# Identifying rotation and tillage practices that maintain or enhance soil carbon and its relation to soil health

Authors: Wepruk, Erin, Diochon, Amanda, Van Eerd, Laura L., Gregorich, Edward, Deen, Bill, et al.

Source: Canadian Journal of Soil Science, 103(1) : 191-199

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjss-2021-0161

Canadian Journal of
Soil Science

OPEN ACCESS | Article

# Identifying rotation and tillage practices that maintain or enhance soil carbon and its relation to soil health

**Erin Wepruk**[a], **Amanda Diochon**[a], **Laura L. Van Eerd**[b], **Edward Gregorich**[c], **Bill Deen**[d], **and David Hooker**[e]

[a]Lakehead University, Department of Geology, Thunder Bay, ON, Canada; [b]School of Environmental Sciences, University of Guelph, Ridgetown, ON, Canada; [c]Agriculture and Agri-Food Canada, Central Experimental Farm, Ottawa, ON, Canada; [d]Department of Plant Agriculture, University of Guelph, Guelph, ON, Canada; [e]Department of Plant Agriculture, University of Guelph Ridgetown Campus, Ridgetown, ON, Canada

Corresponding author: **Amanda Diochon** (email: adiochon@lakeheadu.ca)

## Abstract

Physical fractions of soil organic matter (SOM) are established indicators of management-induced change and have been used to estimate the soil carbon storage capacity and storage potential. Here, we use SOM physical fractions and soil textures to identify management practices that maintain or enhance soil health and carbon storage in agricultural soils in Ontario. Metadata from the National Soil Database were used to estimate carbon storage potentials and calculate carbon deficits. A map was created showing carbon deficits in Ontario's agricultural soils and indicates that these soils have the potential to store an additional 0 to 2 kg $m^{-2}$ in the top 20 cm of the soil. Tillage system generally had no effect on the size of the carbon deficit at four long-term agricultural experiments (Delhi, Elora, Ottawa, and Ridgetown). There was only a significant tillage effect at Ridgetown and only in the maize–soybean crop rotation, where the carbon deficit was 2.95 g C kg $soil^{-1}$ under conventional tillage compared to 8.97 g C kg $soil^{-1}$ with no tillage. A statistically significant effect of crop rotation was detected in Elora and Ridgetown. In Elora, continuous alfalfa had the smallest carbon deficit (7.25 g C kg $soil^{-1}$) and maize–soybean rotation had the largest deficit (12.07 g C kg $soil^{-1}$). In Ridgetown, the maize–soybean rotation had the smallest carbon deficit (2.95 g C kg $soil^{-1}$). Regression analysis showed a weak negative relationship ($R^2 = 0.11$; $P < 0.001$) between carbon storage deficits and soil health scores. This suggests that increasing SOM levels alone may not improve soil health.

**Key words:** crop rotation, tillage, soil organic matter, soil health, CASH

## Introduction

Soil organic matter (SOM) is an important variable in determining soil fertility and productivity. When native soil is converted to agricultural land, about 24% of SOM is lost in the decades following land conversion (VandenBygaart et al. 2003). These losses are attributable to a shift in the balance of inputs of organic matter relative to outputs from decomposition, leaching, and crop removal. Identifying agricultural management practices that minimize loss, or even enhance SOM stores, is crucial for the sustainable management of soils and food production systems, and even more so in a changing climate (Amelung et al. 2020).

SOM regulates critical soil functions, such as nutrient cycling, and shapes a soil's physical, chemical, and biological properties (Carter 2002). Integrating soil's physical, chemical, and biological properties into a single metric or score to describe a soil's health is becoming increasingly common to evaluate management practices (Van Eerd et al. 2021). Soil health is defined by Doran et al. (1996) as the capacity of a soil to function within ecosystems and land-use boundaries to sustain biological productivity, environmental quality, and plant and animal health. Though soil health is inherently a metaphor (Janzen et al. 2021), soil health scores track and integrate management-induced changes in soil properties linked to soil functions and ecosystem services (Bünemann et al. 2018). One key attribute of soil health is SOM (e.g., Seybold et al. 1997), and its measurement is included in many of the commercially available soil health tests, such as the Cornell Soil Health Assessment (Idowu et al. 2008). Though measurement of SOM is straightforward, it can be difficult to assess its status and response to management practices because of the large spatial variability in its distribution (Gregorich et al. 1994).

Organic matter levels in the soil are ultimately determined by environmental factors, such as climate, and inherent soil properties, such as texture. However, land management practices, such as tillage and crop rotation, can alter the amount of SOM stored in the soil by altering the balance of inputs (i.e., quantity and quality of organic matter added to the soil) and outputs (i.e., rate of decomposition of organic matter and leaching) to the system. A change in SOM that occurs in response to management practices is small relative to the large background pool of organic matter in the soil, which makes it difficult to quantify (e.g., Entry et al. 1996; Nelson et al. 2009). Detecting change in SOM in response to management may be enhanced by measuring attributes of SOM that are responsive to changes in the rate of inputs or outputs of organic matter, such as particulate organic matter (e.g., Gosling et al. 2013).

In addition to being a primary attribute of soil health, SOM is also the largest global terrestrial reservoir of organic carbon (Powlson 2005), and changes in SOM stores have the potential to alter $CO_2$ concentrations in the atmosphere (Amelung et al. 2020). Agricultural soils have been identified as having a high carbon storage potential due to the depletion of soil organic carbon (SOC) stocks associated with cultivation and conversion to agricultural production (Lal 2004; Smith 2004). Developing land management strategies to increase organic carbon stores in agricultural soils depends on understanding the key factors that affect SOC stabilization and the capacity of individual soils to stabilize additional SOC.

Hassink (1997) defined the protective capacity of a soil as the maximum amount of soil carbon that can be associated with the clay and fine silt size fractions (<20 μm). Using soils with a wide range of mass proportions of fine soil particles in bulk soil, Hassink (1997) used the mass proportion of fine soil particles in bulk soil to predict the maximal organic carbon content associated with fine soil particles (i.e., the protective capacity) using a least-squares linear regression model:

$$\begin{aligned}&\text{Protective capacity}\ \left(\text{mg C g}^{-1}\ \text{soil}\right)\\&\quad = 0.37\,(\text{soil particles} \ < 20\,\mu\text{m in bulk soil (\%)}) + 4.09\end{aligned}$$

The difference between the protective capacity of the fine fraction and the measured carbon content of this fraction corresponds to the carbon saturation deficit or the carbon storage potential.

Hassink's approach has been used in many studies to examine carbon saturation in agricultural soils (e.g., Six et al. 2002; Carter et al. 2003; Sparrow et al. 2006; Chung et al. 2008; Angers et al. 2011; Feng et al. 2013; Wiesmeier et al. 2014; Beare et al. 2014; Chen et al. 2018). Though this approach has been widely applied, Paterson et al. (2021) reported more robust estimates of stabilized SOC using a quantile regression approach rather than Hassink's linear regression approach, and Zhang et al. (2021) concluded that a boundary line analysis approach was more appropriate than linear regression. Approaches aside, most studies report larger carbon saturation deficits (i.e., the difference between measured carbon and saturated levels) in agricultural systems compared to forests and grasslands (Six et al. 2002; Carter et al. 2003; Chung et al. 2008; Angers et al. 2011; Feng et al. 2013; Chen et al. 2018). The large organic carbon saturation deficit in agricultural soils suggests that agricultural soils are potentially important carbon sinks that could be exploited with proper land use and management practices (Feng et al. 2013; Wiesmeier et al. 2014).

Inherent in the protective capacity is the effect of texture. Carter et al. (2003), in a study of soils collected from 14 agricultural experimental sites in eastern Canada, reported that for soils having silt plus clay contents less than 40%, the carbon associated with the silt and clay particles was near the carbon protective capacity. For soils with clay plus silt contents greater than 60%, the C associated with the fine fraction was 67% of capacity levels. Gregorich et al. (2009) showed that the saturation of the C capacity in the coarse-textured agricultural soils of eastern Canada ranged from 71%–80%, whereas the fine-textured soils there ranged from 59%–62%. Together, these studies indicate that fine-textured agricultural soils may have the greatest potential to sequester additional carbon with proper land use management.

Detecting changes in SOC stores associated with management is enhanced by examining treatment effects in long-term agricultural experiments (Williams et al. 2016; Liptzin et al. 2022). It can take decades for system processes to reach equilibrium following a change in management and long-term experiments with consistent management, allowing us to detect change and attribute it to a cause with greater certainty (Six et al. 2004*a*, 2004*b*; Amelung et al. 2020). For example, West and Post (2002) and Alvarez (2005) reported that SOC under no-till management practices reach a steady state after 25–30 years.

In Ontario, Jarecki et al. (2018) reported that long-term rotations of maize (*Zea mays* L.) that include perennial alfalfa (*Medicago sativa* L.), winter wheat (*Triticum aesitvum* L.), or red clover (*Trifolium pratense* L.) had higher crop yields and increased SOC compared to simple rotations. Rotations that include winter wheat and alfalfa combined with no tillage in some areas have also been found to increase soil health scores in long-term studies in Ontario (Congreves et al. 2015). Similar findings were also reported by Chahal et al. (2021), who found that diverse crop rotations increased soil health indicators. Modelling under future climate scenarios, Jarecki et al. (2018) indicated that diverse crop rotations had lower water stress than simple rotations. Collectively, these findings suggest that higher soil health scores and higher SOC levels may contribute to more resilient agroecosystems.

The goals of this study were to identify management practices that maintain or enhance soil health scores and soil carbon and to identify agricultural soils in Ontario that can further accumulate soil carbon and thereby enhance soil health scores. To do this, we (*i*) define the carbon protective (storage) capacity of soils in long-term agricultural experiments with ongoing studies on soil health and evaluate the carbon storage potential of agricultural soils in Ontario and (*ii*) use empirical models to relate soil health scores calculated in Congreves et al. (2015) and soil carbon storage potentials calculated in the current study.

## Materials and methods

### Site descriptions and soil collection

Soil samples were collected from four long-term experiments (Table 1) in the spring of 2009 in Elora, spring of 2010 for Delhi and Ottawa (Congreves et al. 2014), and spring of 2016 in Ridgetown, resulting in sampling at 29, 22, 18, and 21 years after establishment. All experiments are fully phased. Approximately, 30 soil cores (3.5 cm diameter) were taken from each plot at 0–15 cm depth for a complementary study on soil health. These samples were homogenized, air dried, and sieved to 2 mm, and a representative archived sample was used in this study. Total organic carbon concentrations in these soils are provided in Table S1.

**Table 1.** Location, year of establishment, soil texture and type, and agricultural management systems for the four sites included in this study.

| Site | Coordinates | Established | MAT (°C) | MAP (mm) | Texture | Sand | Silt | Clay | Classification | Rotations* | Tillage system** | Reference(s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Delhi | 42°52′N, 80°31′W | 1988 | 8.3 | 870 | Loamy sand | 75 | 17 | 8 | Brunisol and gray brown luvisol | M–M and S–WW | NT, CT | Wanniarachchi et al. 1999 |
| Elora | 43°52′N, 80°21′W | 1980 | 6.3 | 854 | Silty loam | 27 | 57 | 17 | Gleyed melanic brunisol | M–M–M–M, A–A–A–A, M–M–M–M, M–M–S–S, M–M–S–WW, M–M–S–WW(rc), M–M–A–A | NT, CT | Raimbault and Vyn 1991; Wanniarachchi et al. 1999; Gaudin et al. 2015a |
| Ottawa | 45°23′N, 75°43′W | 1992 | 6.6 | 917 | Sandy loam | 58 | 30 | 12 | Melanic brunisol | S–S–S, WW–WW–WW, M–S–WW | NT, CT | Morrison et al. 2018 |
| Ridgetown | 42°26′N, 81°53′W | 1995 | 9.1 | 776 | Clay loam | 27 | 37 | 36 | Orthic humic gleysol | M–M–M, S–S–S, M–S, S–WW, M–S–WW | NT, CT | Van Eerd et al. 2014 |

**Note:** CT in Delhi is spring mouldboard plough with secondary tillage, CT in Elora and Ottawa is fall moldboard plough and spring cultivation, and CT in Ridgetown is fall moldboard plough with spring tillage. *M, maize; S, soybean; WW, winterwheat; A, alfalfa; rc, red clover.
**NT, no tillage; CT, conventional tillage.

## Soil analyses

The concentration of carbon associated with the silt and clay size fraction of the soil was determined using a modification of the method described by Bolinder et al. (1999). Twenty-five grams of air-dried soil were weighed into a 250 mL centrifuge bottle with 30 glass beads (5 mm diameter) and 125 mL of distilled water. Sample bottles were placed on a reciprocal shaker for 16 h to disrupt aggregates and then immediately dispersed over a 53 μm sieve. Samples were wet sieved with 1 L of water into a 2 L beaker, when 10 mL of 1 mol $L^{-1}$ $CaCl_2$ were added to flocculate the silt- and clay-sized fractions. The sand fraction recovered on a 53 μm sieve (53–2000 μm) represents a quantifiable component of the whole SOM. The sand-sized fraction was washed into a pre-weighed container using distilled water. After settling, the silt and clay fractions were recovered after aspirating the supernatant. The fractions were dried to a constant weight at 60 °C. The dried fractions, as well as a sample of the whole soil, were crushed using a ball mill and passed through a 250 μm sieve before flash combustion analysis using an Elementar Vario EL, after acidifying to remove carbonates with 2 mol $L^{-1}$ HCl. Mass and carbon recoveries were determined for each sample by mass balance.

## Calculations and statistical analyses

We used a modification of the original equation of Hassink (1997), as described in Carter et al. (2003), to calculate the theoretical value of carbon saturation ($C_{sat}$) by including particles 20–53 μm in our estimate of clay + silt where $C_{sat}$ [(g C $kg^{-1}$ = 4.09 + 0.37 (% soil mass < 53 μm)]. To estimate the carbon saturation deficit, we calculated the difference between the theoretical saturation ($C_{sat}$) and the measured carbon concentration in the <53 μm fraction for each sample. We were unable to calculate carbon storage potentials for the long-term experiments because samples for bulk density estimates were not collected at the time of sampling.

All statistical analyses were conducted using SPSS 24.0 (IBM SPSS); due to different crop rotations, each site was analyzed separately. We used an Analysis of variance (ANOVA) to test for the effects of tillage system and crop rotation treatments on soil carbon saturation deficits, with tillage system treatment and crop rotation treatments as fixed effects and two-way interactions in the model. For all data, assumptions of ANOVA were tested with Shapiro–Wilk normality test and homogeneity. Means were separated using the Tukey adjustment at the 0.05 probability level.

To determine whether soil health can be predicted by SOC concentrations and (or) soil carbon saturation deficits, we used a least-squares regression model. To test for a relationship between soil health scores and SOC concentrations, and soil health scores and soil carbon deficits, we used OSHA scores reported by Congreves et al. (2015), which uses the attributes included in the Cornell Soil Health Assessment (Idowu et al. 2008) and the soil carbon concentrations and deficits calculated in this study. Congreves et al. (2015) used weighted means of the individual Cornell Soil Health Assessment scores for each soil attribute, developed using principal components' analysis. The weighting factor was the sum

**Table 2.** Summary of *P* values from ANOVA showing effects of tillage system and crop rotation on soil carbon saturation deficits at four long-term agricultural experiments in Ontario.

| Site | Tillage system | Crop rotation | Tillage system × Crop rotation |
|---|---|---|---|
| Delhi | 0.060 | 0.823 | 0.245 |
| Elora | 0.875 | **0.021** | 0.624 |
| Ottawa | 0.336 | 0.115 | 0.650 |
| Ridgetown | 0.604 | 0.130 | **0.004** |

**Table 3.** Soil carbon saturation deficits at four long-term agricultural experiments in Ontario. Mean values (±standard deviations) followed by different letters are significantly different at the $\alpha = 0.05$ level of significance based on Tukey's LSD test. Upper case letters denote differences in crop rotations, while lower case letters denote differences in tillage systems.

| Site | Crop rotation treatment* | No tillage | Conventional tillage | Mean of tillage systems** | Mean of rotation treatments** |
|---|---|---|---|---|---|
| | | Carbon saturation deficit (g C kg soil$^{-1}$) | | | |
| Delhi | M–M | 7.77 (0.73) | 8.62 (1.11) | — | — |
| | S–WW | 8.03 (0.52) | 8.23 (0.54) | — | — |
| | | | | | 8.61 (0.79) |
| Elora | M–M–M–M | 9.98 (2.17) | 10.97 (2.67) | 10.48 (2.31)AB | — |
| | A–A–A–A | 7.60 (1.25) | 6.89 (3.68) | 7.25 (2.57)A | — |
| | M–M–A–A | 10.01 (2.51) | 7.57 (4.14) | 8.79 (3.42)AB | — |
| | M–M–S–S | 11.98 (2.48) | 12.15 (2.59) | 12.07 (2.35)B | — |
| | M–M–S–WW | 9.60 (2.23) | 10.64 (2.56) | 10.12 (2.29)AB | — |
| | M–M–S–WW(rc) | 9.40 (2.83) | 10.66 (2.26) | 10.03 (2.46)AB | — |
| Ottawa | M–M–M | 5.96 (1.28) | 4.99 (1.84) | — | — |
| | S–S–S | 4.87 (3.20) | 5.32 (2.31) | — | — |
| | WW–WW–WW | 3.04 (3.24) | 3.43 (1.54) | — | — |
| | M–S–WW | 3.20 (2.81) | 3.65 (3.65) | — | — |
| | | | | | 3.31 (3.93) |
| Ridgetown | M–M–M | 5.35 (0.55) | 7.02 (2.14)AB | — | — |
| | S–S–S | 8.13 (0.25) | 7.90 (3.36)A | — | — |
| | M–S–M | 8.97 (1.55)a | 2.95 (2.53)bB | — | — |
| | S–WW–S | 5.44 (2.62) | 6.00 (1.54)AB | — | — |
| | M–S–WW | 7.11 (1.76) | 7.93 (2.48)A | — | — |

*M, maize; S, soybean; WW, winterwheat; A, alfalfa; rc, red clover.
**The mean soil carbon saturation deficit if there was no significant effect of tillage and (or) rotation at a site.

of the first four eigenvectors for each soil attribute. The four components were selected based on the inflection point from Scree plot and Kaiser's Rule (eigenvalues > 1). The score (%) is the sum of each CSHA score for each soil attribute and the % of sand, silt, and clay multiplied by the weighing factor, divided by the sum of the weighting factors. Carbon concentrations and deficits in this study were calculated using archived sub-samples of the soils used to determine the OSHA scores by Congreves et al. (2015).

## Mapping

A map illustrating carbon storage potentials in the top 20 cm of Ontario's agricultural soils was produced using metadata from the National Soil Database and ArcMap 10.4.1 (ESRI). Metadata from the National Soil Database were first filtered based on land classification (agricultural land) and then by soil depth (<20 cm). Carbon saturation was calculated using the combined proportions of silt and clay for each soil polygon following the original approach of Hassink (1997).

Hassink (1997) defined the protective capacity of a soil as the maximum amount of soil carbon that can be associated with the clay and fine silt size fractions (<20 μm). He used the mass proportion of fine soil particles in bulk soil to predict the maximal organic carbon content associated with fine soil particles (i.e., the protective capacity) using a least-squares linear regression model:

$$\text{Protective capacity}\left(\text{mg C g}^{-1}\text{ soil}\right) = 0.37\left(\text{soil particles} < 20\,\mu\text{m in bulk soil }(\%)\right) + 4.09$$

Because the carbon concentrations for the fine fraction were not available in the database, we calculated carbon saturation deficits ($C_{def}$) following Angers et al. (2011) as the difference between the protective capacity and stable total organic carbon. Using this approach, we estimated that 85% of total SOC is stable, which is in agreement with a literature review by Gregorich et al. (2006) based on 434 particle-

**Fig. 1.** Relationship between soil organic carbon concentration and Ontario Soil Health Assessment (OSHA) scores (Congreves et al. 2015) in long-term agricultural experiments in Ontario (Delhi, Elora, Ottawa, and Ridgetown).

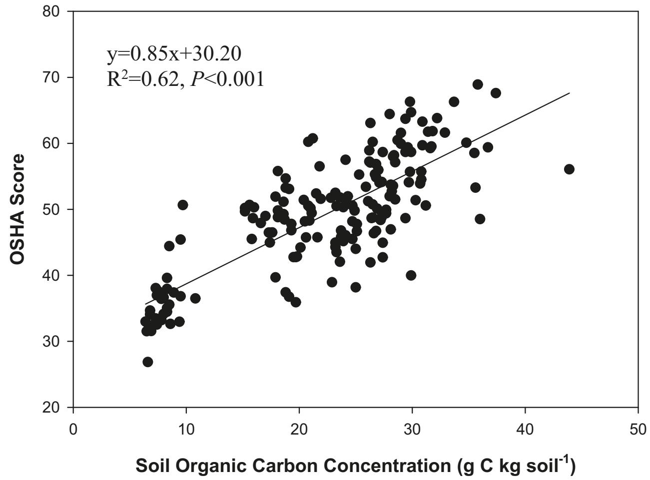
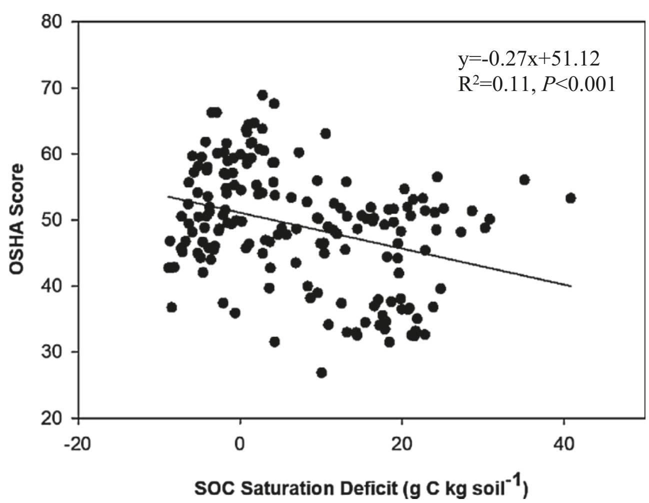



**Fig. 2.** Relationship between the soil organic carbon (SOC) saturation deficit and OSHA scores (Congreves et al. 2015) based on four long-term agricultural experiments in Ontario. Negative values indicate that the soils are saturated with organic carbon, while positive values indicate that soils are undersaturated with organic carbon (deficit).




size analyses. Carbon storage potential ($C_{seq}$) was calculated as $C_{seq} = C_{def} \times BD \times T \times 10^{-2}$, where $C_{seq}$ is the storage potential (kg m$^{-2}$), $C_{def}$ is the C saturation deficit (mg g$^{-1}$), BD is the bulk density (g cm$^{-3}$), and $T$ is the soil thickness (20 cm). Carbon storage potentials were grouped into 1 kg m$^{-2}$ bins to create the map.

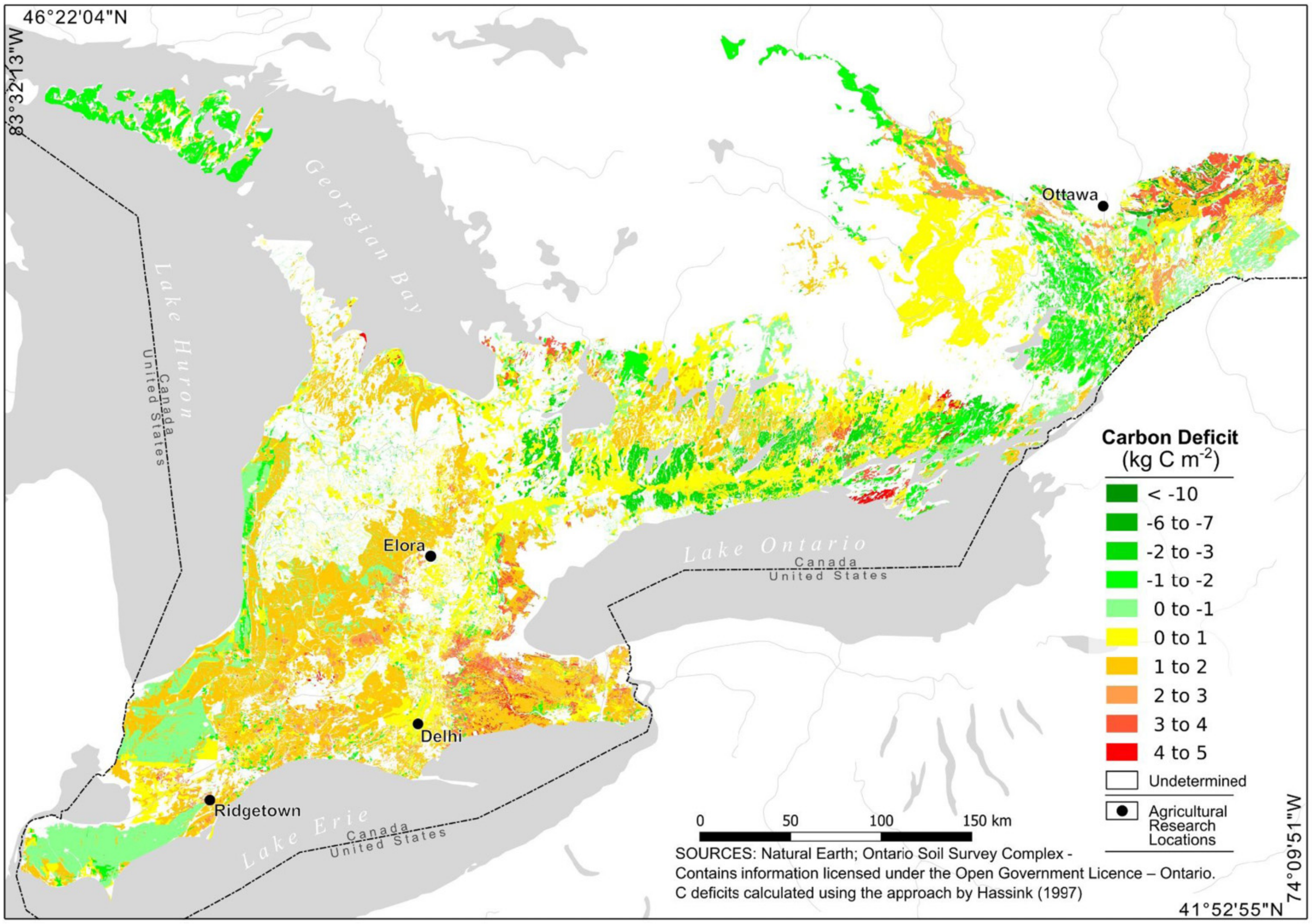
## Results and discussion

Carbon saturation deficits were evident in all tillage and crop rotation systems in the long-term agricultural experiments included in this study (Tables 2 and 3). Deficits were smallest in the Ottawa soils (3.31 g C kg soil$^{-1}$) and largest in soils in Elora (12.07 g C kg soil$^{-1}$). There was only a significant effect of tillage system on carbon saturation deficits in Ridgetown and only under the maize–soybean crop rotation (Tables 2 and 3), where the deficit was 2.95 g C kg soil$^{-1}$ with conventional tillage and 8.97 g C kg soil$^{-1}$ with no tillage. These deficits are also consistent with estimates using the boundary line approach described by VandenBygaart (2016).

A significant effect of crop rotation was detected in Elora and Ridgetown but only under conventional tillage in the latter (Tables 2 and 3). In Elora, the crop rotation of continuous alfalfa had the smallest deficit, followed by maize in rotation with alfalfa. Maize in rotation with soybean had the largest deficit at this site. Growing alfalfa continuously has been shown to increase both aboveground and belowground C inputs, which contribute to an accumulation of SOC compared to more diverse rotations (Li et al. 2019; King et al. 2019). Alfalfa, either as a monoculture or as part of a rotation, has also been shown to promote aggregate mean weight diameter (King et al. 2019). Meyer-Aurich et al. (2006) reported higher carbon storage in crop rotations of maize and alfalfa in Elora; the lowest soil carbon levels were in the soybean–maize rotation, which is consistent with our findings and those previously reported (Chahal et al. 2021). In Ridgetown, rotations of continuous soybean and soybean in rotation with maize and winter wheat had significantly larger deficits compared to the other crop rotation systems under conventional tillage. Maize in rotation with soybean had the smallest deficit of any rotation under conventional tillage and the largest deficit of any rotation under no tillage. This may be attributable to higher yields and rates of residue return under conventional tillage, but the yield data across tillage systems did not differ (Janovicek et al. 2021; Gaudin et al. 2015*b*). There was no effect of crop rotation in Delhi or Ottawa, which may be related to soil texture; i.e., both Delhi and Ottawa have coarser textured soils and a climate that promotes more rapid cycling of organic matter inputs (Congreves et al. 2014), which may negate a rotation effect.

While the small carbon deficits in perennial systems (i.e., alfalfa and alfalfa rotated with maize) were expected (Jarecki et al. 2018; King and Blech 2018; King et al. 2019), we anticipated that diverse crop rotations would have the smallest carbon deficits (Drinkwater et al. 1998; West and Post 2002; Congreves et al. 2014). Rotating crops is known to reduce insect and disease pressure, helping to increase yields, which leads to greater residue biomass and soil carbon input (Drury and Tan 1995). Additionally, the difference in residue types may contribute to the accumulation of SOC based on chemical characteristics and other mechanisms. The general lack of annual crop rotation effect was consistent in a North American-wide assessment of SOM (Liptzin et al. 2022; Rieke et al. 2022). We suggest that the quantity of carbon inputs (i.e., higher inputs with maize) and the duration of carbon inputs (i.e., continuous living plants, alfalfa) are more important than the number of crop species rotated. The role of perennialization on SOC and soil health indicators has been well documented in Elora (Gaudin et al. 2015*a*; Jarecki et al. 2018; King et al. 2019; Chahal et al. 2021). However, it is not known whether carbon gains are due to the perennial nature

**Fig. 3.** Map of carbon storage potential of agricultural soils (0–20 cm) in Ontario. Negative values indicate that the soils are saturated with organic carbon, while positive values indicate a deficit and the potential to store additional soil organic carbon. Bins from −4 to −6 and −7 to −10 are not shown because there were no data in those bins. White areas have insufficient soil data to estimate the carbon storage potential.




of alfalfa or due to the influence of legumes on tightening of carbon and nitrogen cycles (Drinkwater et al. 1998).

Congreves et al. (2015) demonstrated significant tillage system and crop rotation effects on soil health at these sites. Soils with no-tillage management in Ridgetown, Delhi, and Elora had higher OSHA scores, and there was no effect of tillage system in Ottawa. In Ridgetown and Elora, the lowest OSHA scores were reported in crop rotations of continuous maize and maize in rotation with soybean, while crop rotations containing alfalfa or winter wheat had the highest scores. We observed a significant positive relationship between SOC concentrations and OSHA scores (Fig. 1), consistent with the role that SOM plays in influencing soil properties and the observation that SOM is typically around 50% carbon. But the relationship was only moderate ($R^2 = 0.62$; Fig. 1), which was not what we anticipated, and suggests that other environmental factors play a significant role. Further, we observed a very weak ($R^2 = 0.11$; Fig. 2), but significant ($P < 0.001$), negative relationship between carbon deficits and OSHA scores. The negative relationship is consistent with our expectations that soils with smaller deficits would have higher scores, while soils with larger deficits would have lower scores, but clearly the potential to store additional carbon explains very little of the variation in the OSHA scores in this study. The weak relationship suggests that simply increasing SOM stores may not necessarily translate into improvements in soil health scores and that other factors, such as the biochemical composition of SOM (e.g., Gillespie et al. 2014; Diochon et al. 2015) and (or) or inherent site factors, play an important and more significant role in determining soil health.

The majority of agricultural soils in Ontario have the potential to store 0–2 kg m$^{-2}$ of additional carbon (Fig. 3). Given a conservative estimate of 5.4 million ha of agricultural land in Ontario (Statistics Canada 2010), and assuming full potential of soil to store carbon, this could amount to a reduction of 108 million Mg of atmospheric C. Sequestering carbon in the soil has the potential to reduce atmospheric concentrations of $CO_2$ and enhance soil health, though as previously mentioned, the effects on soil health may be less pronounced.

SOM is a key attribute of soil health and also defines the amount of carbon stored in the soil. Historically, agricultural practices have resulted in decreases in the stores of SOM. Declines in SOM may have compromised soil health and released significant quantities of $CO_2$ to the atmosphere because of increased rates of decomposition associated with conventional tillage systems and reduced return of inputs to the soil from harvesting biomass. Identifying management practices that maintain and enhance SOM will consequently improve soil health and sequester carbon in the soil, resulting in a win-win for the agricultural sector. Maximizing those gains by identifying soils that have the greatest potential to store carbon enhances the benefits (Amelung et al. 2020). Healthy soils are productive soils, and storing additional carbon could potentially lead to reductions of $CO_2$ in the atmosphere.

## Conclusion

Our findings indicate that the majority of agricultural soils in Ontario are capable of storing more carbon and have a carbon deficit of up to 2 $kg\,m^{-2}$. There was generally no effect of tillage system on the size of the carbon deficit in the soils included in this study. The effects of crop rotation on carbon deficits were less clear. The relationship between SOC concentrations and OSHA scores demonstrates the significant role and effect that SOC has in influencing the soil's biological, chemical, and physical properties. Although the quantity of SOM plays a key role in determining soil health, the inverse relationship between the potential for sequestering carbon in the soil and soil health scores was weak, albeit statistically significant. This highlights the complexity and dynamic nature of soil and indicates that there may be a limit on the extent to which soil health may be improved with increases in SOM alone. Other factors, such as the quality or biochemical composition of the SOM and soil mineralogy, may also be important in determining the extent to which soil health can be improved.

## Acknowledgements

This research was supported by funding from the Grain Farmers of Ontario and the Ontario Ministry of Agriculture, Food and Rural Affairs (New Directions Program).

## Article information

### History dates

Received: 1 November 2021
Accepted: 4 July 2022
Accepted manuscript online: 15 September 2022
Version of record online: 19 January 2023

### Notes

This paper is part of a Collection entitled "Soil Health Evaluation: Methods and Directions".

### Copyright



### Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

## Author information

### Author ORCIDs

Amanda Diochon https://orcid.org/0000-0002-6366-2955
Laura L. Van Eerd https://orcid.org/0000-0001-9789-4685

### Author contributions

Conceptualization: EW, AD, LVE, EG, BD, DH
Data curation: AD
Formal analysis: EW, AD
Funding acquisition: AD, LVE
Investigation: EW, AD
Methodology: EW, AD, LVE
Project administration: EW, AD
Resources: LVE, EG, BD, DH
Supervision: AD
Writing – original draft: EW
Writing – review & editing: AD, LVE, EG, BD, DH

### Competing interests

The authors declare there are competing interests.

## Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/CJSS-2021-0161.

## References

Alvarez, R. 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manage. **21**: 38–52. doi:10.1079/SUM2005291.

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., et al. 2020. Towards a global-scale soil climate mitigation strategy. Nat. Commun. **11**: 5427. doi:10.1038/s41467-020-18887-7.

Angers, D.A., Arrouays, D., Saby, N.P.A., and Walter, C. 2011. Estimating and mapping the carbon saturation deficit of French agricultural topsoils. Soil Use Manage. **27**: 448–452. doi:10.1111/j.1475-2743.2011.00366.x.

Beare, M.H., McNeill, S.J., Curtin, D., Parfitt, R.L., Jones, H.S., Dodd, M.B., and Sharp, J. 2014. Estimating the organic carbon stabilization capacity and saturation deficit of soils: a New Zealand case study. Biogeochemistry, **120**: 71–87. doi:10.1007/s10533-014-9982-1.

Bolinder, M.A., Angers, D.W., Gregorich, E.G., and Carter, M.R. 1999. The response of soil quality indicators to conservation management. Can. J. Soil Sci. **79**: 37–45. doi:10.4141/S97-099.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., et al. 2018. Soil quality – A critical review. Soil Biol. Biochem. **120**: 105–125. doi:10.1016/j.soilbio.2018.01.030.

Carter, M.R. 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron. J. **94**: 38–47.

Carter, M.R., Angers, D.A., Gregorich, E.G., and Bolinder, M.A. 2003. Characterizing organic matter retention for surface soils in eastern

Canada using density and particle size fractions. Can. J. Soil Sci. **83**: 11–23. doi:10.4141/S01-087.

Chahal, I., Hooker, D.C., Deen, B., Janovicek, K., and Van Eerd, L.L. 2021. Long-term effects of crop rotation, tillage, and fertilizer nitrogen on soil health indicators and crop productivity in a changing climate. Soil Tillage Res. **213**: 105121. doi:10.1016/j.still.2021.105121.

Chen, S., Martin, M.P., Saby, N.P.A., Walter, C., Angers, D.A., and Arrouays, D. 2018. Fine resolution map of top- and subsoil carbon sequestration potential in France. Science of The Total Environment, **630**: 389–400. doi:10.1016/j.scitotenv.2018.02.209.

Chung, H., Grove, J.H., and Six, J. 2008. Indications for soil carbon saturation in a temperate agroecosystem. Soil Sci. Soc. Am. J. **72**: 1132–1139. doi:10.2136/sssaj2007.0265.

Congreves, K.A., Smith, J.M., Nemeth, D.D., Hooker, D.C., and Van Eerd, L.L. 2014. Soil organic carbon and land use: processes and potential in Ontario's long-term agroecosystem research sites. Can. J. Soil Sci. **94**: 317–336 10.4141/cjss2013-094.

Congreves, K.A., Hayes, A., Verhallen, E.A., and Van Eerd, L.L. 2015. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. Soil Tillage Res. **152**: 17–28. doi:10.1016/j.still.2015.03.012.

Diochon, A., Gregorich, E.G., Kellman, L.M., Morrison, M.J., and Ma, B.L. 2015. Greater soil C inputs accelerate loss of C in cropping systems with low N input. Plant Soil, **400**: 1–13. doi:10.1007/s11104-015-2718-8.

Doran, J.W., Sarrantonio, M., and Liebig, M.A. 1996. Soil health and sustainability. Adv. Agron. **56**: 1–54. doi:10.1016/S0065-2113(08)60178-9.

Drinkwater, L.E., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, **396**: 262–265. doi:10.1038/24376.

Drury, C.F., and Tan, C.S. 1995. Long-term (35 years) effects of fertilization, rotation and weather on corn yields. Can. J. Plant Sci. **75**: 355–362. doi:10.4141/cjps95-060.

Entry, J.A., Mitchell, C.C., and Backman, C.B. 1996. Influence of management practises on soil organic matter, microbial biomass and cotton yield in Alabama's "Old rotation". Biol. Fertil. Soils, **23**: 353–358. doi:10.1007/BF00335906.

Feng, W., Plante, A.F., and Six, J. 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. Biogeochemistry, **112**: 81–93. doi:10.1007/s10533-011-9679-7.

Gaudin, A.C.M., Janovicek, K., Deen, B., and Hooker, D.C. 2015a. Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems. Agric. Ecosyst. Environ. **210**: 1–10.

Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., and Deen, W. 2015b. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS ONE, **10**(2): e0113261. doi:10.1371/journal.pone.0113261.

Gillespie, A.W., Diochon, A., Ma, B.-L., Morrison, M.J., Kellman, L.M., Walley, F.L., et al. 2014. Nitrogen input quality changes the biochemical composition of soil organic matter stabilized in the fine fraction—a long-term study. Biogeochemistry, **117**: 337–350. doi:10.1007/s10533-013-9871-z.

Gosling, P., Parsons, N., and Bending, G.D. 2013. What are the primary factors controlling the light fraction and particulate organic matter content of agricultural soils? Biol. Fertil. Soils, **49**: 1001–1014. doi:10.1007/s00374-013-0791-9.

Gregorich, E.G., Carter, M.R., Angers, D.A., Monreal, C.M., and Ellert, B.H. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. **7**: 367–385 10.4141/cjss94-051.

Gregorich, E.J., Beare, M.H., McKim, J.F., and Skjemstad, J.O. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Sci. Soc. Am. J. **70**: 975–985. doi:10.2136/sssaj2005.0116.

Gregorich, E.G., Carter, M.R., Angers, D.A., and Drury, C.F. 2009. Using a sequential density and particle-size fractionation to evaluate carbon and nitrogen storage in the profile of tilled and no-till soils in eastern Canada. Can. J. Soil Sci. **89**: 255–267. doi:10.4141/CJSS08034.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil, **191**: 77–87. doi:10.1023/A:1004213929699.

Idowu, O.J., Van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., and Bilgili, A.V. 2008. Farmer-orientated assessment of soil quality using field laboratory, and VNIR spectroscopy methods. Plant Soil, **307**: 243–253. doi:10.1007/s11104-007-9521-0.

Janovicek, K., Hooker, D., Weersink, A., Vyn, R., and Deen, B. 2021. Corn and soybean yields and returns are greater in rotations with wheat. Agron. J. **113**(2): 1691–1711. doi:10.1002/agj2.20605.

Janzen, H.H., Janzen, D.W., and Gregorich, E.G. 2021. The 'soil health' metaphor: Illuminating or illusory?. Soil Biol. Biochem. **159**: 108167. doi:10.1016/j.soilbio.2021.108167.

Jarecki, M., Grant, B., Smith, W., Deen, B., Drury, C., VanderZaag, A., et al. 2018. Long-term trends in corn yields and soil carbon under diversified crop rotations. J. Environ. Qual. **7**: 635–643. doi:10.2134/jeq2017.08.0317.

King, A.E., and Blesh, J. 2018. Crop rotations for increased soil carbon: perenniality as a guiding principle. Ecol. Appl. **28**: 249–261. doi:10.1002/eap.1648.

King, A.E., Congreves, K.A., Deen, B., Dunfield, K.E., Voroney, R.P., and Wagner-Riddle, C. 2019. Quantifying the relationships between soil fraction mass, fraction carbon, and total soil carbon to assess mechanisms of physical protection. Soil Biol. Biochem. **135**: 95–107. doi:10.1016/j.soilbio.2019.04.019.

Lal, R. 2004. Agricultural activities and the global carbon cycle. Nutr. Cycling Agroecosyst. **70**: 103–116. doi:10.1023/B:FRES.0000048480.24274.0f.

Li, Q., Zhou, D., Denton, M.D., and Cong, S. 2019. Alfalfa monocultures promote soil organic carbon accumulation to a greater extent than perennial grass monocultures or grass-alfalfa mixtures. Ecological Engineering, **131**: 53–62. doi:10.1016/j.ecoleng.2019.03.002.

Liptzin, D., Norris, C.E., Cappellazzi, S.B., Bean, G.M., Cope, M., Greub, K.L.H., et al. 2022. An evaluation of carbon indicators of soil health in long-term agricultural experiments. Soil Biol. Biochem. **172**: 108708. doi:10.1016/j.soilbio.2022.108708.

Meyer-Aurich, A., Weersink, A., Janovicek, K., and Deen, B. 2006. Cost efficient rotation and tillage options to sequester carbon and mitigate GHG emissions from agriculture in eastern Canada. Agr. Ecosyst. Environ. **117**: 119–127. doi:10.1016/j.agee.2006.03.023.

Morrison, M.J., Cober, E.R., Gregorich, E.G., Voldeng, H.D., Ma, B., and Topp, G.C. 2018. Tillage and crop rotation effects on the yield of corn, soybean and wheat in eastern Canada. Can. J. Plant Sci. **98**: 183–191.

Nelson, K.L., Lynch, D.H., and Boiteau, G. 2009. Assessment of changes in soil health throughout organic potato rotation sequences. Agric. Ecosyst. Environ. **131**: 220–228. doi:10.1016/j.agee.2009.01.014.

Patterson, K.C., Cloy, J.M., Rees, R.M., Baggs, E.M., Martineau, H., Fornara, D., et al. 2021. Estimating maximum fine-fraction organic carbon in UK grasslands. Biogeosciences, **18**: 605–620. doi:10.5194/bg-18-605-2021.

Powlson, D. 2005. Climatology: will soil amplify climate change? Nature, **433**: 204–205. doi:10.1038/433204a.

Raimbault, B.A., and Vyn, T.J. 1991. Crop rotation and tillage effects on corn growth and soil structural stability. Agron. J. **83**: 979–985. doi:10.2134/agronj1991.00021962008300060011x.

Rieke, E.L., Cappellazzi, S.B., Cope, M., Liptzin, D., Bean, G.M., Greub, K.L.H., et al. 2022. Linking soil microbial community structure to potential carbon mineralization: a continental scale assessment of reduced tillage. Soil Biol. Biochem. **168**: 108618. doi:10.1016/j.soilbio.2022.108618.

Seybold, C.A., Mausbach, M.J., Karlen, D.L., and Rogers, H.H. 1997. Quantification of soil quality. *In* ; Soil processes and the carbon cycle, *Edited by* ; R. Lal, J. Kimble and B.A. Stewart. CRC Press, Boca Raton, FL. pp. 387–404. doi:10.1201/9780203739273-27.

Six, J., Conant, R.T., Paul, E.A., and Paustian, K. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil, **241**: 155–176. doi:10.1023/A:1016125726789.

Six, J., Bossuyt, H., Degryze, S., and Denef, K. 2004a. A history of research on the link between (micro) aggregates soil biota, and soil organic matter dynamics. Soil Tillage Res. **79**: 7–31. doi:10.1016/j.still.2004.03.008.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., and Paustian, K. 2004b. The potential to mitigate global warming with no-tillage management is only realized when practised in the long-term. Glob. Change Biol. **10**: 155–160 10.1111/j.1529-8817.2003.00730.x.

Smith, P. 2004. How long before a change in soil organic carbon can be detected? Global Change Biol. **10**: 1878–1883. doi:10.1111/j.1365-2486.2004.00854.x.

Sparrow, L.A., Belbin, K., and Doyle, R. 2006. Organic carbon in the silt + clay fraction of Tasmanian soils. Soil Use Manage, **22**: 219–220. doi:10.1111/j.1475-2743.2006.00021.x.

Statistics Canada. 2010. Table 32-10-0152-01 Number and area of farms and farmland area by tenure, Census of Agriculture historical data, 1921 to 2016, inactive, Statistics Canada, Government of Canada websit. https://doi.org/10.25318/3210015201-eng. [accessed 5 January 2023].

Van Eerd, L.L., Congreves, K.A., Hayes, A., Verhallen, A., and Hooker, D.C. 2014. Long-term tillage and crop rotation effects on soil quality, organic carbon, and total nitrogen. Can. J. Soil Sci. **94**: 303–315. doi:10.4141/cjss2013-093.

Van Eerd, L.L., Congreves, K., Arcand, M., Lawley, Y., and Halde, C. 2021. Soil health and management. *In* Digging into Canadian soils: an introduction to soil science. *Edited by* M. Krzic, F.L. Walley, A. Diochon, M.C. Paré and R.E. Farrell. Canadian Society of Soil Science, Pinawa, MB. pp. 463–517. Available from https://openpress.usask.ca/soilscience/chapter/soil-health-and-management/.

VandenBygaart, A.J., 2016. The potential to regain organic carbon in degraded soils: a boundary line approach. Can. J. Soil Sci. **96**: 351–353. doi:10.1139/cjss-2016-0008.

VandenBygaart, A.J., Gregorich, E.G., and Angers, D.A. 2003. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can. J. Soil Sci. **83**: 363–380 10.4141/S03-009.

Wanniarachchi, S.D., Voroney, R.P., Vyn, T.J., Beyaert, R.P., and MacKenzie, A.F. 1999. Tillage effects on the dynamics of total and corn-residue-derived soil organic matter in two southern Ontario soils. Can. J. Soil Sci. **79**: 473–480. doi:10.4141/S97-096.

West, T.O., and Post, W.M. 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J. **66**: 1930–1946. doi:10.2136/sssaj2002.1930.

Wiesmeier, M., Schad, P., von Lützow, M., Poeplau, C., Spörlein, P., Geuß, U., et al. 2014. Quantification of functional soil organic carbon pools for major soil units and land uses in southeast Germany (Bavaria). Agriculture, Ecosystems & Environment, **185**: 208–220. doi:10.1016/j.agee.2013.12.028.

Williams, A., Hunter, M.C., Kammerer, M., Kane, D.A., Jordan, N.R., Mortensen, D.A., et al. 2016. Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: time to invest in soil organic matter? PLoS ONE, **11**(8): e0160974. doi:10.1371/journal.pone.0160974.

Zhang, L.M., Wu, Y.N., Yan, L.B., Wang, Y., Chen, J., and Yu, L.F. 2021. Modeling the maximal organic carbon saturation capacity in karst forest soils of China: comparing the existing models. Appl. Ecol. Environ. Res. **19**: 4115–4128. doi:10.15666/aeer/1905_41154128.