by 12% below their baseline. They have three options to meet their reduction goal: emission performance credits, emission offsets, and technology fund credits. The Alberta Offset System operates under a set of policies, rules, standards (known as Offset Quantification Protocols) and Guidance Documents to ensure that offsets are of the highest rigor and quality to ‘offset’ regulated companies’ requirements. The development of offset protocol that Alberta follows includes expert engagement, defensible scientific methodologies, a rigorous peer review process, and documented transparency.

The Alberta Offset System also requires a properly functioning market. For a C market to function well, it needs a range of science-based quantification protocols developed transparently with a technical review to help provide certainty to buyers and sellers and reduce transaction costs. The carbon market also relies on aggregator companies, which aggregate credits from a number of sources (typically a group of farmers or land holders) to assemble projects that interest the 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 – thereby driving increased uptake of positive practices that favor soil conservation and carbon sequestration.

Although several protocols for agriculture have been developed, here we address the Conservation Cropping Protocol (CCP), previously known as the Soil Till System Management Protocol. This protocol focuses on sequestration of additional SOC attributable to a change from conventional to conservation (usually no-till) cropping practices. It has been the most sought after type of agricultural GHG project, and conservation tillage offsets have made up roughly 30% or better of the annual market share to deliver over 1.5 million tonnes of offsets since the system began in 2002. It uses Canada’s National Emissions Tier II methodology, which developed 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 C sequestration coefficients to provide a low-range estimate of increased SOC stocks that might be expected for a change from conventional tillage to no-till cropping 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.

Eligible actions for offsets typically must be new and additional to business as usual. Since reduced and no tillage practices are being adopted already 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. Essentially the sequestration coefficient was discounted for the slope of the increase of no-till and reduced till adoption 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 current adoption rates of zero or reduced 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). 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 (laggards get less).

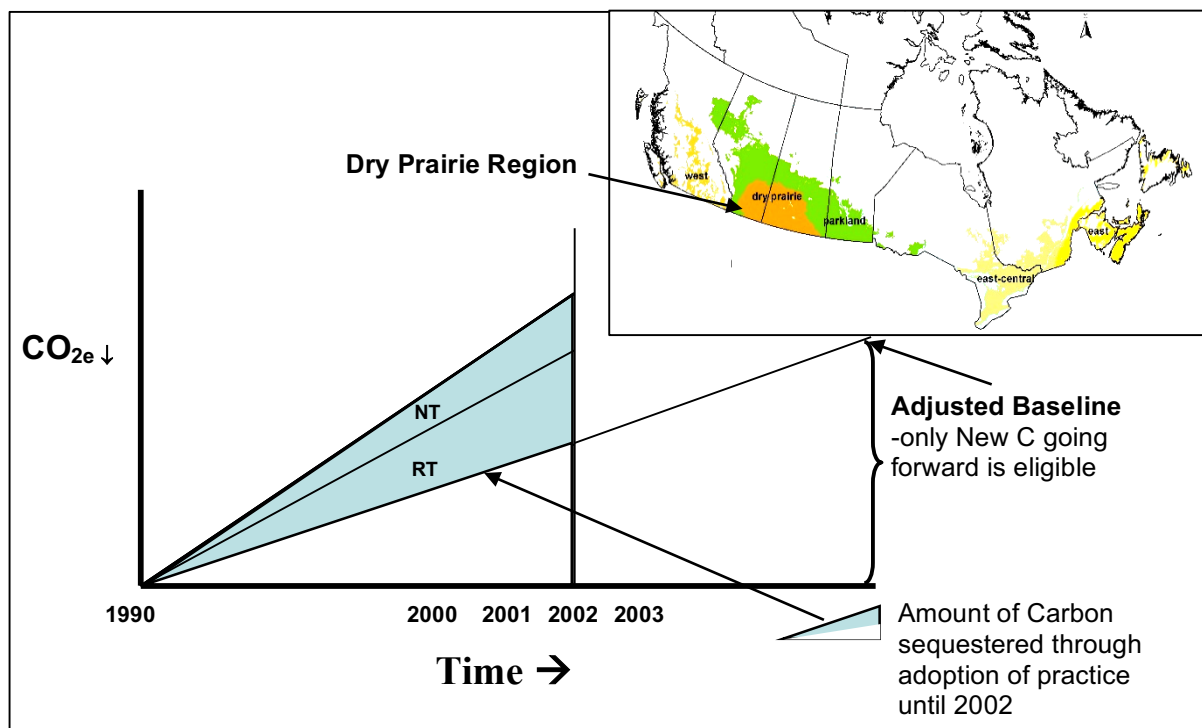


Figure 3. Schematic of the Adjusted Regional Baseline for the Dry Prairie Region - discount based on the adoption rate of reduced till (RT) and no-till (NT) practice for the Baseline Year (2002).

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 CO₂-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.

However, no protocol is perfect. Regardless of how good the scientific basis, 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 costs when designing offset markets. To minimize risks and keep transaction costs from escalating, Alberta Agriculture and Forestry (2017) has created and maintained a website to help inform the industry stakeholders of rules and guidance materials for the sector. Another burden that sometimes goes unseen is the cost of verification, which does not conform to discrete records of financial transactions or recording meters on factory pipes or smokestacks. Similar to designing a project with the end in mind, offset design should keep in mind the verification needs and associated costs.

c. Saskatchewan, Canada

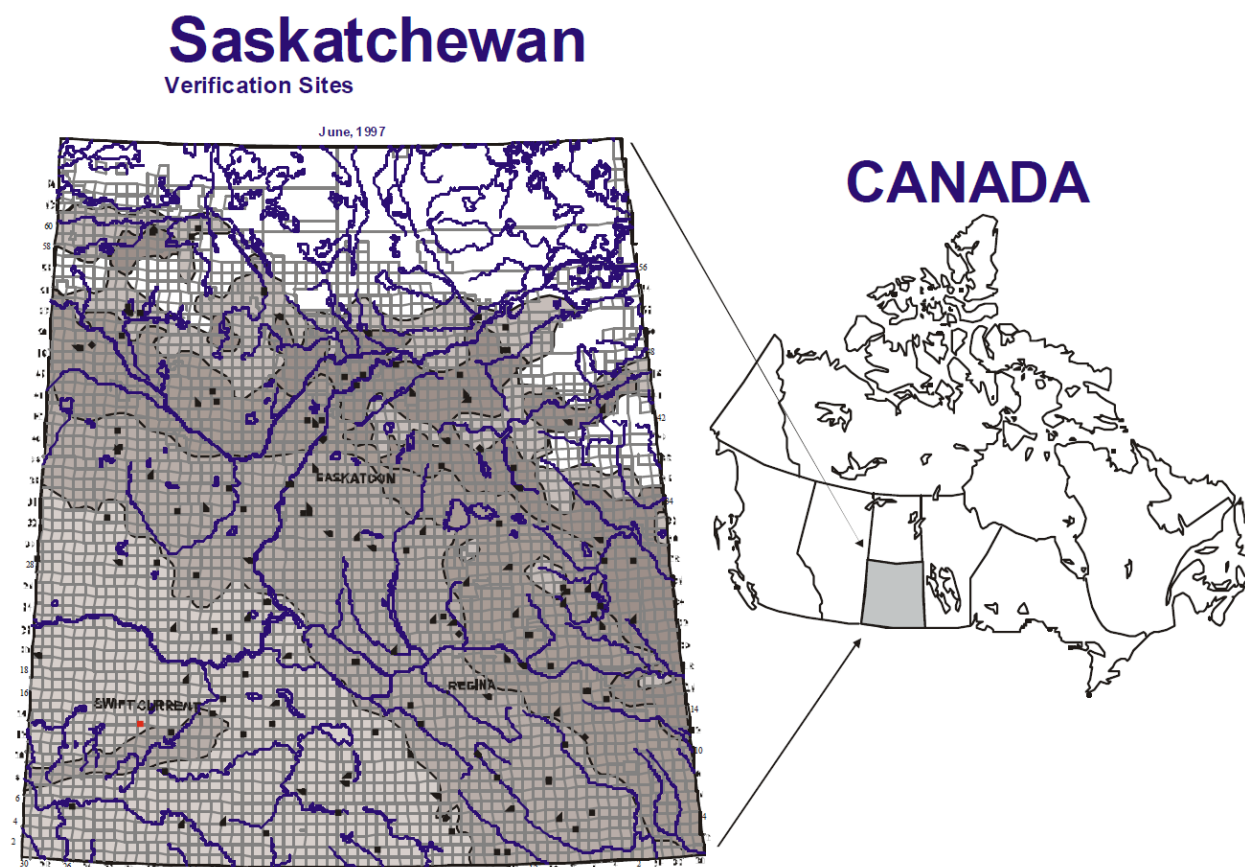


Figure 4. Locations of 137 sites established in 1996 to assess soil organic carbon change in the PSCB project. The background map depicts the soil zones of Saskatchewan.

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 (McConkey, 2013). 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 greenhouse gas (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 occurred (in 1996 or 1997) (Figure 4). The soil sampling and analyzing strategy followed the protocol outlined in Ellert et al. (2001). 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.

During the 15 year course of the study, there were continual changes in the owner or land manager where the sites were located, and sites were lost to attrition. In 2005 121 sites were sampled, but at the last sampling in 2011, 82 sites had the required management data and manager authorization for inclusion in the project. In one representative field, the spatial variation among eight microsites (each 4 x 7 m) was found to be large (95% CI ± 3 Mg C ha⁻¹ for the 30 cm depth). Thus, as anticipated, the number of microsites required to measure SOC change for an individual field (30-65 Ha) would render the approach prohibitively expensive.

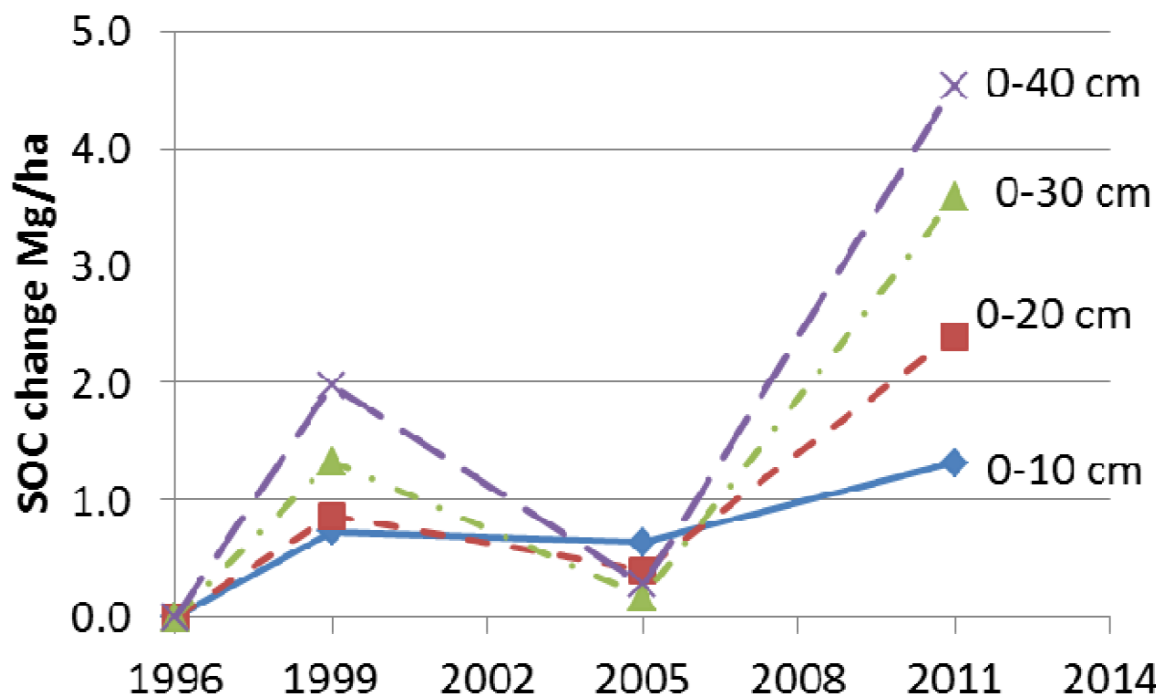


Figure 5. Changes in soil organic carbon after adoption of no-till in 1996 (n=80 sites available in 2011 plotted for all sampling years; 95% confidence interval typically was ± 1.5 for the 30 and 40 cm depths; ± 0.5 in 1996; adapted from McConkey et al., 2013).

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 (Fig. 5). The temporal changes varied among sampling times, and in 2005 were indistinguishable from zero, possibly because the 2001-2003 drought restricted C inputs to a greater extent than decomposition. By the 2011 sampling, SOC stocks had rebounded, and the gains in soil C increased with the cumulative depth or soil mass considered (Fig. 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 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.

4. FUTURE DIRECTIONS/RESEARCH NEEDS

As demonstrated by this paper, there has been substantial progress toward recognizing the key role of SOC in relation to many core ecosystem services, as well as in measuring and modeling changes in SOC pools in response to both environmental and agricultural management factors. As a result of this progress, entrepreneurial programs and methods are being developed that can help lead the way toward a more comprehensive inclusion of SOC in farmers' and ranchers' decision-making going forward. While many issues still require significant research and attention (such as questions regarding SOC saturation and carbon sequestration reversal, co-benefits and tradeoffs of practices that maximize SOC, the need to ensure food security and equitable outcomes, open data and privacy issues, etc.), a critical mass of information is now available and serves as a foundation for forward movement.

Accurate information on SOC quantification is crucial to the development of a new soil information service, the need for which is building. In 2012, a report from the U.S. President's Council of Advisors on Science and Technology concluded that the U.S. is not adequately prepared to face the agricultural challenges that lie ahead. One such major challenge is to adequately protect, properly manage and, where necessary and viable, restore one of the nation's most critical strategic assets and one of humanity's most fundamental assets; our land and soil resources. While reliable data are scarce, one global estimate suggests that more than 50% of land used for agriculture is "moderately to severely" degraded (Hamdy and Aly 2014). And while the U.S. can properly point to significant success in its public investments and programs that have supported farmers in maintaining and improving their overall land productivity over decades, there are growing signs of problems ahead especially if farmers face more variable and extreme climatic conditions. One necessity in better preparing ourselves to face these emerging challenges, that will also enable proactive, targeted and cost-effective responses, is to transform the land and soil resource information architecture and functionality that underpins our ability to characterize these resources in near real time.

The two workshops on which this paper is based, and a number of other consensus gatherings convened by government, industry, individual philanthropists and non-profit organizations reflect the growing consensus among land managers, soil scientists, government, and technology communities of the need to build a new soil information service. This service will fully leverage the unparalleled technological opportunities to capture, curate, share, and explore more granular and dynamic data and knowledge resources in a learning, deeply interactive, open system. 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 motivated stakeholders.

The pathway of this vision builds on the unique foundation established through the longstanding efforts of USDA (NRCS) and leverages the examples in Australia, Canada and elsewhere. The soil measurement, monitoring and open reporting systems established by NRCS have served the nation well. But there remains significant scope for modernization. The new soil information service will

have a more holistic perspective on the current and future needs for land and soil resource information (e.g. across multiple scales and beyond the agricultural sector) and, be more nimble, pluralistic and collaborative.

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