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Date: May 11, 2022

# Protocol for Budgeting Soil Organic Carbon Sequestration through No-Tillage Agricultural Management Practices (GHG0003)

Regions: Canadian Prairies, Western Canada (Alberta, Saskatchewan, and Manitoba)

GHG Registry

# Content

# Executive Summary

Protocol GHG0003 provides methodology for budgeting soil organic carbon (SOC) sequestration through no-tillage (NT) agricultural management practices for the Canadian Prairie, Western Canada. The conversion from conventional tillage (CT) to NT involves two distinct mechanisms implicated in carbon offsets from land—additionality and avoidance. The former refers to the carbon accumulation in soils due to continuous NT management. Additionality in this protocol is composed of historic rewards for past SOC sequestration accumulated through NT management and/or future SOC sequestration attained through NT management. Soil carbon offsets through NT agricultural management are conceptualized as the amount of SOC that has been sequestered over the project time period in a specific project area. The 'project start' is defined as the time when arable land was converted from CT to NT and may be in the past or at current time. The baseline SOC stock represents the soil carbon storage at the current time (nowcasting). The historic stewardship role of farmers in adopting NT practices in the Canadian Prairie is rewarded through backcasting or ex-post analysis (historic additionality → historic SOC sequestration), while present carbon accounting (nowcasting) and forecasting facilitate to project SOC sequestration rates (ex-ante analysis).

**The methodology of GHG0003 requires the completion of the following tasks:**

1. Identification of project boundary and characterization of project.
2. Assessment of baseline conditions (i.e., nowcasting of current soil carbon storage).
3. Recording of soil and climatic conditions as well as crop type and management during the project time period.
4. Quantification of SOC sequestration rates and total SOC sequestration amount under NT for the project area and project time period.
5. Provision of a verification project report that ensures reliability of farm-specific crop, soil, and climatic data and uncertainty assessment of SOC change under NT for the project area and project time frame (ex-post analysis).

**All projects using the methodology of this protocol must meet the following conditions:**

1. Adoption of NT agricultural management within the project time frame. There is no minimum of land area required.
2. The project time frame is defined by land under NT agricultural management up to a maximum of 20 years. At project start the land was converted from CT or reduced tillage to NT.
3. Sustained NT management without interruptions by intermittent tillage operations during the project time frame. If a tillage operation is performed while otherwise NT management is used a temporary reduction in SOC sequestration of 25-50% (possibly higher or lower depending on site-specific conditions) can be expected for 1-3 years (possibly shorter or longer depending on site-specific conditions).
4. The project start time is the year in which NT practice was adopted. The project time period cannot exceed more than 20 years. However, the practice to be followed beyond the time frame to maintain permanence.
5. As of the project start date, all of the project area consists of croplands.
6. Crops under this protocol refer to common crop types planted in the Canadian Prairie.
7. The land under this protocol must be cropped during the project time frame. If for whatever reason total crop failure occurs in one season a temporary reduction in SOC sequestration may occur in the range of 25-50% (possibly higher or lower depending on site-specific conditions).

Once the protocol has been adopted by a farmer/landowner, monitoring of NT and crop management as well as climatic conditions (e.g., drought conditions) is done on an annual basis to provide accountability.

**The objectives of protocol GHG0003 are:**

**Objective 1:** Identify project boundary and characteristics to assess whether all mandatory protocol requirements are met.

**Objective 2:** Identify the baseline SOC conditions for the project area, that is, quantify SOC stocks within the project area. The purpose of nowcasting (i.e., baseline SOC stock quantification) is to identify a reference for verification of backcasting and forecasting carbon assessments.

**Objective 3:** Assess SOC sequestration for the project area over the project period under continuous NT management and verify results through SOC measurements.

**Methodology to meet objectives**: The quantification of SOC sequestration over the project period entails either backcasting or forecasting depending on when NT was adopted in a given project (NT adoption in the past → select backcasting; NT adoption now → select forecasting). The optional methods (3.1 to 3.4) are applicable to both backcasting and forecasting. The baseline SOC stocks from nowcasting (i.e., SOC measurements at current time or within the following 3-5 years) are used to verify the modeled/simulated SOC sequestration rates and stocks for the project area. The allowable approaches in this protocol to model and verify SOC sequestration and stocks include:

**Method 3.1:** Model SOC sequestration using the Canadian Holos model. Carbon conversion coefficients in Holos are based on the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System.

**Method 3.2**: Simulate SOC sequestration using (quasi) process-based carbon simulation models, such as DayCent, Century, Roth-C, DNDC. These carbon compartment models assume different carbon pools (e.g., active/fast, intermediate, and passive/slow pools) with specific turnover rates.

**Method 3.3:** Model SOC sequestration based on SOC measurements from long-term agronomic field experiments and meta-analysis integrated into a dynamic decision-tree model.

**Method 3.4:** Model SOC sequestration based on Pedometrics-AI modeling.

or hybridized combinations of methods 3.1 to 3.4.

The quantified SOC sequestration accumulated in NT systems derived through any of the four methods are convertible into carbon dioxide equivalent **($CO_2$e**) and **carbon credits.**

# 1. Objectives of GHG0003 Protocol

The objectives of the GHG0003 protocol are to provide the methodology to:

1. Assess the carbon offsets from lands through NT agricultural management over time— historic to current time and/or in the future. Carbon offsets are the carbon sequestered in soils through NT.
2. Verify the carbon sequestered in soils in NT.

The regional scope of this protocol is the Canadian Prairies in western Canada that entails the provinces Alberta, Saskatchewan, and Manitoba and the Canadian portion of the Great Plains.

# 2. Summary Description of the Methodology

The methodology in this protocol is informed by scientific understanding of the global carbon cycle and state-of-the-art carbon assessment approaches. This protocol focuses on the soil carbon pool (below-ground carbon) that interacts with other carbon pools, for example vegetation/crops (biomass carbon) and atmospheric carbon (Figure 1).

Soil carbon sequestration (SOCseq) is the process of capturing and storing atmospheric carbon dioxide ($CO_2$) in soils. The primary processes involved in SOCseq are carbon uptake from the atmosphere into soil via photosynthesis, carbon inputs (residue and amendments), organic matter decomposition, soil respiration (i.e., release of CO2 from soils into the atmosphere), and emissions of other greenhouse gases (GHG) from soils into the atmosphere (Figure 1).

The following main environmental drivers were identified impacting both SOC sequestration and GHG emissions after conversion from conventional tillage (CT) to NT based on long-term agronomic field experiments and meta-analysis (Ogle et al., 2019; Six et al., 2002; Sun et al., 2020; Nicoloso & Rice, 2021): Geographic regional conditions, climatic conditions, soils, and crop-specific factors (Figure 2).

To assess carbon offsets from land through NT the accurate assessment of SOC sequestration rates is critical. In this protocol the SOCseq rates are assessed over the timeframe from reference 'start' (i.e., the time when CT converted to NT) which is labeled 'project start' (MM/DD/YYYY). The 'reference start' serves as starting point on the time continuum extending from historic time (no more than 20 years back in time), current and into the future under which NT is adopted and carbon offsets are calculated (Figure 3). This protocol is focused to quantify the SOC sequestration through adoption of NT over the project time frame.

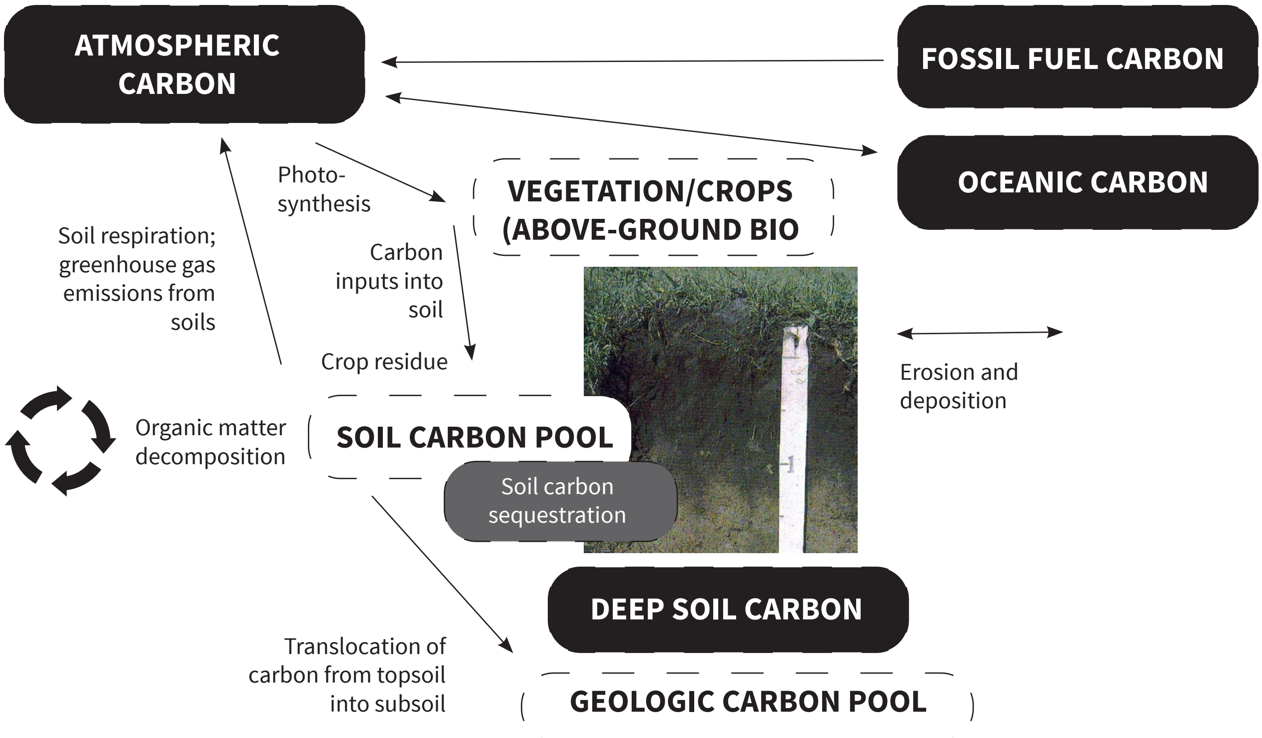



Figure 1. Major carbon pools and primary pathways of the carbon cycle that impact the soil carbon pool and soil organic carbon sequestration (soil image source: Orthic Black Chernozem, Alberta, Canada from the Canadian System of Soil Classification: https://sis.agr.gc.ca/cansis/taxa/cssc3/fig08.jpghttps://sis.agr.gc.ca/cansis/taxa/cssc3/fig08.jpg).

## 2.1 Justification

The conversion from CT to NT involves two distinct mechanisms implicated in carbon offsets from land—avoidance and additionality (Figure 4). Avoidance captures the reduction in GHG emissions ($CH_4$, $CO_2$, and $N_2O$) due to climate/carbon smart management under continuous NT after conversion from CT, while additionality points to the carbon accumulation in soils due to continuous NT management. Additionality and avoidance are interconnected processes since they both are part of the global carbon cycle. Measurements of SOC change (Δ) under NT are available from long-term experiments (20+ years) and have been summarized in the form of meta-analysis (see Grunwald & Biswas, 2022). Measurements of GHG fluxes from soils vary widely across space (from site, field, farm, region to global scale) and across time (e.g., minute to hourly scale) (Bond-Lamberty & Thomson, 2010; Grunwald, 2022; Rochette et al., 1991). It was observed that tilled soils emitted 21% more $CO_2$ than untilled soils in a global meta-analysis (Abdalla et al., 2016). According to Huang et al.'s (2018) global meta-analysis, NT compared to CT reduced GHG emissions and increased crop yield in dry climate, but not in humid climates; and NT reduced the global warming potential (GWP) only at sites with acidic soils. The net effect of NT (relative to CT) was highly variable and influenced by several environmental and agronomic factors (climatic conditions, tillage duration, soil texture, pH, and crop species). In contrast, the global meta-analysis by Shakoor et al. (2021) found opposite trends suggesting that NT increased $CO_2$, $N_2O$, and $CH_4$ emissions by 7.1, 12.0, and 20.8%, respectively, when compared to CT. Overall, the GWP decreased by 7.6% due to conversions from CT to NT, however, with high site-specific variations depending on crop type, climatic zone, water management, nitrogen (N) fertilization, soil pH, and soil texture. The influence of NT on GHG emission measurements remains inconsistent with high variations in outcomes ranging from positive, insignificant to negative effects due to site-specific environmental conditions. The uncertainty in GHG measurements and derived carbon offsets in cases of conversion from CT to NT is substantially higher when compared to SOC sequestration measurements due to the highly dynamic nature and volatility of trace gases compared to SOC.

Earlier studies assumed that SOC sequestration linearly increases following conversion from CT to NT (Figure 4). For example, in a global meta-analysis measured SOC sequestration averaged 337 kg C $ha^{-1}$ per year for 20 years demonstrating a linear increasing trend in SOC following conversion from CT to NT (West & Marland, 2002). However, other global meta-analysis found nonlinear increases in SOC sequestration suggesting that newly converted NT systems increase GWP relative to CT practices, in both humid and dry climate regimes. Longer-term adoption of NT (>10 years) only significantly reduces GWP in humid climates (Six et al., 2004). In this global meta-analysis, only long-term (20 yrs.+) continuous NT in dry climate reduced the mean cumulative GWP due to N2O emissions that are the main drivers for GWP trends. Soil carbon sequestration was rapidly increasing in the topsoil in humid climate (+195, +213, and +222 kg C $ha^{-1}$ $yr^{-1}$) after 5, 10, and 20 years, respectively, while SOC change trends in dry climate was -305, -37, and +97 kg C $ha^{-1}$ $yr^{-1}$, respectively. Linear and nonlinear increasing trends in SOC change in long-term NT were compared side-by-side in a semiarid cool region in the U.S. (Carr et al., 2015). The shapes of curves of SOC sequestration in NT are modulated by site-specific climate, soil factors, and/or crop-specific management.

Importantly, the long-term positive effect to sequester carbon in soils under NT is disrupted by intermittent tillage that leads to a temporary (often few years) decline in SOC sequestration rates and increased GHG emissions. Yang et al. (2013) juxtaposed short and longer-term effects of CO2 emissions from soils and SOC mineralization in “pure” continuous NT compared to soils with occasional moldboard ploughing which are highly complex. Evidence suggests that the continuity in NT management matters to reap the full benefits to sequester soil carbon and reduce GHG emissions. In Figure 4 idealized curves of SOC sequestration as well as the effect of intermittent tillage that disrupts NT and decreases SOC sequestration temporarily are shown. The shape and steepness of increase in SOC over time differs based on site-specific conditions. A simplified generalized form is to assume that SOC increases linearly under NT cropping over many years. Though long-term experiments showed that the increase in SOC declines with time (after about 20 years) and eventually reaches a plateau with a new carbon equilibrium in the soil (Lal, 1998). According to West and Six (2007), the sequestration durations averaged 21 years for a change to NT with estimated total change in soil carbon capacity averaged across climate regimes of 16% for a change to NT. Though SOC sequestration in NT may extend up to 40+ years or even longer, though typically at relatively small rates.

A detailed account of SOC sequestration in NT compared to CT can be found in Grunwald and Biswas (2022).

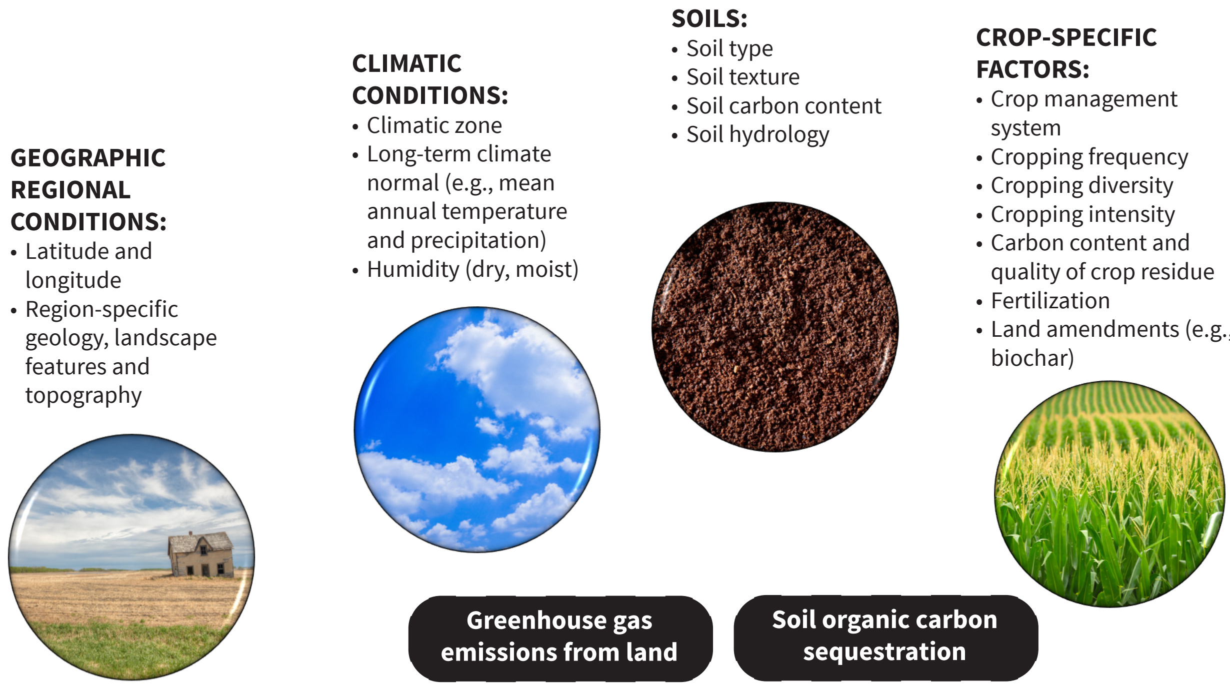
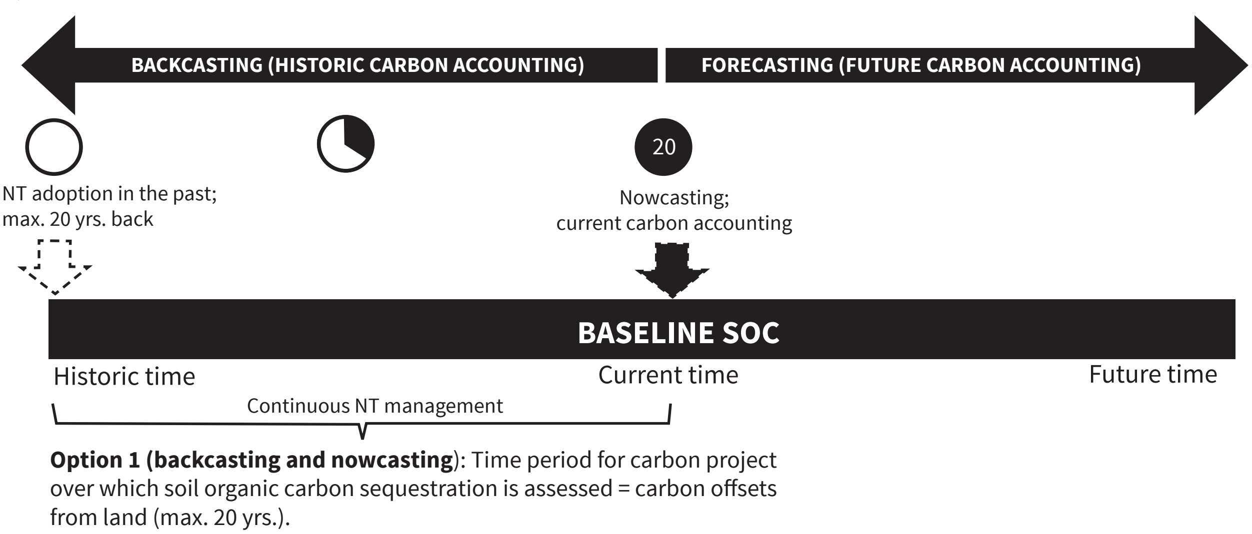



Figure 2. Main environmental factors that impact carbon offsets (greenhouse gas emission reductions from land and soil organic carbon sequestration) due to conversion from conventional tillage to no-tillage

a)



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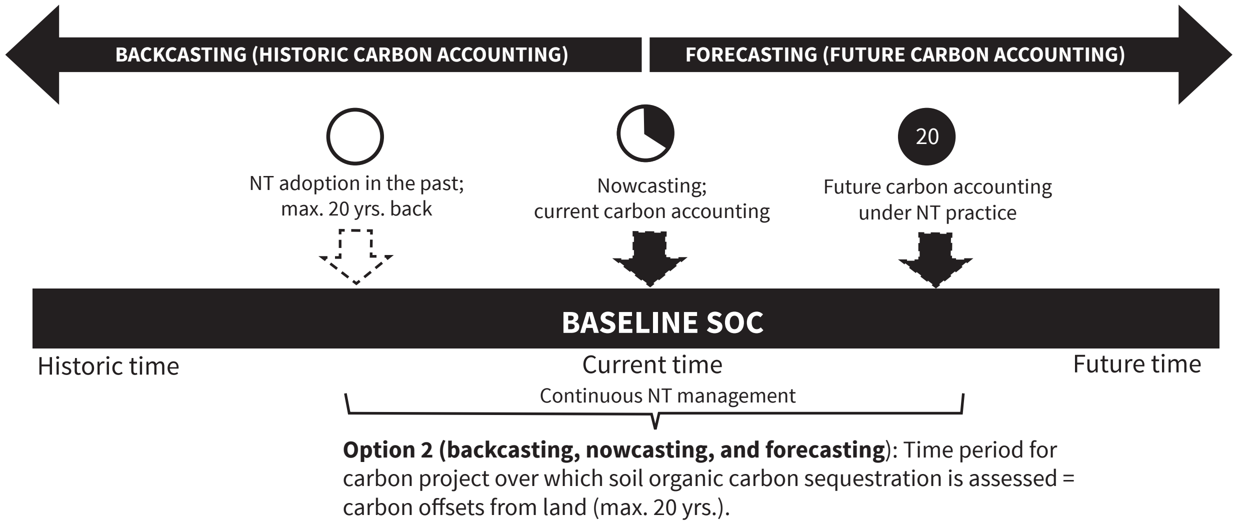


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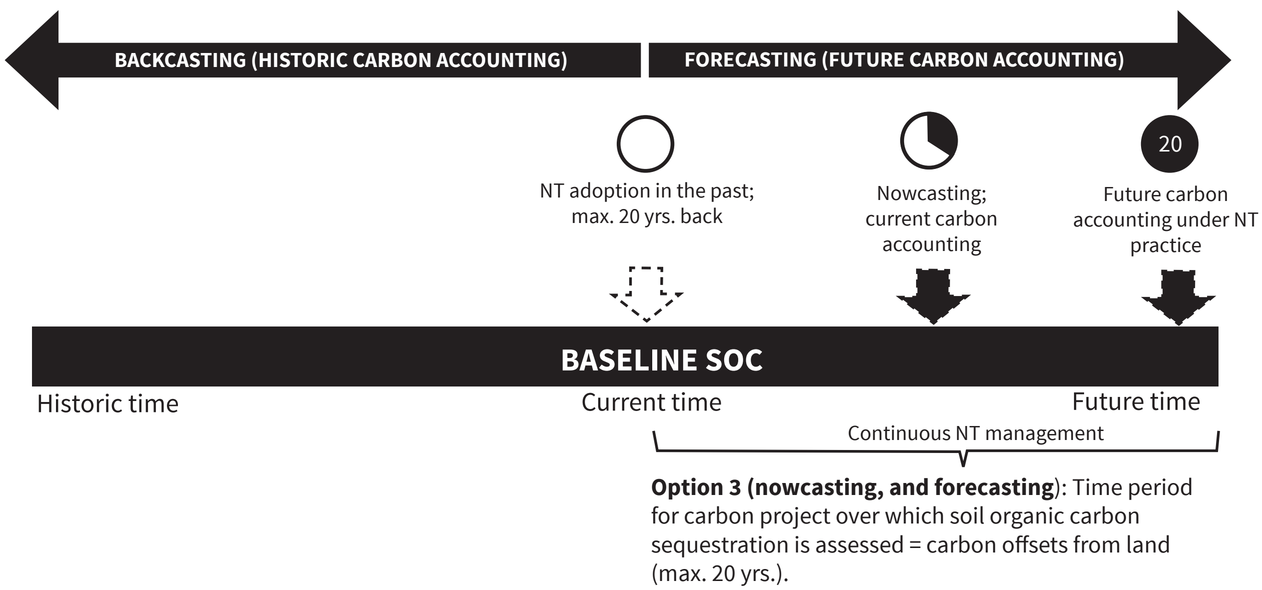



Figure 3. Project timeline for carbon project over which carbon offsets are assessed depending on the time when conventional tillage was converted to no-tillage: a) Historic carbon accounting via backcasting and nowcasting of soil organic carbon sequestration under no-tillage, b) Carbon accounting via backcasting, nowcasting, and forecasting of soil organic carbon sequestration under no-tillage, c) Future carbon accounting via nowcasting and forecasting of soil organic carbon sequestration under no-tillage.

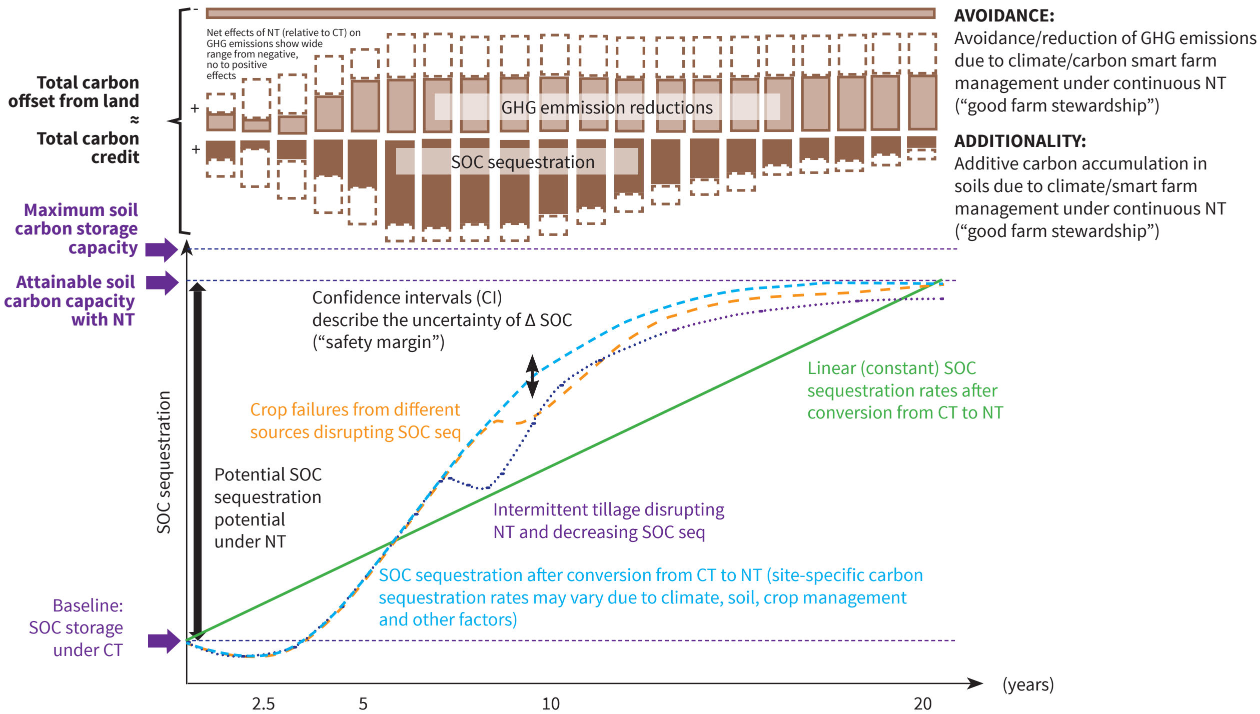



Figure 4. Generalized conceptual understanding of soil carbon sequestration (SOCseq) and greenhouse gas (GHG) emission reductions after conversion from conventional tillage (CT) to no-tillage (NT) over a 20-year period. Both avoidance (i.e., GHG emission reductions) and additionality (i.e., SOCseq) play a role in carbon offsets from land and carbon accounting and crediting. After conversion to NT, the baseline SOC storage changes soil carbon storage over time eventually reaching ‘attainable soil carbon capacity’, and ‘maximum soil carbon storage capacity’. The idealized average SOCseq rates (after West & Six, 2007) may deviate from individual site-specific SOCseq due to soil, climate, crop management, and other environmental factors. Crop failure due to different reasons and intermittent tillage may disrupt average SOCseq rates. The confidence interval (CI) for SOCseq (in Mg C $ha^{-1}$ $yr^{-1}$) express the uncertainty of annual SOC change (Δ) from multiple measurements in fields in NT.

## 2.2 Additionality and Farmers Carbon Stewardship

Soil carbon offsets through NT agricultural management are conceptualized as the amount of SOC that has been sequestered over the project time period in a specific project area. The baseline SOC stock represents the soil carbon storage at the current time in all three options (Figure 3). Site-specific SOC measurements in the past may or may not be available, while verification of SOC stocks and sequestration rates is possible from current time into the future. Therefore, the nowcasted baseline SOC stock serves as verification reference for carbon accounting.

Additionality in this protocol is composed of historic rewards for past SOC sequestration accumulated through NT management (options 1 and 2, Figure 3) and/or future SOC sequestration attained through NT management (options 2 and 3, Figure 3). The time period under this protocol is limited to 20 years because the majority of SOC accumulation after conversion from CT to NT occurs within this time frame based on carbon research. Also the uncertainty in SOC sequestration rates in NT 20-yrs+ is high due to the sparsity of data (Grunwald & Biswas, 2022).

The historic stewardship role of farmers in adopting NT practices in the Canadian Prairie is rewarded through backcasting or ex-post analysis (historic additionality → historic SOC sequestration), while present carbon accounting (nowcasting) and forecasting facilitate to project SOC sequestration rates (ex-ante analysis).

## 2.3 Methodology of Protocol GHG0003

The GHG0003 protocol builds on scientific understanding of carbon dynamics and carbon accounting as outlined by the Intergovernmental Panel on Climate Change (IPCC, https://www.ipcc.ch/) as well as the scientific carbon literature. Various optional carbon offset approaches that consider SOC stock and SOC sequestration measurements, estimation methods, and modeling are included in the GHG0003 protocol. The protocol explicitly targets farms that have converted from CT agricultural practices to NT and have adopted NT management. No minimum period of NT adoption is required to participate in the protocol adoption.

The methodology presented in this protocol has been designed to be applicable to agricultural conservation management projects that have been implemented for the purpose of climate-carbon smart agriculture or regenerative agriculture, enhancement of soil health, and/or bundled soil-crop ecosystem service optimization (e.g., crop yield, soil fertility, water conservation management, nutrient regulation, or soil carbon sequestration ecosystem services).

To implement the GHG0003 protocol requires some level of technical expertise to accurately assess SOC sequestration and uncertainties over the project time frame. Landowners and farmers who wish to adopt this protocol may seek specific technical and scientific services to complete the development of a soil carbon project description that meets the standard levels of SOCseq evaluation and uncertainty assessments. Projects that follow this protocol must be located within the Canadian Prairies.

The methodology of GHG0003 requires the completion of the following tasks:

1. Identification of project boundary and characterization of project.
2. Assessment of baseline conditions (i.e., nowcasting of current soil carbon storage).
3. Recording of soil and climatic conditions as well as crop type and management during the project time period.
4. Quantification of SOC sequestration rates and total SOC sequestration amount under NT for the project area and project time period.
5. Provision of a verification project report that ensures reliability of farm-specific crop, soil, and climatic data and uncertainty assessment of SOC change under NT for the project area and project time frame (ex-post analysis).

# 3. GHG Registry Protocols

The methodology in this protocol GHG0003 is embedded in the modular design approach of the GHG Registry which entails various interconnected protocols that provide project specific guidelines and carbon accounting approaches. The Registry protocols comprise:

- GHG0001 Vers. 1.0 Methods to Determine Projects: Boundaries and Qualifications of Projects.
- GHG0002 Vers. 1.0 Protocol for Budgeting Carbon Offsets from Lands through Alternate Agricultural Land Management Practices (Alberta, Canada).
- **GHG0003 Vers. 1.0 Protocol for Budgeting Soil Organic Carbon Sequestration through No-Tillage Agricultural Management Practices (Canadian Prairies, Western Canada).**
- GHG0004 Vers. 1.0 Carbon Offsets from Lands through Shelterbelts (Canada).

Note, that GHG0003 protocol focuses on SOC sequestration quantification only. Specific methodologies for GHG emission reductions are described in detail in protocol GHG0002.

Supporting scientific background information for protocol GHG0003 can be found in the whitepaper “Synthesis of Soil Organic Carbon in No-Tillage, Conservation and Conventional Tillage” (Grunwald & Biswas, 2022).

# 4. Definitions

| Terms | Definitions |
|---|---|
| **Backcasting of carbon** | Historic carbon accounting over a project time that extends into the past. In this protocol historic carbon accounting is limited to maximum of 20 years. |
| **Baseline conditions (current reference SOC)** | The total amount of soil organic carbon up to a profile depth of 1 m at current time (nowcasting) within the project area in no-tillage.. |
| **Carbon project** | See protocol GHG0001. |
| **Climate-smart agriculture (CSA)** | Climate-smart agriculture involves a suite of integrated management practices, among them NT, to increase soil carbon sequestration, that abate global climate change and transform food production systems toward green and climate resilient agro-ecosystems. |
| **Conservation tillage (CT); Conservation agriculture (CA)** | Conservation tillage and conservation agriculture are the collective umbrella terms commonly given to NT, minimum tillage and/or ridge tillage, to denote that the inclusive practices have a conservation goal of some nature. |
| **Conventional tillage** | Conventional tillage is a tillage system using cultivation as the major means of seedbed preparation and weed control. |
| **Ex-ante** | Before the fact; looking into the future. Projection of values or conditions in the future. |
| **Ex-post** | After the fact; backward looking. Estimation of values or conditions in the past. |
| **Forecasting of carbon** | Future carbon accounting over a project time that extends into the future. In this protocol future carbon accounting is limited to maximum of 20 years. |
| **Greenhouse gas emission (GHG) from soils/land** | GHG emissions from soil/land entail mainly carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). |
| **Inorganic soil carbon (IC)** | Consists of mineral forms of carbon (primarily calcium and magnesium carbonates), either from weathering of parent material in which soils form, or from reactions of soil minerals with atmospheric carbon dioxide (CO2). |
| **Meta-analysis** | A statistical analysis that combines the results from multiple independent scientific studies of the same subject in order to determine overall trends. |
| **Meta-analysis applied to soil carbon sequestration** | Meta-analysis applied to long-term plot or field experiments that measured soil organic carbon sequestration. Meta-analysis use specific regions, climatic zones, or the whole globe as geographic domain. |
| **Monitoring event** | The time at which monitoring of all the relevant variables is undertaken, to determine the net change in atmospheric carbon attributable to the project. |
| **Monitoring period (or project period)** | The time period during which soil carbon sequestration was assessed by the project. |
| **Monitoring plan** | Plan in which a monitoring schedule and methods are documented. |
| **No-tillage (NT)** | Refers to agricultural practices also known as direct-drilling, direct-seeding or zero-tillage. Typically, NT minimizes tillage operations that are considered as soil disturbance. Intermittent conventional tillage operations are not allowable in NT which interrupts soil carbon sequestration. |
| **Nowcasting of carbon** | Current carbon accounting of a project. Nowcasting assesses the baseline soil organic carbon stocks for a project. |

| | |
|---|---|
| **Project Area** | The area of land on which the project proponent has/will undertake the project activities. |
| **Project Crediting Period** | The historic period over which no-tillage was implemented. This period is not to exceed 20 years. |
| **Project Scenario** | The actions, events, or management which are expected to occur as a result of implementing the project. |
| **Project start (reference start)** | The time when arable land was from conventional tillage to no-tillage. |
| **Residue farming (RF)** | Residue farming describes conservation tillage practices in which residue retention is the primary objective. |
| **Soil organic carbon (SOC) concentration (%)** | Soil organic carbon refers to the organic carbon compounds in soils (e.g., fresh or decomposing plant and animal matter, root exudates, simple sugars, and other decomposition by-products). |
| **Soil organic carbon stock (Mg C ha-1)** | Soil organic carbon concentration multiplied by the bulk density of soils for a specific soil profile depth over a specific land area. |
| **Soil organic carbon sequestration (SOCseq) (Mg C ha-1 yr-1)** | Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide in soils. The processes involved in SOCseq are carbon uptake via photosynthesis, carbon inputs (residue and amendments), organic matter decomposition, and soil respiration (i.e., release of CO2 from soils into the atmosphere). |
| **Soil profile depth** | The soil depth (cm) from the soil surface to the subsoil. In this protocol the topsoil is defined as soil depth 0-30 cm, while the total soil depth profile is 0-100 cm. |
| **Stratum (Plural Strata)** | An area of land within which the value of a variable, and the processes leading to change in that variable, are relatively homogenous. |
| **Transfer function** | Transfer functions allow to apply results from meta-analysis to specific regions. Transfer functions facilitate to transfer results from global or regional meta-analyses—that analyzed measured SOCseq rates after conversion from CT to NT management of individual long-term agronomic experiments—to specific sites, farms, or regions. |
| **Total soil carbon (TC)** | The total amount of soil carbon in the soil.<br>SOC + IC = TC.<br>In many soils the SOC carbon is the dominant pool of TC. |
| **Verification Date** | A date, at which an independent verifier audits the results of monitoring. |

# 5. Canadian Prairies

The Canadian Prairie comprises extensive areas of farmland in the Prairie ecozone with some extension onto the southern fringe of the Boreal Plain ecozone. The western prairie covers the Canadian provinces Alberta, Saskatchewan, and Manitoba with large reserves of soil organic carbon (SOC). According to Janzen et al. (1998), soils in this region comprise Borolls (Brown, Dark Brown, Black, and Dark Gray Chernozem soils) and Boralfs (Gray Chernozem soils). The southern part of the Canadian Prairie, originally a semi-arid grassland, is dominated by Brown Chernozem soils with comparatively low SOC content. With progressive decrease in moisture stress toward the north and east, the SOC content tends to increase in the Dark Brown Chernozem soils and is highest in the Black and Dark Gray Chernozem soils. In the Boreal Plain ecozone there are vast areas of Boralfs, developed under forest, with relatively low SOC content and only at the southern fringe of this ecozone agriculture predominates (Bueckert & Clarke, 2013; Janzen et al., 1998). Chernozemic soils show typical soil organic matter of 2.5 to 3.4 % (Brown), 3.5 to 5.0 % (Dark Brown), 5 to 8.5 % (Black), and 3.5 to 5.5 % (Dark Gray), which is substantially higher than SOC in arable land elsewhere (Canadian Society of Soil Science, 2020).

The mean annual temperature ranges from 0°C to 5°C based on long-term weather station records with high annual moisture deficit from about 80 to 400 mm (Janzen et al., 1998). The Great Plains region has infrequent and limited spring and summer precipitation with total annual rainfall of only 300 to 450 mm (Sauchyn, 2010). Moisture stress (droughts) and short growing season on the Canadian Prairies are limiting factors to crop yield in this region. The Canadian Prairie is classified as cool continental climate or semi-arid steppe with long cold winters (Bueckert & Clarke, 2013). Climate ensemble projections for the western prairie provinces of Canada indicate significant increase of change in summer climate moisture variability posing more challenges to arable production. The mean summer surface temperature increases are projected to become significant around 2035, and the median precipitation change around 2070 in winter and in 2080 in spring compared to background noise of natural climate variability (pre-industrial control) (Barrow & Sauchyn, 2019).

Historically, the Canadian Prairie was dominated by grasslands (tallgrass prairie, mixed grass prairie, and fescue prairie) of which a large proportion was converted into temperate cereal production (durum wheat); however in recent decades canola, pulses, dry beans, peas, and lentils have been included in crop rotations (Bueckert & Clarke, 2013). Farm-level adaptations to climate change and variability have spawned crop diversification in the Canadian Prairies based on over 15,000 operations for the period 1994-2002. The average number of crops per farm was about 4.2 in 2002 (Bradshaw et al., 2004). Summer fallow and increased adoption of NT in the Canadian Prairies has contributed to substantial carbon sequestration in soils. However, caution has been raised that the SOCseq in Canada is starting to decline as the legacy effects of these practices are starting to decrease and a new equilibrium is attained  (Angers and McConkey cited in Minasny et al., 2017).

# 6. Applicabilty Conditions

## 6.1. Mandatory Conditions for Protocol GHG0003

All projects using the methodology of this protocol must meet the following conditions:

1. Adoption of NT agricultural management within the project time frame (Figure 3). There is no minimum of land area required.
2. The project time frame is defined by land under NT agricultural management up to a maximum of 20 years. At project start the land was converted from CT or reduced tillage to NT.
3. Sustained NT management without interruptions by intermittent tillage operations during the project time frame. If a tillage operation is performed while otherwise NT management is used a temporary reduction in SOC sequestration of 25-50% (possibly higher or lower depending on site-specific conditions) can be expected for 1-3 years (possibly shorter or longer depending on site-specific conditions).
4. The project start time is the year in which NT practice was adopted. The project start time cannot exceed more than 20 years. However, the practice to be followed beyond the time frame to maintain permanence.
5. As of the project start date, all of the project area consists of croplands.
6. Crops under this protocol refer to common crop types planted in the Canadian Prairie (see section 5.)
7. The land under this protocol must be cropped during the project time frame. If for whatever reason total crop failure occurs in one season a temporary reduction in SOC sequestration may occur in the range of 25-50% (possibly higher or lower depending on site-specific conditions).
8. Once the protocol has been adopted by a farmer/landowner, monitoring of NT and crop management as well as climatic conditions (e.g., drought conditions) is done on an annual basis to provide accountability. SOC conditions are monitored in intervals over the project time frame.

## 6.2. Optional Conditions for Protocol GHG0003

The following conditions do not need to be met to utilize the methodology. These optional conditions provide additional opportunities for carbon offsets and/or have shown positive effects on SOCseq and soil health in general.

1. Carbon offsets through shelterbelts which can be assessed using protocol GHG0004.
2. NT combined with other conservation practices (e.g., residue management or cover crops) may provide additional effects improving soil health and crop resilience.
3. NT combined with increased cropping intensity (frequency) can result in SOC gains.
4. Both crop types and crop rotations impact SOCseq and optimizing these can substantially increase SOC sequestration.
5. NT combined with amendments (e.g., biochar) are likely to substantially increase SOCseq.
6. NT combined with water conservation management practices can enhance overall soil health and crop resilience.

7. NT implemented in marginal soils or carbon-poor soils have higher potential capacity to sequester more carbon in soils than carbon-rich Chernozem soils.
8. Soil in NT management have shown capacity to reduce GHG emissions when compared to CT. Reduction in GHG emissions from soils correlates positively with SOCseq rates. The quantification of GHG emissions from soils is optional.
9. Organic or inorganic fertilizations have shown positive effects on crop yield (biomass production, residue composition and amounts) which may enhance soil health.
10. Fallow in crop rotations is optional.

## 6.3. Non-Significant and Adverse Conditions for Protocol GHG0003

Projects that have adopted specific management practices may not have accumulated substantial carbon offsets from land even though NT was adopted. There are also specific site-specific circumstances under which SOCseq is limited under NT management. Climatic events or human-induced accidents may also disrupt SOC accumulation in soils under NT management.

1. NT combined with increased crop diversity has shown no significant SOCseq or in even SOC losses.
2. NT effects on SOCseq are typically smaller in cool-dry climate than in warm-humid climate.
3. In instances of wildfires or fire accidents significant carbon losses from soil and vegetation occur, which interrupts and limits to attain positive SOCseq rates in NT.
4. Extreme multi-hazard climatic disasters (e.g., extreme droughts or storms) may negatively impact SOCseq.
5. Crop rotations that include fallows may accrue more limited amounts of SOC.

## 6.4. Projects Not Considered under Protocol GHG0003

There are certain conditions that are outside the scope of this carbon offset protocol. Among them are:

1. Projects that are outside the boundaries of the Canadian Prairie.
2. Projects that have adopted NT management for more than 20 years are not considered under this protocol due to the uncertainty of backcasting capabilities and data availability to verify SOC sequestration. Only projects with NT adoption within the past 20 years fall within the domain of this protocol.
3. Projects without reliable crop management data.
4. Conversions from other land uses (e.g., grasslands, ponds, wetlands, urban areas) are not considered under this protocol which is limited to conversion of cropland into NT agricultural management and cropland under continuous NT.
5. Carbon offsets from vegetation (above-ground biomass) are not considered under this protocol.
6. Carbon offsets from other farm operations (e.g., livestock management, manure management) are not considered under this protocol.
7. Soil carbon offsets deeper than the 0-100 cm soil profile are not considered due to sparse availability of SOC and total carbon (TC) measurements in subsoils and the increased uncertainty of estimated or simulated SOC and TC in deeper soil layers.

# 7. Project Boundaries

**Objective 1**: Identify project boundary and characteristics to assess whether all mandatory protocol requirements are met.

**Method 1**: GHG0001 Vers. 1.0 Methods to Determine Projects: Boundaries and Qualifications of Projects; and evaluation whether all mandatory conditions for protocol GHG0003 (see section 6.1) are met. The project area must have been converted within the past 20 years from arable CT to NT production; or must have been managed as NT continuously for up to 20 years.

# 8. Baseline SOC Conditions

**Objective 2**: Identify the baseline SOC conditions for the project area, that is, quantify SOC stocks within the project area. The purpose of nowcasting (i.e., baseline SOC stock quantification) is to identify a reference for verification of backcasting and forecasting carbon assessments.

**Method 2**: The workflow for method 2 to assess baseline SOC conditions is outlined in Figure 5.

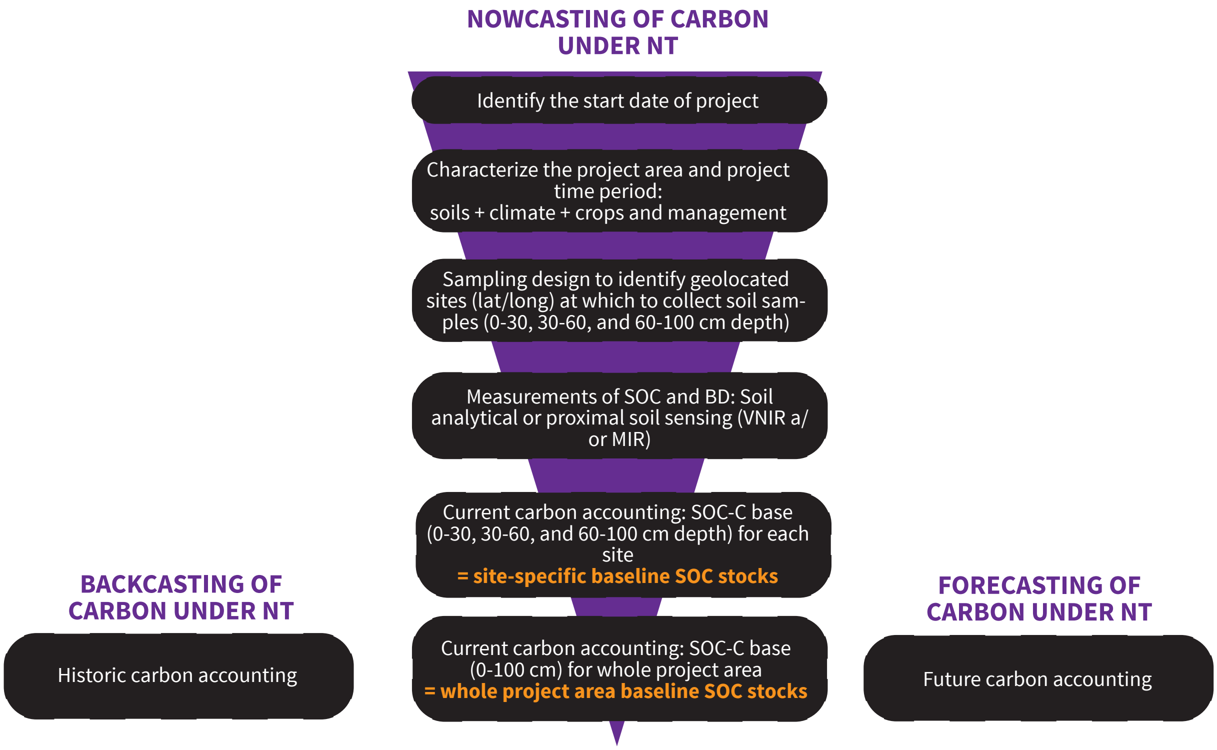



Figure 5. Workflow methodology to assess site-specific and whole project area baseline soil organic carbon (SOC) stocks. The approach is called nowcasting of carbon under no-tillage (NT) which allows to assess the current carbon storage in soils within the project area. Nowcasting captures the current SOC stocks, while backcasting refers to historic carbon accounting and forecasting refers to future carbon accounting through assessment of SOC sequestration rates under continuous NT management over the project period.

To implement method 2, identify the start date of project (month/day/year) and project time period according to Figure 3. The date at which NT was adopted can be identified by:

- **Option 1**: Farmer's records that are provided and verifiable.
- **Option 2**: Remote sensing derived approach that can distinguish between CT and NT (e.g., remote sensing derived vegetation indices that sense residue on the ground). The accuracy of the method needs to meet a standard of 80% or higher to identify the 'NT' class correctly.

Identify the geographic location of fields/areas enrolled in a project (latitude/longitude geographic coordinates) and assign unique identifiers for each homogenous field/area within the project.

Homogenous fields/areas are grouped together based on the same (or "very similar"):

a) soils (soil type and soil texture),

b) climate normals (long-term [20 to 40 years] mean annual temperature and mean annual precipitation)

c) crop management data (crop type(s), crop yield, crop rotation, crop frequency, crop diversity, fertilization, amendments) during the project time period. In case crop management has changed over the project time period it must be recorded.

**Baseline SOC conditions: Nowcasting – Current carbon accounting** (i.e., the baseline SOC at current time (MM/DD/YYYY) when a farmer adopts protocol GHG0003) (Figure 3). Soil organic carbon current (SOC-Cbase) represents the SOC stocks in a project area at current time. To assess SOC-Cbase applies to all three optional tracks: Backcasting, nowcasting, and forecasting of carbon accounting under NT. A baseline SOC assessment under protocol GHG0003 is required to be conducted either:

- at current time (nowcasting of SOC) when a farmer adopts protocol GHG0003,

  or

- within the following 3 to 5 years.

This baseline SOC assessment is denoted as **SOC-C$_{base}$** and assessed using the following methodology.

**Sampling design to assess SOC-C$_{base}$**: The design adopts a strategic approach to identify representative sampling locations based on soil, crop, and climatic factors that occur in the project area.

- **Option 1**: Random-stratified sampling design with strata of soil type-crop type-climate zone factor combinations where random sample locations are identified within strata with minimum sampling density of 1 sample per acre in a given project area. If there is only one soil type, crop type, and/or climate zone in the project area sampling sites can be randomly selected within the area, however, the minimum sample density needs to be met.
- **Option 2**: Strategic smart sampling design that captures the variability of soil type-crop type-climate zone factor combinations; this smart sampling strategy is called Conditioned Latin Hypercube (cLHC) sampling (Minasny & McBratney, 2006). A minimum sampling density of 1 sample per acre within the project area is recommended. If there is only one soil type, crop type, and/or climate zone in the project area sampling sites can be randomly selected within the area, however, the minimum sample density needs to be met.

**Sample collection and identification to assess SOC-C$_{base}$**: Each sampling site is characterized by geographic coordinates (latitude/longitude) and a unique identification number (ID). A global positioning system (GPS) is used to identify sampling locations in the field that are then sampled. Soil samples are collected in the topsoil (0-30 cm depth) and subsoil (30-60 and 60-100 cm depth) with an auger. In addition, bulk density samples are collected for each of the soil depths. For each sampled site, crop type, and amount of residue are recorded along with the time of sampling (MM/DD/YYYY) and then entered into a database.

**Measurements of SOC and BD**: Traditional SOC laboratory analytical methods have shown differences in measuring SOC (e.g., dry combustion or elemental analysis, wet combustion, Walkley-Black method) with dry combustion hailed the most accurate analytical method for soil carbon (Davis et al., 2018; Johns, 2017; Smith et al., 2020); though an expensive method. Roper et al. (2019) found that soil organic matter (SOM) measurements differed significantly among four laboratory methods (dry combustion, humic matter colorimetry, Walkley Black, and loss on ignition) to assess agronomic effects. Therefore, in SOC protocols only one specific laboratory method should be ideally adopted for measurement to assess the SOC sequestration rate. According to Davis et al. (2018), to compare SOC measurements across sites, regions, and nations one and the same SOC protocol and measurement approach should be adopted. Historically, many different SOC/SOM measurements laboratory techniques have been applied globally. Some of the methods are highly sensitive to soil characteristics (e.g., acidity) that influence SOC/SOM measurements. A reliable global SOC sequestration protocol will need to rely on a standardized approach to measure SOC through time that is applicable around the globe irrespective of different soil types. Both dry combustion and diffuse reflectance soil spectroscopy meet this criterion meaning that they can be applied widely on different soil types. The dry combustion relies on combustion of samples at high temperature (around 900 °C) and measurement of the CO2 gas that is combusted, while spectroscopy relies on measured reflectance values of light on soil in the visible/near-or mid-infrared regions (Viscarra Rossel

& Hicks, 2015). Though soil spectroscopy is much cheaper than dry combustion. Soil proximal sensing has been extensively studied in various regions and has shown excellent results to infer SOC from VNIR and MIR spectra (Clingensmith & Grunwald, 2022; McDowell et al., 2012; Ng et al., 2019; Vasques et al., 2010; Viscarra Rossel et al., 2016; Viscarra Rossel & Hicks, 2015).

- **Option 1 (sampling & laboratory measurements):** The soil samples are analyzed by dry combustion to measure SOC concentration (%) and bulk density using standard laboratory methodology according to the Natural Resources Conservation Service (Burt & Soil Survey Staff, 2019).
- **Option 2 (sampling & proximal soil sensing):** The soil samples are scanned using a portable or lab-based spectroradiometer in the visible/near-infrared spectral range (350 – 2,500 nm) and/or mid-infrared spectroscopy (500 to ~4,000 $cm^{-1}$) (Bellon-Maurel & McBratney, 2011). The spectral data are paired with soil analytical measurements of SOC to calibrate/train a SOC prediction model and validate/verify using an independent dataset. Typically, artificial intelligence, AI (machine learning or deep learning algorithms) is used for soil spectral modeling. Detailed instructions how to develop soil spectral SOC prediction models are provided in protocol GHG0002. Validated regional and global SOC prediction models can be used in this protocol GHG0003. However, the following uncertainty standards of AI SOC spectral prediction models need to meet the following minimum standards: R2 > 0.80; residual prediction deviation (RPD) > 2 (for normally distributed data); and Ratio of Performance to Interquartile Distance (RPIQ) > 3.0 (>3.5 preferable for skewed distributed data). Consult Bellon-Maurel et al., 2010; Bellon-Maurel & McBratney, 2011; Williams, 1987) for further instructions how to derive error metrics and uncertainty assessment.

Emergent technology of $^{\text{in-situ}}$ VNIR measurements using low-cost portable field spectroradiometers have shown promising results to accurately predict and reproduce soil carbon and other soil health properties (e.g., soil microbial properties) when compared to lab-based diffuse reflectance spectral measurements (Cambou et al., 2021; Dhawale et al., 2022; Hutengs et al., 2019; Hutengs et al., 2021; Semella et al., 2022; Sharififar et al., 2019). Such field portable SOC sensing makes the verification of SOC over the project period affordable, and yet provides accurate carbon accounting.

**The spatially-explicit SOC-$C_{base}$ stocks (baseline**) are calculated using SOC concentration (%) and bulk density data (g $cm^{-3}$) for each of the sampled sites within the project area:

$$\text{SOC-C}_{base} = \frac{(SOCc \times BD \times PDi)}{1000} \qquad \text{Eq. (1)}$$

| | |
|---|---|
| SOC-$C_{base}$: | Soil organic carbon stocks (kg C $m^{-2}$) at current time for specific PDs with i: 0-30, 30-60<br>or 0-100 cm soil profile depth, respectively |
| BD: | Bulk density (g $cm^{-3}$) |
| SOCc: | Soil organic carbon concentration (%) |
| PDi: | Profile depth with i = 0.3, 0.6 or 1.0 m, respectively |

The site-specific SOC-$C_{base}$ stocks (kg C $m^{-2}$) are aggregated over the whole soil profile depth (SOC-$C_{base}$ (0-100 cm)) and then upscaled to the whole project area:

$$\text{SOC-C}_{base}\text{ (0-100 cm)} = \text{SOC-C}_{base}\text{(0-30 cm)} + \text{SOC-C}_{base}\text{ (30-60 cm)} + \text{SOC-C}_{base}\text{ (60-100 cm)} \qquad \text{Eq. (2)}$$

The SOC-Cbase (0-100 cm) for individual project areas (PA in ha) that were sampled by specific soil-crop-climate strata are multiplied by the respective areal coverage of a given strata to derive the baseline soil carbon stocks for the whole project area. In case of homogenous soil, crop, and climate zones within the project area the $SOC\text{-}C_{base}$ (0-100 cm) is derived using Eq. (3).

$$SOC\text{-}C_{base}\text{-}T = SOC\text{-}C_{base}\ (0\text{-}100\ cm) * PA \qquad \text{Eq. (3)}$$

$SOC\text{-}C_{base}\text{-}T$: Soil organic carbon stocks (kg C $ha^{-1}$) for profile depth 0-100 cm for the total (T) project area

$SOC\text{-}C_{base}$ (0-100 cm): Soil organic carbon stocks (kg C $ha^{-1}$) for profile depth 0-100 cm measured at individual sites

PA: Project area (ha)

[unit conversions: 1 kg C $m^{-2}$ = 10,000 kg C $ha^{-1}$; and 1 kg C m-2 = 10 Mg C $ha^{-1}$]

# 9. Quantification of Soil Carbon Sequestration

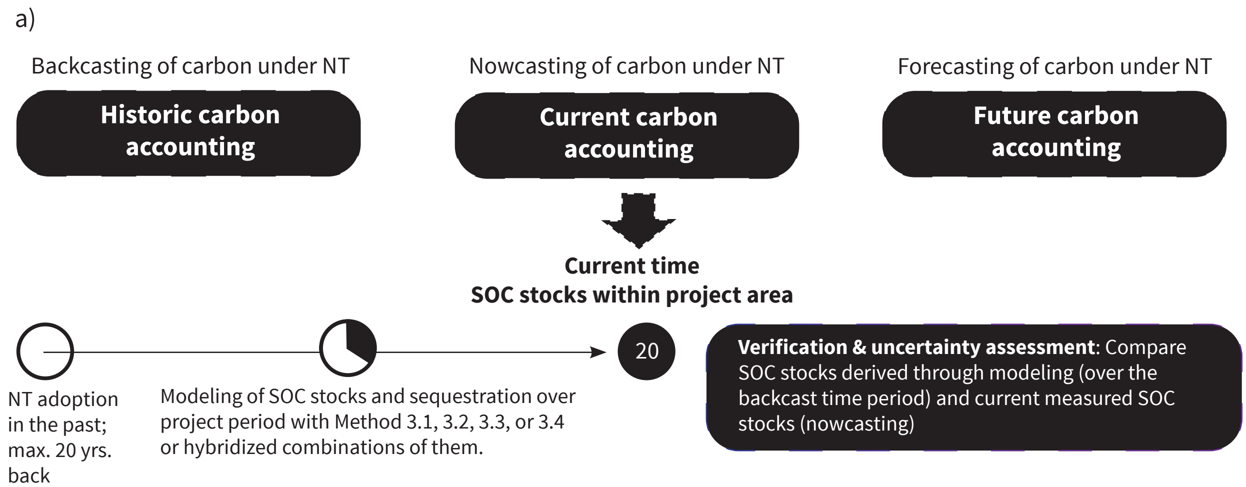
**Objective 3**: Assess SOC sequestration for the project area over the project period under continuous NT management.

**Method 3**: The quantification of SOC sequestration over the project period entails either backcasting or forecasting depending on when NT was adopted in a given project (NT adoption in the past → select backcasting; NT adoption now → select forecasting). The optional methods described below are applicable to both backcasting and forecasting. The baseline SOC stocks from nowcasting (see section 8) are used to verify the modeled/simulated SOC sequestration rates and stocks for the project area (Figure 6). The verification and uncertainty assessment using backcasting of SOC under NT is shown in Figure 6a, using combined backcasting and forecasting is shown in Figure 6b, and forecasting is shown in Figure 6c.

The allowable approaches in this protocol to model and verify SOC sequestration and stocks include:

> **Method 3.1**: Model SOC sequestration using the Canadian Holos model. Carbon conversion coefficients in Holos are based on the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System.
>
> **Method 3.2**: Simulate SOC sequestration using (quasi)process-based carbon simulation models, such as DayCent, Century, Roth-C, DNDC. These carbon compartment models assume different carbon pools (e.g., active/fast, intermediate, and passive/slow pools) with specific turnover rates.
>
> **Method 3.3**: Model SOC sequestration based on SOC measurements from long-term agronomic field experiments and meta-analysis integrated into a dynamic decision-tree model.
>
> **Method 3.4**: Model SOC sequestration based on Pedometrics-AI.
>
> or hybridized combinations of methods 3.1 to 3.4.

For the implementation of any of the methods above to assess SOC stocks and change, good scientific practices are to be followed to minimize inaccuracies and imprecisions (Petrokofsky et al., 2012). The quantification of soil carbon in agricultural systems has faced many challenges, such as high site-specific variability, high costs and standardization issues for direct measurements with destructive and laborious sampling. According to Paustian et al. (2019), both empirical and process-based models provide means for cost-effective SOC quantification to support carbon policies and marketing. Empirical models (Methods 3.3 and 3.4) are data-driven, while process-based models (Method 3.2) assume that carbon and other ecosystem processes can be mechanistically described and are readily applied in unsampled regions. Simulation models rely on accurate site-specific empirical data to populate them; and some modeling approaches are hybrids of quasi-process simulation models (e.g., Method 3.1).

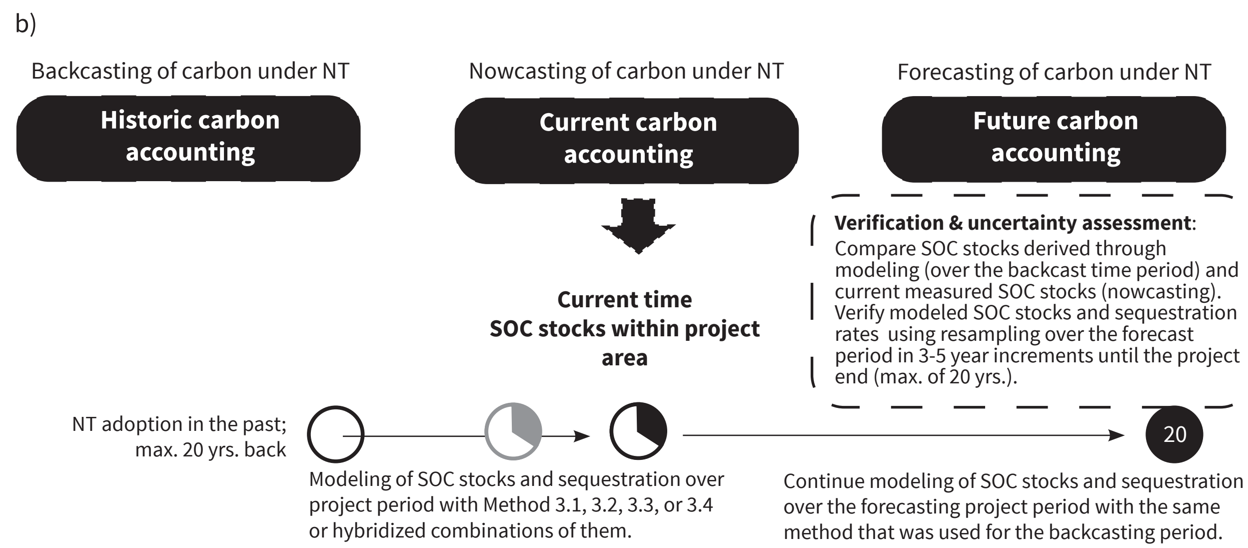



**Method 3.1**: Model SOC sequestration using the Canadian Holos model. Carbon conversion coefficients in Holos are based on the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System.

**Method 3.2**: Simulate SOC sequestration using (quasi)process-based carbon simulation models, such as DayCent, Century, Roth-C, DNDC. These carbon compartment models assume different carbon pools (e.g., active/fast, intermediate, and passive/slow pools) with specific turnover rates.

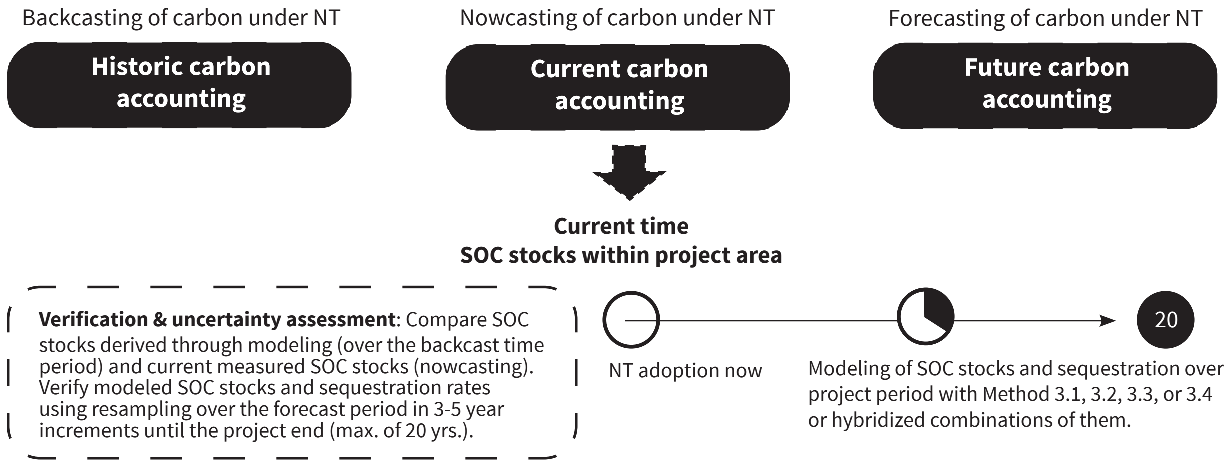
**Method 3.3**: Model SOC sequestration based on SOC measurements from long-term agronomic field experiments and meta-analysis integrated into a dynamic decision-tree model.

**Method 3.4**: Model SOC sequestration based on Pedometrics-AI modeling.




**Method 3.1:** Model SOC sequestration using the Canadian Holos model. Carbon conversion coefficients in Holos are based on the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System.
**Method 3.2:** Simulate SOC sequestration using (quasi)process-based carbon simulation models, such as DayCent, Century, Roth-C, DNDC. These carbon compartment models assume different carbon pools (e.g., active/fast, intermediate, and passive/slow pools) with specific turnover rates.
**Method 3.3:** Model SOC sequestration based on SOC measurements from long-term agronomic field experiments and meta-analysis integrated into a dynamic decision-tree model.
**Method 3.4**: Model SOC sequestration based on Pedometrics-AI modeling.

c)




**Method 3.1:** Model SOC sequestration using the Canadian Holos model. Carbon conversion coefficients in Holos are based on the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System.
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**Method 3.3:** Model SOC sequestration based on SOC measurements from long-term agronomic field experiments and meta-analysis integrated into a dynamic decision-tree model.
**Method 3.4**: Model SOC sequestration based on Pedometrics-AI modeling.

Figure 6. Overview of available methods (Methods 3.1, 3.2, 3.3, and 3.4 or hybridized combinations of them) and verification approaches to quantify SOC stocks and sequestration under protocol GHG0003. Historic carbon accounting under NT (backcasting), current carbon accounting in NT (nowcasting), and future carbon accounting under NT (forecasting) allow to model SOC sequestration over the project period and project area. 6a) Backcasting of carbon under NT, 6b) combination of backcasting and forecasting under NT, and 6c) forecasting of carbon under NT.

## 9.1 Benefits and Limitations of Methods to Model SOC Sequestration

### 9.1.1 Pros and Cons of Method 3.1: Holos Modeling

The benefit of Method 3.1 is that the Holos model has been adapted to Canadian conditions. The SOC sequestrations based on carbon change coefficients are easy to calculate if soil, crop, management, and climatic farm data are readily available. The limitations of Methods 3.1 are that the carbon change coefficients were developed some time ago based on the Canadian National Carbon and Greenhouse Gas Accounting and Verification System (NCGAVS) and require systematic updating since climatic and GHG emissions fluctuate temporally in Canada. The coefficients show narrow variations across regions in Canada and deviate substantially from measured SOC sequestration rates derived from long-term experimental studies in Canada that investigated tillage conversions (e.g., conversion from CT to NT) (Grunwald & Biswas, 2022; VandenBygaart et al., 2008). The coefficients are simplified static constants which do not reflect well the measured SOC sequestration rates derived from long-term NT experiments that are non-linear over long periods of time (e.g., 10 or 20 years) (e.g., Six et al. 2004). Another limitation of the Holos model is that simulations are limited to the topsoil (0-20 cm).

### 9.1.2 Pros and Cons of Method 3.2: Quasi-process-based Modeling

The pros of Method 3.2. are that (quasi)process-based models are widely used by scientists and modelers. If model performance of these models was successfully validated (evaluated) in a region these (quasi)process-based models can be readily applied to simulate SOC stocks and SOC sequestration over a project area and project period. The cons of Method 3.2 are that process-based simulation models require scientific and technical expertise. These models are often demanding to populate with comprehensive sets of soil, climatic, crop management, and other environmental data. Most of these process-based simulation models are quasi-mechanistic because they use some empirical factors for some of the ecosystem algorithms that require calibration with measurements which are costly. In some model applications default values for these empirical factors are used to run models which may or may not be appropriate for a region resulting possibly in substantial uncertainties. The carbon pools in process-based models are conceptualized pools that are operational, but very difficult to actually measure and replicate in laboratory or field studies. Even though process-models are considered mechanistic and physically-based they do show differences in modeling of SOC in side-by-side comparisons using the same input data (Smith et al., 1997).

#### 9.1.3 Pros and Cons of Method 3.3: SOC Measurements from Meta-Analysis and Dynamic Decision-tree Modeling

One benefit of Method 3.3 is that SOC sequestration rates in NT are based on measurements from long-term field experiments which is considered the gold standard of knowledge in carbon science. Meta-analysis compiles hundreds and thousands of SOC measurements into transfer functions that document the effects of site-specific factors, such as soil type, crop type, management, and climate (temperature and precipitation), when converting from CT to NT. In the Canadian Prairie and other regions, SOC measurements and meta-analysis provide empirical evidence of the long-term trends (20+ years) under NT management. The integration of SOC meta-analysis into dynamic ensembled decision-tree models provide annual SOC sequestration results that use direct knowledge from field observations. Thus, this kind of meta model approach is sophisticated and more direct than (quasi)process-based simulation models that often make multiple assumptions for the modeling process and also rely on empirical factors derived from field or lab measurements. Specifically, remote sensing derived crop, climate and GHG emission data can be integrated into these type of models. The cons of Method 3.3 is that long-term experimental data and meta-analysis are sparse and may not capture exhaustively the spatial and temporal variability in soil, crop, and climatic conditions in a region. As new published meta-analysis and SOC-NT transfer functions become available in the future these decision-trees require updating.

#### 9.1.4 Pros and Cons of Method 3.4: Pedometrics-AI

The pro of pedometrics-AI is that it provides a holistic approach to incorporate the key factors, such as soils, climate, topography, crop, management, geology, into the AI model to predict SOC stocks or sequestration (Grunwald, 2021). AI algorithms (machine learning and deep learning algorithms) to model soil properties have shown good to excellent model performance in different regions to assess SOC (McBratney et al., 2018, Grunwald, 2022b). Especially, deep learning AI has shown superior results to model soil carbon and other soil health properties when compared to other approaches (Padarian et al., 2019). Remote sensing data and proximal soil sensing data can be readily integrated into AI soil carbon models providing the capabilities to update SOC predictions as new sensor data are collected. A drawback of AI-SOC models is that they required specialized technical expertise in geoscience data mining, cloud computing, and coding.

## 9.2. Estimations/Simulations Based on Region-Specific Carbon Offset Coefficients

**Method 3.1**: Apply carbon conversion coefficients (k) to estimate $CO_2$ change for tillage changes (kg $CO_2$ yr-1) with conversion from intensive (or reduced) tillage to NT for different regions (zones) and soil texture classes (fine, medium, coarse) in Canada (after McConkey et al., 2007). Conversion coefficients are available for:

- Reduced tillage to NT with k varying between minimum of 0.0101 (fine; Montane Cordillera) to maximum of 0.0331 (fine; Boreal Shield West); in Semiarid Prairies k is assigned a value of 0.0239 (coarse), 0.0230 (medium) and 0.0194 (fine).
- Intensive tillage to NT with k varying between minimum of 0.0121 (fine; Pacific Maritime) to maximum 0.0403 (fine; Boreal Shield West); in Semiarid Prairies k is assigned a value of 0.0252 (coarse), 0.0266 (medium) and 0.0240 (fine).

The k coefficients presented by McConkey et al. (2007) are used in the Holos simulation model to model the annual change in $CO_2$ and SOC sequestrations. To implement method 3.1. use the Holos model to simulate the

$CO_2$ change yr-1 for the project period and project area with either of the project scenarios: 1) 'after conversion from CT to NT', or 2) 'continuous NT' for different regions(zones) in Canada and soil texture classes (fine, medium, coarse) (Little et al., 2013). Note that the Holos model 2.0 does not include a SOC module, which is available in the forthcoming Holos model Version 4.0. The SOC module of Holos 4.0 was described by Kröbel et al. (2016).

The carbon conversion coefficients in the Holos model were derived from McConkey et al. (2007). The Holos model typically assumes a 0-20 cm soil depth for SOC simulations. Equations in Holos to calculate CO2 change for tillage conversions are derived from Little et al. (2013):

$$y = currentYear - yearOfChange \quad \text{Eq. (4)}$$

$$\Delta C = lumC_{max} * (e^{[-k*(y-1)]} - e^{[-k*y]}) \quad \text{Eq. (5)}$$

$$C_{tillage} = \Delta C * 10 * area \quad \text{Eq. (6)}$$

$$CO_{2tillage} = -1 * Ctillage * 44/12 \quad \text{Eq. (7)}$$

| | |
|---|---|
| y: | Time since management change (years) |
| currentYear: | Current year |
| yearOfChange: | Year of tillage change |
| ΔC: | C change rate for tillage (g $m^{-2}$ $yr^{-1}$) |
| $lumC_{max}$: | Maximum C produced by management change (g $m^{-2}$) (see Table 7, by management change, reporting zone, soil texture in Little et al., 2013) |
| e: | Exponential function |
| k: | Rate constant (see Table 7, by management change, reporting zone, soil texture in Little et al., 2013) |
| $C_{tillage}$: | C change for tillage (kg C $yr^{-1}$) |
| 10: | Conversion from g m-2 to kg $ha^{-1}$ |
| Area: | Area of management change (ha) – total cropland area (includes annual crops, fallow and perennial forages) |
| $CO_{2tillage}$: | $CO_2$ change for tillage (kg $CO_2$e $yr^{-1}$) |
| 44/12: | Conversion from C to $CO_2$ |

Multiplying by -1 converts the result to an emission. (Positive value is an emission, negative value is SOC sequestration) (Little et al., 2013).

To calculate SOC sequestration for the whole project area and period under NT:

$$T\text{-}CO_{2tillage} = CO2tillage * PA * YNT \quad \text{Eq. (8)}$$

| | |
|---|---|
| T-CO2tillage: | Total soil organic carbon accrual for the total project area with soil depth 0-20 cm under no-tillage (t CO2e) |
| PA: | Project area (ha) |
| YNT: | Years in no-tillage within the project period (yr) |

**Verification and Uncertainty Assessment of Method 3.1**: Compare site-specific and whole project SOC stocks derived through Holos modeling (over the backcast time period) and current measured SOC stocks (nowcasting) and assess uncertainties using various error metrics (Figure 6a). In forecasting mode over the project period (Figure 6b or 6c) verify modeled SOC stocks and sequestration rates using resampling over the forecast period in 3-5 year increments until the project end (max. of 20 yrs.).

The formulas for error metrics to conduct the uncertainty assessment are available from Bellon-Maurel et al. (2010), Bellon-Maurel & McBratney (2011), and (Williams, 1987). The modeled SOC stocks compared to measured SOC stocks (Eq. 1, nowcasting) are expected to meet the following minimum standards of this protocol GHG0003: R2 > 0.80; RPD > 2 (for normally distributed data); and RPIQ > 3.0 (preferable >3.5 for skewed distributed data). Note that Holos models SOC sequestration over 0-20 cm, while SOC baseline measurements (Eq. 1) are for topsoil 0-30 cm. Therefore, standardize the horizon depths to allow fair verification of Holos model simulations.

For conversion of SOC stocks in kg C m-2 to CO2equivalents (CO2e) use the following:

1 kg C $m^{-2}$ = 10 Mg C $ha^{-1}$ (Mg: Mega gram)

1 Mg C $ha^{-1}$ $yr^{-1}$ = 1 metric t C $ha^{-1}$ $yr^{-1}$

1 t of C equals 3.67 t of $CO_2$e.

SOC storage within the whole project area: Measured SOC-$C_{base}$-T (0-20 cm) in t C $ha^{-1}$ * 3.67 = SOC-$C_{base}$-T (0-20) in t $CO_2$e that can be compared to Holos model results T-$CO_{2tillage}$ in t $CO_2$e (from Eq. 8).

The Holos modeled T-$CO_{2tillage}$ (0-20 cm) in t $CO_2$e should be within the 95$^{th}$ confidence interval of the mean of measured SOC-$C_{base}$-T (0-20) in t $CO_2$e for the same project area and project time period (backcasting mode). Similarly, the Holos modeled T-$CO_{2tillage}$ (0-20 cm) in t $CO_2$e should be within the 95$^{th}$ confidence interval of the mean of future re-measured SOC-Future-T (0-20) in t $CO_2$e for the same project area and project time period (forecasting mode). If these conditions are not met Method 3.1 is deemed unreliable not meeting quality control standards under protocol CT0003. In this case, the carbon change coefficients (k) may be re-fitted (calibrated) to achieve being within the 95$^{th}$ confidence interval of the project region-specific mean of measured SOC-$C_{base}$-T (0-20) or SOC-Future-T (0-20). Calibrations of coefficients can be implemented by increase/decrease of them by ±5, ±10, ±15, ±20, ……, n % (Monte-Carlo simulation approach) until SOC model simulations fall within the 95th confidence interval of the mean of measured SOC values. After successful calibration of coefficients, they can be used to rerun the Holos model to compute SOC sequestration for all sites in the project area and project time period to meet quality standards under protocol CT0003.

In the verification report include all soil, crop, climate, and farm specific data, k coefficients, and model procedures with Holos (e.g., calibration/testing and model validation), Holos model version as well as simulated SOC sequestration and SOC stocks and measured SOC stocks for the project area and project period.

## 9.3. Simulate Soil Carbon Sequestration Using a Carbon Pool Model

**Method 3.2**: Use one of the (quasi)process-based carbon simulation model to simulate SOC stocks, SOC sequestration rates, and total SOC sequestration under NT for the whole project area and time period.

Process-based simulation models such as DayCent, Century, Roth-C, DNDC or other models use carbon pools (e.g., active/fast, intermediate, slow/passive carbon pools) to simulate carbon turnover.

The verification and uncertainty assessment of Method 3.2 use the same procedure as described above for Method 3.1

For verification and uncertainty assessment of Method 3.2 adopt the same procedures as described above for Method 3.1. The modeled total SOC storage amount is required to be within the 95% confidence interval of the measured ones (either SOC stock baseline derived by nowcasting; or re-sampled SOC stock for the forecasting phase) for the same profile depth, project area, and project time period. If these expectations are not met it is essential to improve the process-based simulation model, calibrate the model, and/or improve input data quality to populate the model to meet uncertainty standards of protocol GHG0003.

In the verification report include all soil, crop, management, climate, and farm specific data, , and model procedures and model version  (e.g., calibration/testing and model validation) as well as simulated SOC sequestration  and SOC stocks and measured SOC stocks for the project area and project period.

## 9.4. Dynamic SOC Modeling linked with Meta-analysis and Decision-Tree Transfer Functions

**Method 3.3**: Quantify SOC sequestration rates and total SOC stocks accumulated within the project area and period from field-based measured SOC data derived from meta-analyses and transfer functions (TF).

A comprehensive review of SOC sequestration in NT of various meta-analyses and long-term experimental studies was presented by Grunwald and Biswas (2022). A grouping of global SOC-NT meta-analyses based on geographic region, climatic, soil, and cropping specific effects on SOC sequestration in NT are shown in Figure 7. The meta-analyses are derived from direct SOC and BD measurements that were made on plots or fields under a variety of site-specific conditions. Thousands and thousands of these empirical measurements over many years (20+) have been collected around the globe that were integrated into meta-analyses and transfer functions that are described in detail below. In addition, meta-analysis studies also compare SOC stocks in CT compared to NT to identify if significant differences between these two cropping systems exist (see Grunwald & Biswas, 2022).

Global NT meta-analyses provide rough estimates in SOC sequestration. However, the inclusion of soil-crop-management-climatic and other factors into the meta-analyses allow to characterize environmental variability within specific regions, climatic zones, and around the globe. These empirical data provide a rich resource to build inferential SOC sequestration models to make predictions at local scales within a project area.

Method 3.3 adopts the following workflow process to compute SOC sequestration rates in NT specific to sites (with specific soil texture, cropping management, and climate) located within the whole project area (Figure 8). The SOC sequestration rates from transfer functions are re-calculated annually for the topsoil (0-30 cm) and soil profile (0-100 cm) over the project period (max. of 20 yrs.). This dynamic modeling approach considers climatic fluctuations (e.g., temperature and precipitation; droughts and floods through the Humidity Index, HI) and crop management (e.g., rotations and crop intensities) that are likely variable over the project period. First, SOC sequestration rates using individual transfer functions are calculated as shown in Figure 8. Second, the mean, minimum, maximum, and standard error of the mean (SE) of the mean of ensembled SOC sequestration rates (Mg C $ha^{-1}$ $yr^{-1}$) derived from individual transfer functions are computed. The SE expresses the uncertainty of SOC sequestration ensembles. Third, apply weighting effects (positive, indifferent, or negative weights) that express differences between CT and NT depending on specific soil and crop-specific factors and transfer functions. Finally, aggregate the weighted SOC sequestration rates for each site to compute the SOC sequestration for the whole project area.

The verification and uncertainty assessment of Method 3.3 adopt the same procedures as described above for Method 3.1. The modeled total SOC storage amount is required to be within the 95% confidence interval of the measured ones (either SOC stock baseline derived by nowcasting; or re-sampled SOC stock for the forecasting phase) for the same profile depth, project area, and project time period.

A verification report that contains the soil, climatic, and crop-specific data to populate the transfer-functions provides accountability. Remote sensing data to assess NT implementation and crop data, available geodatasets, soil maps and databases, and long-term climatic data for Canada are used to the fullest extend to verify farm-specific field data and should be included in the verification report with all data sources.

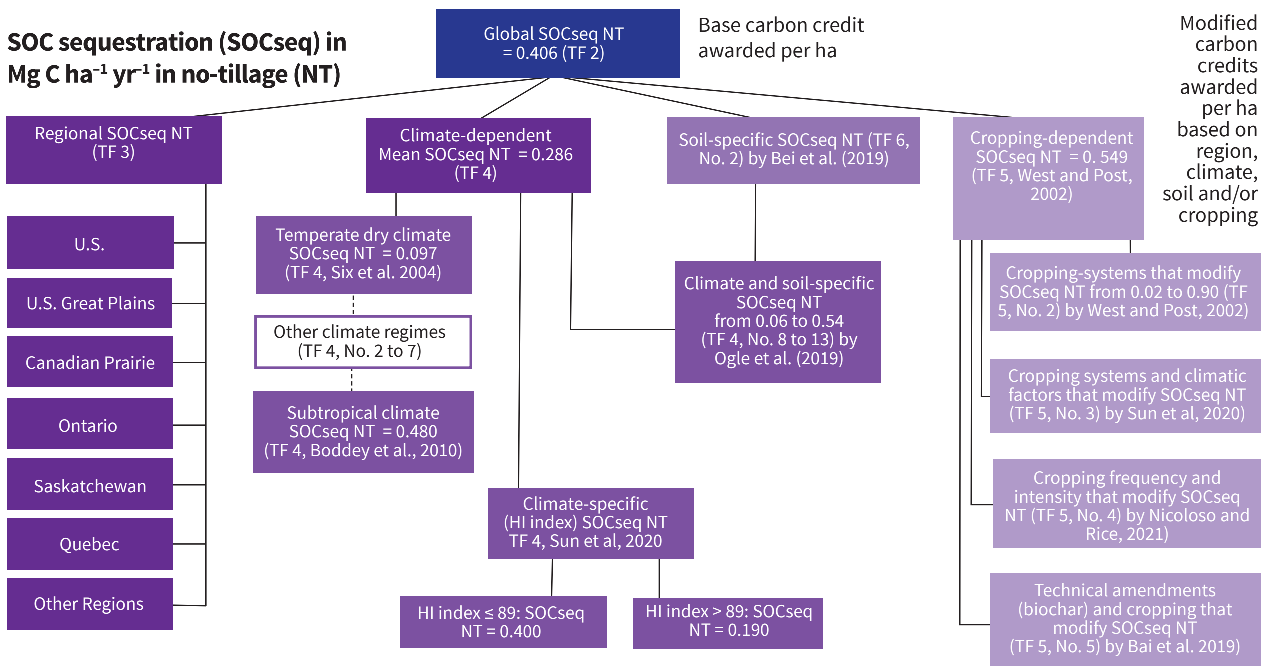


Figure 7. Grouping of global meta-analyses based on geographic region, climatic, soil, and cropping specific effects on soil organic carbon (SOC) sequestration in no-tillage (NT) systems.

## 9.5. Backcasting and Forecasting through Pedometrics-AI

**Method 3.4**: Modeling of SOC stocks at historic, current, and/or future project time periods based on the pedometrics-artificial intelligence (AI) approach.

This method is documented in GHG0002 Vers. 1.0 Protocol for Budgeting Carbon Offsets from Lands through Alternate Agricultural Land Management Practices (Alberta, Canada).

The 'total SOC sequestration amount' for the soil profile depth, project area, and project time frame is calculated by subtracting 'estimates of SOC stocks historic time' and 'estimates of SOC stocks current time' (backcasting mode). The 'total SOC sequestration amounts' for the profile depth, project area, and project time frame is calculated by subtracting 'estimates of SOC stocks future time' and 'estimates of SOC stocks current time' (forecasting mode).

**Verification of Method 3.4**: Uncertainty assessment for 'estimated SOC stock historic and future time' and 'estimated SOC stock current time' as described in GHG0002 are adopted to verify the approach.

The verification and uncertainty assessment of Method 3.4 adopt the same procedures as described above for Method 3.1. The modeled total SOC storage amount is required to be within the 95% confidence interval of the measured ones (either SOC stock baseline derived by nowcasting; or re-sampled SOC stock for the forecasting phase) for the same profile depth, project area, and project time period.

# 10. Conversion of SOC Sequestration into Carbon Credits

To convert the SOC sequestration accumulated in NT systems derived through any of the quantification methods above into $CO_2e$ and carbon credits the following equations are applied:

1 t of C equals 3.67 t of $CO_2$ or 3670 kg of $CO_2$

therefore, SOC stocks in t C $ha^{-1}$ * 3.67 = t $CO_2e$ $ha^{-1}$ Eq. (9)

therefore, SOC stocks in kg C $ha^{-1}$ * 3670 = kg $CO_2e$ $ha^{-1}$ Eq. (10)

t $CO_2e$ $ha^{-1}$ * CAD per $CO_2e$ $ha^{-1}$ = carbon credit awarded per hectare Eq. (11)

or

kg $CO_2e$ $ha^{-1}$ * CAD per $CO_2e$ $ha^{-1}$ = carbon credit awarded per hectare Eq. (12)

# 11. Permanence and Carbon Offset Crediting principle

The permanence of a soil carbon sink is defined as the longevity of the sink, i.e., how long it continues to remove carbon from the atmosphere. Permanence is a necessary condition for creditable CO2 emissions offsets. Sequestered C must remain sequestered during the period of the offset credits, which are typically issued for a 100-year period (although in newer markets, temporary credits can be issued for periods as short as 20-25 years). Critically, in practice, permanence typically refers to the duration for which a C-sequestering practice is carried out, rather than the soil C itself. It is assumed that once the management practice ends, any accumulated soil C will be quickly lost (Smith, 2005). Thus, maintaining certain agricultural practice that are adopted to generate carbon credits in the project is a must to ensure permanence.

As the protocol GHG0003 calculates the amount of carbon sequestered through NT practices over time, it is necessary to continue the NT practice to ensure permanence. Now considering the maximum project duration (i.e., 20 years) and the duration of NT practice (could be as long as 20 years), a project must continue to showcase the permanence for at least 10 years. If a project adopted conversion of CT to NT within last 10 years, the minimum of the rest 10 years of the project will ensure the permanence of the sequestered carbon and would allow issuance of the carbon offset credits. However, if a project adopted conversion of CT to NT 10+ years ago, the project must show permanence by continuing the NT practice for at least another 10 years, which may add challenges in adoption.

The protocol suggests two carbon offset crediting principles to enhance the adoption through ‘hold-back’ issuance of the carbon offset credits. Based on the duration of the project (years of adoption of NT), GHG0003 protocol will calculate the total and year-wise carbon offset credits generated from the project. While the issuance of the whole accumulated carbon offset credits from past practice may generate quick interest to participate in the project, shorter completion time may motivate adopters to modify the practices quickly at the completion of the project and restart a new project. This practice will not show the permanence of the carbon sequestered through this project. Thus, the full amount of the accumulated carbon offset credits from the past practices may not be issued at the start of the project and a certain portion of those credits can be ‘held back’ and issued over a duration of the project for at least 10 years. Under the principle 1, the issuance of the portion of the total credits generated from the past practices can be done as a lump-sum (say 50%) at the start of the project and the rest (say 50%) of the accumulated carbon offset credits from the past practices can be issued over time (10 years or the rest of the project duration). Under principle 2, the accumulated carbon offset credits from the past practices can be issued as a ‘top up’ over the future duration of the project (e.g., equally or at a certain decreasing rate distributed over the duration of the project or at least 10 years). However, the projects that adopted NT 10+ years ago, it must continue to practice NT for at least 10 years to ensure permanence. The issuance of accumulated carbon offset credits over a 10-year period will ensure the continuation of the project and the permanence of the carbon sequestered through the NT practices.

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