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Evaluating Carbon Sequestration and Ecological Performance in Diverse Regenerative Agricultural Settings

Prepared for the Ivey Centre for Building Sustainable Value by CarbFarm, Inc.:

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Abbreviations

AAFC = Agriculture and Agri-Food Canada

BMP = best management practice

CH_4 = methane

CO_2 = carbon dioxide (gas)

CSHA = Cornell Soil Health Assessment

CT = conventional tillage

GHG = greenhouse gas

IPCC = Intergovernmental Panel on Climate Change

LOI = loss on ignition

MP = moldboard plow

N_2O = nitrous oxide (gas)

NT = no-tillage or no-till

NUE = nitrogen use efficiency

OSHA = Ontario Soil Health Assessment

PCA = principal component analysis

POC = particulate organic carbon

RT = reduced tillage

SOC = soil organic carbon

SOM = soil organic matter

TBI = tree-based intercropping

TC = total carbon

TN = total nitrogen

ZT = zero-tillage

Lay Summary

The goal of this report was to examine the literature for farming best management practices (BMPs) for southern Ontario farms. This included regenerative agricultural techniques such as cover cropping, tillage, crop rotations, and agroforestry. Although the scope was limited to this geographical region in Canada, both carbon sequestration and soil health were addressed as they affect soil fertility and crop yields as well as sustainable agriculture at large. Climatic conditions were humid continental temperate, while soil textures varied from fine- to coarse-grained soils, and sampling depth was generally kept within 60 cm of the surface. Other variables considered in this work were the type of crops grown, how farms were managed, and duration representing the management history. A total of 36 sources were examined for Ontario, with a focus on soil organic carbon (SOC) as a measure of both carbon sequestration potential in soils and soil health. The overarching ambition was to help inform Ontario farmers using evidence-based research synthesis. The findings indicated the benefit of diversity cropping (crop rotations) and keeping a ground cover (cover crops, perennials) while reducing soil disturbance (using reduced tillage or no-tillage, NT), which supports regenerative agricultural practices. These practices also supported carbon sequestration in soils, including below-ground roots such as using deeply-rooted cover crops. Yields reflected above-ground biomass, which varied by crop type – with crops such as oats having greater yields. Carbon sequestration in soils can improve labile SOC content and soil organic matter (SOM), which are known to improve soil health. The main rotation crops used in southern Ontario (corn, soybeans, winter wheat) tend to be associated with soils that have similar amounts of SOC. Incorporating at least a couple of BMPs is more beneficial than just one – for example, using NT with crop rotations or crop rotations and cover crops. Appropriate levels of nitrogen fertilizer also need assessment, as for soybean growers, since planting legumes makes it possible to introduce nitrogen from plants into soils. The research tended to focus on certain crops (e.g., cover crops like oats, rye, red clover, oilseed radishes; crop rotations like grain corn, soybeans, winter wheat), which were supported by the modeling results as being associated with higher yields or SOC accrual. More research is needed to investigate crop blends like cover crop mixtures that can improve the biodiversity of contemporary farms. Studies need at least 5-10 years of data (and preferably >10 years) to measure SOC changes after BMPs have been implemented, although the length of studies or experiment duration varies. There were also other considerations regarding soil depth and whether volumes or masses of soil should be measured for SOC. Many of the published studies tended to measure SOC within 15-cm depth of the surface, which is where there is most variability and makes it challenging to track trends. There were also complications attributable to (loam) soil texture, which varied regionally but also with depth. Rooting depth of different plants may retain carbon at different soil depths, bringing it lower in the soil profile for deeply rooted crops.

1. Introduction

This report investigates the best management practices (BMPs) for southern Ontario farms, primarily focusing on regenerative agricultural methods such as cover cropping, different tillage practices, crop rotations, and agroforestry. It examines the extent by which these approaches

can improve soil health, carbon sequestration, and crop yields, ultimately contributing to sustainable agriculture. By exploring the impact of various regenerative practices, this report aims to provide recommendations for optimizing soil fertility and sustainability in agricultural systems across Ontario. Specific conditions and variables, including soil texture, climate, sampling depth, location, crops grown, management practice, and study duration, are investigated for their potential to provide tailored insights. Through a detailed analysis of 36 sources for Ontario, encompassing contemporary (published) journal articles, government reports, and books as well as farmer interviews and greenhouse gas (GHG) modeling in Holos software, we investigated practical and effective methods for improving soil organic carbon (SOC) levels, overall soil health, and ensuring long-term agricultural productivity. Ultimately, the findings aim to support Ontario farmers in adopting sustainable practices that benefit both the environment and their soils.

1.1. Improving "Soil Health"

Regenerative agriculture aims to improve "soil health," which is a broad concept referring to the ability of a soil to be part of an ecosystem that sustains biological productivity, environmental quality, and plant and animal (including human) health (Doran et al., 1996). The emphasis of regenerative agriculture is on not disturbing the land for agricultural purposes (Khangura et al., 2023), be it through the use of no-tillage (NT) or other agricultural practices that preserve soil structure, reducing soil erosion and maintaining moisture and nutrients (such as crop rotations and animal grazing) as well as reducing disturbances due to exposure (as by retaining surface cover in the use of cover crops and agroforestry). These practices also constitute conservation agriculture, which has minimal mechanical disturbance along with permanent soil organic cover and crop diversification (Francaviglia et al., 2023).

Each practice, including also agroforestry, will be considered for their potential contribution to soil properties that may affect overall soil health and ecosystem processes like carbon sequestration. It is important to consider cover crops, tillage, and crop rotations because they are known BMPs for Ontario (Potter et al., 2024; Shah et al., 2022). Each practice will be considered as part of the literature review for understanding soil health and its indicators along with physical soil properties and its link to ecosystem processes like carbon sequestration, particularly focused on Ontario soils. This report focuses on Ontario soils to provide a regional perspective, given that soil properties as indicators of soil quality and health can vary depending on climate, soil texture and type, and other regional factors.

1.2. Rationale

With declines in soil organic matter (SOM) observed in 82% of Ontario agricultural soils, there is a pressing need for more sustainable management practices (Government of Ontario, 2018). Ontario's agricultural landscape is particularly vulnerable to soil erosion, with approximately half of Ontario's cropland at high risk (Rotz et al., 2019). According to Blois (2024) and other sources, the relatively wetter climate in eastern Canada has increased soil compaction and, therefore, the need for tilling. Moreover, there have been land management and land-use

changes that have reduced SOC levels – such as the conversion from perennial to annual crops – that have affected the year-round coverage of soils in eastern Ontario, southern Quebec, and parts of the Maritimes, leading to a higher risk of degradation. The decline in soil quality highlights the urgent need for sustainable management practices capable of reversing the current trend of ecosystem degradation driven by (industrial) farming practices.

Addressing the challenges of environmental sustainability in Ontario's agricultural sector necessitates a focused analysis and strategic adaptation of farming practices. Regenerative agriculture offers a viable solution by focusing on enhancing ecosystem services such as carbon sequestration and soil fertility. In Ontario, where erosion control is paramount, the implementation of regenerative practices such as cover cropping and reduced tillage (RT) could significantly mitigate soil degradation (Rhodes, 2017).

Moreover, Ontario farmers face economic pressures from the rising costs of production inputs, which regenerative practices can help alleviate. By reducing dependency on fertilizer, industrial machinery, and pesticides through regenerative practices, farmers can decrease input costs (Pearson, 2007). However, transitioning to regenerative agriculture does involve overcoming substantial barriers, including the costs of changing practices and the economic risks associated with adopting new farming methods. Financial incentives and supportive policy frameworks are, therefore, critical to facilitate this transition. The findings in this report will provide valuable insights to farmers, policymakers, and stakeholders, promoting ecologically and economically sustainable practices.

2. Methodology

2.1. Literature Review

A literature review searched for published works relevant to carbon sequestration and soil health within regenerative agriculture (**Figure 1**). The study area was restricted to Canada, and Ontario was used as a "case" region of interest for detailed analysis. Two search engines were deployed in the search, namely Google Scholar and the Web of Science, which have been used by other researchers (Manzeke-Kangara et al., 2023; Sharma et al., 2021; Van Eerd et al., 2023; Yanni et al., 2018). The research question in this systematic review was: How do regenerative agricultural practices affect soil health and carbon sequestration? Word strings employed in the Google Scholar search included "carbon sequestration" OR "soil health" AND "best management practice" OR "regenerative agriculture" AND Ontario, Canada. Similar searches were used in the Web of Science, including "carbon sequestration" OR "soil health" AND Ontario, Canada. A total of 587 items were found mainly published between 2020 and 2024, as papers from the search were selected from this time span with some exceptions for earlier influential or classic studies sourced from the contemporary search results and added to the report.
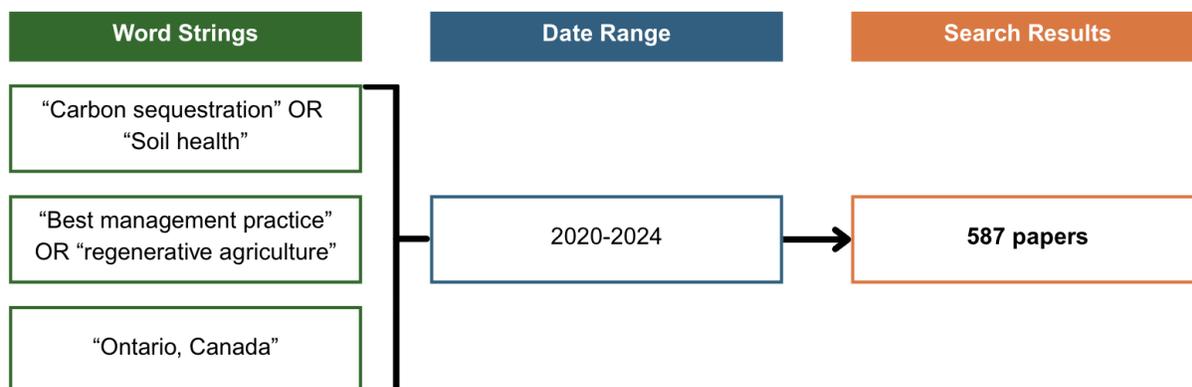
Word Strings	Date Range	Search Results
"Carbon sequestration" OR "Soil health"		
"Best management practice" OR "regenerative agriculture"	2020-2024	587 papers
"Ontario, Canada"		

Figure 1. Literature review search executed in Google Scholar and the Web of Science.

Terms such as "agroecology" were not included in the literature search since they are analogous to regenerative agriculture but by comparison would substantially broaden the scope and results. The scope was analogous to "conservation agriculture" to retain a practical focus on agricultural management techniques rather than a theoretical ecological breadth. Moreover, agroforestry was included among BMPs considered for carbon sequestration and soil health as part of agrosystems.

The scope of this literature review was for Ontario, Canada, although some geographically broader publications were considered to provide broader case support for similar climates (humid continental temperate) in the North American context. Farming practices in the research articles involved some BMPs such as crop rotations, cover crops, NT or RT, agroforestry, and more. The papers were then chosen selectively based on climate (humid continental temperate) and soil textural group, encompassing a range from clay loam, silt loam, and sandy loam to represent fine, medium, and coarse (loam) soils (Chahal et al., 2023). The soils in this region mainly represent Luvisolic, Gleysolic, and Brunisolic soil orders in southwestern Ontario (Congreves et al., 2014). The justification for focusing on this region is that while it represents only 0.1% of Canada's total landmass, it accounts for more than half of its Class 1 prime agricultural land (Obregon et al., 2023). These soils are manageable and can be cropped without difficulty, having moderately high to high productivity for a variety of crops.

2.1.1. Scope Context

Other studies have employed 30 articles (Audette et al., 2021) and 36 studies (Kadykalo et al., 2020) in their reviews based on their selection criteria. Similarly, 36 sources were retained under a provincial scope (for Ontario) in the current study, with sufficient information to extract location, climate, soil texture and type, soil depth, crops, practice, and experiment duration to compare across BMPs. Fluctuations in SOC sequestration rates from regenerative practices are likely affected by climate, soil properties, initial SOC levels, crop type (arable versus woody), management (rainfall versus irrigated), and the duration of experiments (Francaviglia et al., 2023). Other authors related factors that must be considered before regenerative agriculture is

implemented, including climatic (precipitation, temperature), soil type, farm enterprise mix, markets, and individual preferences (Khangura et al., 2023). However, not all factors were included in the literature review due to a lack of reporting in papers (e.g. farm enterprise mix). Such studies reflected the overarching research ambition to investigate regenerative agriculture in Ontario based on carbon sequestration and soil health. For BMPs, this means that conservation agricultural practices are included such as NT or RT, crop rotations, and cover crop use, rather than intensive conventional agricultural methods (Potter et al., 2024). These aspects of regenerative agriculture are focal in this report, including in the modeling portion next.

2.2. GHG Modeling

CarbFarm conducted farmer interviews and surveys understanding current management practices to model greenhouse gas emissions. In total, 31 farms were studied across southern Ontario (**Table 1**), similar to the number of participants in other studies that have included between 29 and 40 respondents (McGrath et al., 2023; Silva et al., 2023). The sample included farmers spanning the full spectrum of regenerative agriculture adoption. CarbFarm's outreach methods consisted of leveraging existing relationships within the agricultural industry combined with contacting various agricultural trade organizations in Ontario. Based on this outreach technique, the team utilized snowball sampling to reach their target sample size as research participants assisted in the recruitment of other farmers. Farms were then categorized into their respective (loam) soil textures from 18 different municipalities in southern Ontario. These farmers were surveyed on their farm location, yield, and management practices. The inputs used in modelling included, but were not limited to, the type of crop(s) farmed, type of tillage used on the cropland (i.e. NT, RT, intensive tillage), yield of crops, type of fertilizer and manure used on the cropland, as well as the application rate.

Table 1. Breakdown of farms interviewed by CarbFarm for Holos modelling

Total farms studied	31
Clay loam farms	12
Silt loam farms	5
Sandy loam farms	7
Mixed/non-loam farms	7

CarbFarm estimated GHG emissions and changes in soil carbon using Holos – which is among GHG tools assessed by Wilton et al. (2024) – a model developed by Agriculture and Agri-Food Canada (AAFC). The purpose of using Holos was to evaluate all GHG emission sources and SOC based on different management practices in comparison to the literature. Holos breaks down total emissions into several categories, including direct nitrous oxide (N_2O) and upstream carbon dioxide (CO_2). Holos models SOC by integrating a dynamic SOC algorithm based on the Introductory Carbon Balance Model that is modified for Canadian conditions but is based on IPCC tier 2 methods – that are more detailed and accurate (country-specific) for estimating

GHG emissions. It models based on continuous SOC change affected by crop residues, animal manure, and other SOM additions and losses as well as decaying young and old pools of SOC to simulate SOM turnover.

There are some limitations to consider for Holos modeling. Climatic data and soil types are regional, making it necessary to calibrate findings using field data for specific fields at subregional scale. Additionally, Holos emissions outputs have a varying level of uncertainty, from 20% for methane (CH_4) to 40% for total energy CO_2 because the effect of soil properties, climate, and farming practices on GHG emissions is poorly known (Wilton et al., 2024). Other limitations include not having the option to add agroforestry (and related amendments, e.g. wood chips) as a management practice in southern Ontario. Consequently, results must be interpreted with caution, recognizing the potential for the model to produce inaccurate predictions. Nevertheless, the Holos model provides a standardized method to predict GHG emissions based on different BMPs.

3. Findings

3.1. Literature Review

The **Appendix** contains information collected from the different sources in the literature review. It conveys data for the 36 literature items for Ontario, summarizing location, soil texture and type, soil depth, crops, practice, and experiment duration details. These findings are presented next based on management practices and productivity, and carbon sequestration based on the literature search, as well as GHG modeling outcomes.

3.1.1. Management Practices and Productivity

- **Cover Crops**

The use of cover crops can improve productivity, which may be associated with improved soil health. For instance, research has found increased average crop yields of 7.9-22% when cover crops are used (Chahal and Van Eerd, 2018). These findings were based on a sandy loam (Orthic Humic Gleysol) located in Ridgetown, Ontario, comprising 3.8% SOM based on loss on ignition (LOI) to 15-cm depth. Crops at this site included oats, winter cereal rye, oilseed radishes, and tomatoes, and represented a typical crop rotation of vegetable production for southwestern Ontario.

In another study, yields of processing Ontario tomatoes were considered, again based on the long-term cover cropping experiment located at the Ridgetown Campus, using data from 2010-2020 (Kerr et al., 2023). These authors discovered over a 6-year period that soils with radishes and mixed radish-rye cover crops had significantly higher yields of tomatoes of $1120 ha^{-1} and $604 ha^{-1}, respectively. The field was tile-drained and other crops such as peas, sweet corn, spring and winter wheat, grain corn, squash, and soybeans were planted in these fields. The cover crop experiment also included oats and cereal rye. Both crop rotation and cover crops appear at this site, which also tested for wheat crop residue and nitrogen fertilizer.

- **Tillage**

The metaanalysis by Congreves et al. (2014) examined long-term agricultural management effects on SOC in Ontario. This included tracking trends for NT versus CT as well as crop rotations and nitrogen fertilizer. For tillage, they found higher SOC content in NT than CT - in agreement with previous research. Rotation-tillage trials in Elora and Ridgetown, Ontario by Janovicek et al. (2021) including wheat in rotation in the last 16 years measured increased levels of corn-soybean yields with red clover for CT versus NT plots (4.2 versus 9.9%) than without red clover (11.8 versus 5.3%). Another study by Mesgar et al. (2024) discovered greater SOC stocks under NT and rotations including alfalfa and cover crops. More specifically, NT plots had more aromatic-C, whereas CT had an abundance of aliphatic-C compounds with a higher alkyl/O-alkyl-C ratio, indicating a higher degree of SOC decomposition. Evidently, there was higher SOC thermal stability in CT than NT systems; however, both NT and crop rotations including cover crops conserved more labile SOC.

A long-term experiment in Ridgetown (Van Eerd et al., 2014) considered tillage system and crop rotation. Both SOC and TN were higher for NT plots and rotations that included winter wheat. NT had 14% higher SOC than CT with moldboard plowing up to 100-cm depth in a clay loam soil. Another long-term experiment by Wepruk et al. (2023) found significant tillage effects at Ridgetown in the corn-soybean rotation, which had a carbon deficit of 2.95 g C kg^{-1} soil under CT compared to 8.97 g C kg^{-1} soil with NT.

- **Agroforestry**

A microclimatic study conducted on imperfectly drained silt loam at the Agroforestry Research Site in Guelph, Ontario during the growing season of 1992 by Williams and Gordon (1995), tested effects of tree rows of black walnut, poplar, and other tree seedlings intercropped with corn, soybeans, and winter wheat. Previous research had shown corn to have the best tree seedling growth, and this is slightly lower with soybeans but significantly lower with small grains such as wheat. Young trees were found to be most affected by soil moisture early in the growing season. Little difference in available soil moisture was evident in corn and soybeans early in the growing season, but considerably less available soil moisture was evident for wheat. Early in the season wheat better protected tree seedlings, whereas this occurred later in soybeans, when it was nearly identical to wheat. The poor growing conditions during the growing season in 1992 resulted in slightly depressed height growth that reduced the amount of shading, especially in corn.

- **Crop Rotations**

Yields were tested at other sites for crop rotations representing diversification. At the Honourable Eugene F. Whelan Experimental Farm in Woodslee, Ontario, in 2018 (Agomoh et al., 2021), soybean rotations were used to examine the impact of soil nitrogen on crop yields in poorly drained Brookston clay loam soil (Mesic Typic Argiaquolls). Soybean yields increased 39-44% for 2-year rotations and 48-52% for 3-year rotations, and more diverse rotations were 22-35% greater than continuous soybeans. The latter planted with corn and winter wheat had the

greatest yields and most positively impacted soil health, likely because cereal crops (e.g., corn, winter wheat) as well as red clover residues enhanced soil carbon.

This work has been supported by other research that measured increased yields when wheat was included in long-term rotations with soybeans and corn (Janovicek et al., 2021). In the last 16 years, including wheat in corn-soybean rotations in the first and second years resulted in conventional tillage (CT) corn with red clover augmented yields by 0.43 and 0.98 Mg ha^{-1}, respectively; and in NT corn without red clover by 0.78 and 0.45 Mg ha^{-1}, respectively. This can be compared to soybean yields that increased by 0.34 Mg ha-1 in the first year. Yields in Elora were up 10% in a 4-year corn-soybean rotation that contained wheat in a Woolwich silt loam (Gleyed Melanic Brunisol). Other studies using long-term NT corn-soybeans combined with strip-row farming, as in Dunnville, Ontario, discovered 18.35 t ha^{-1} or 75% more grain yield compared to CT, for mainly sandy loam (Islam et al., 2015).

3.1.2. Soil Health Indicators

- **Cover Crops**

Organic matter is one of the key indicators of soil fertility and health. For example, cover crops are known to benefit SOM as well as provide nitrogen that can be used for later crops (Yanni et al., 2018). They can be integrated into soil to retain nutrients in the soil and reduce soil erosion due to surface runoff. Researchers measuring soil health based on principal component analysis (PCA) for a dataset with five indicators pointed to cereal rye and a mixture of oilseed radish and rye leading to greater soil health, for a sandy loam (Orthic Humic Gleysol) to a depth of 15 cm, in the medium term of 6 years than other tested cover crops. Cover crops increased soil microbial activity, improving the concentration of SOC over time. They relayed that soil pH and SOM are the most common indicators used in soil quality tests. However, results may vary according to climate, soil type, production system, and management practice.

Work by other authors has revealed for Ontario organic farms that soil health is best measured using active carbon as the key indicator. Such work, based on three sites in Dundalk, Lucknow, and St. Thomas in southwestern Ontario, measured soil health using 40 soil samples to which they applied the Haney soil health test and nutrient test (Hargreaves et al., 2019). The soil samples constituted loam to sandy loam (St. Thomas), silt loam (Dundalk), and loam to silt loam (Lucknow). The cover crop mix used in 2015 comprised oats/barley/peas followed by soybeans/millet/sunn hemp/sunflowers, with the field being split into three sections of daikon radishes, oats/barley/peas and winter cereal rye/hairy vetch for the fall and winter. Crops in 2013 included mustard followed by one section of buckwheat and another of winter cereal rye undersown with red clover. Measuring a selection of soil health indicators that had previously shown to be sensitive to management, the authors found active carbon to be the only indicator that was sensitive, repeatable, and consistent across the three farms tested in their study. SOM estimated using LOI was highly repeatable and consistent. Therefore, active carbon and SOM were the most useful measures indicating changes in management practices, and likely soil health for these organic farms.

- **Tillage**

Experiments in Ridgetown, Ontario, show the long-term effects between 11 and 15 years of tillage system as well as crop rotation, with soil quality measured based on the Cornell Soil Health Assessment (CSHA) (Van Eerd et al., 2014). Clay loam conveys greater storage of carbon and nitrogen, thereby improving soil health. These authors recommended that growers in southwestern Ontario adopt NT and include winter wheat in rotation.

For Ontario, derived Ontario Soil Health Assessment (OSHA) scores were significantly greater for NT plots located in Ridgetown, Elora, and Delhi (respectively clay loam, silt loam, and sandy loam) (Congreves et al., 2015). Furthermore, Ridgetown and Elora crop rotations and cover crops respectively comprising winter wheat or alfalfa had higher scores, whereas corn monocultures and soybean-corn rotations had the lowest scores. These findings have been supported by soil samples from Elora silt loam (Mesgar et al., 2024).

- **Agroforestry**

Agroforestry is another way to affect active soil carbon, influencing soil health. Three indicators were deployed that included active soil carbon for soil health as well as diversity of soil bacterial communities and nutrient acquisition via total root biomass (Rolhauser and Isaac, 2024). Measurements varied according to plant cover on 13 farms located in southwestern Ontario. It was discovered that active carbon and root biomass (in the top 6 cm of soil) were highest in forests, intermediate in grasslands, and lowest in croplands.

Tree-based intercropping (TBI) systems have demonstrated a more efficient nutrient cycle, particularly with nitrogen. Including trees leads to enhanced nitrogen cycling within the system due to deeper root systems that tap into subsoil nutrients that are otherwise inaccessible to crops (Thevathasan and Gordon, 2004). This interaction helps in reducing the dependency on synthetic fertilizers.

Nitrogen levels between 75 and 100 kg N ha^{-1} were considered to be ideal for maximizing productivity in an agroforestry system intercropped with barley (Ntayombya and Gordon, 1995). Sandy loam in their study produced 12% more biomass on average than loam soil. Soil nitrogen availability was enhanced in these soils due to nitrogen mineralization associated with intercropping.

- **Crop Rotations**

Researchers developed the OSHA as a soil health index based on multiple soil attributes (Congreves et al., 2015). This was applied to various Ontario sites at depths between 10 and 120 cm on crop rotations using 3-8 crops and cover crops, including corn, soybeans, winter wheat, rye, tobacco, alfalfa, oats, barley, and red clover. In Ridgetown and Elora, those that included winter wheat or alfalfa had higher OSHA scores, whereas monocultures of continuous corn and soybean-corn rotations had the lowest scores. These findings have been supported by other research, indicating that diversification of corn and soybean rotations and monocultures with cover crops, perennials, and small grain cereals enhance soil health indicators (measured

to a depth of 15 cm) by 32% at Ridgetown over 21 years and 49% at Elora over 36 years; and crop productivity increased 16% at Ridgetown and 29% in Elora (Chahal et al., 2021).

3.1.3. Other Soil Properties

- **Cover Crops**

Cover cropping affects soil temperature. A study employing a crimson clover and white clover mix, hairy vetch, and red clover at Woodslee, Ontario, found that winter soil temperatures beneath living cover crops were greater at depths up to 45 cm and especially at a 15-cm depth (Yang et al., 2021). Conversely, spring soil temperatures were lower at depths up to 60 cm. At 15 cm, a soil temperature gradient was found that dropped 0.24°C for every 1 Mg ha^{-1} increase in live cover crop biomass. Evidently, this vegetative growth has a moderating effect on soil temperatures, which has implications for seed germination and soil moisture content among other physical soil properties and processes as well as encouraging earthworms. This can be attributed to above-ground biomass of the different crops, with hairy vetch not providing a consistent biomass cover (due to its susceptibility to winter-kill) resulting in inconsistent temperature effects.

- **Tillage**

In addition to affecting soil chemistry, tillage systems can also impact some physical properties of soils. For instance, lower soil bulk densities were measured in southwestern Ontario Brookston clay loam for NT due to lower soil compaction compared to moldboard plow (MP) of a corn-soybean rotation (Shi et al., 2012). However, in their study, RT produced the lowest measured soil bulk density. Moreover, measured soil penetration resistance was lower for CT than NT to a depth of 21 cm, although the resistance increased beyond this depth. These findings have implications for root growth and deeper root development as well as water content and plant water availability, since RT had more moisture retention in furrows. Studies have shown that zero-tillage (ZT) increased the surface soil bulk density of silt loam at 5-10 cm depth to 1.43 g cm^{-3} (Deen and Kataki, 2003), while spring MP maintained a bulk density of 1.29 g cm^{-3}. This has implications for root penetration and soil hydrology. NT augments bulk density and the surface resistance, although cover cropping could counteract these effects as could early planting (Islam et al., 2015).

- **Agroforestry**

The paper by Bezkorowajnyj et al. (1993) addressed the impact of foot traffic by cattle on soil compaction. This has implications for reduced water infiltration and the growth rate of tree seedlings. By adding leaf nitrogen, it was possible to counteract these effects and improve seedling growth in medium-highly compacted soils. The soil in their study was sandy loam located in Grand Valley, Ontario, and was measured to 30-cm depth. Tree seedlings in this 5-month silvopasture study included poplar.

Another study that intercropped 10 tree species with yearly rotations including maize, wheat, and soybeans (Price and Gordon, 1998), investigated seasonal changes in the abundance and

distribution of earthworms for a temperate intercropping system that was 11 years old. To a depth of 40 cm in sandy loam with an Ap horizon ranging in depth from 28 to 53 cm, the authors quantified significant variations in earthworm biomass and density between three tree species, including poplar, silver maple, and white ash. More specifically, the total mean earthworm density was greater within poplar rows (182 m^{-2}) than white ash rows (90 m^{-2}) and silver maple (71 m^{-2}).

3.1.4. Carbon Sequestration

It is possible to capture and store CO_2 in photosynthesizing crops from the atmosphere through the process of carbon sequestration. This can happen either naturally or through human intervention, as with the case of using crops to sequester CO_2 (Mercer and Burke, 2023). Measuring CO_2 as a GHG is complex because of the many sources and sinks – both need to be considered to compute the net amount. For example, while crops may be net sinks for CO_2, tilling land requires machinery that are net emitters. Therefore, different management practices contribute to sequestering carbon in agricultural lands, and their contributions need to be measured as part of GHG accounting.

- **Cover Crops**

In a medium-term field experiment conducted from 2007 to 2016 at the University of Guelph, Ridgetown Campus, the efficacy of cover crops in a humid temperate climate on sandy loam soil (Orthic Humic Gleysol) was studied, highlighting the significant role of cover crops in carbon sequestration and enhancing SOC storage. Over the 9-year period, oilseed radishes demonstrated the highest total (cumulative) plant carbon, averaging 22.8 Mg C ha^{-1}, markedly higher than the 13.8 Mg C ha^{-1} from plots without cover crops (Chahal et al., 2020). With regards to SOC content specifically, a combination of oilseed radishes and winter cereal rye was the most effective treatment in SOC levels, surpassing oilseed radishes alone, winter cereal rye, and oats. Overall, the study found that cover crops exhibited 8.4-9.3% higher average SOC concentrations than plots with no cover (Chahal and Van Eerd, 2018). Optimal soil sampling times identified in the study were two weeks after tillage and at harvest, representing critical moments when agricultural practices most influence soil properties (Chahal and Van Eerd, 2020).

The increased SOC concentrations in cover crop plots can be attributed to the balance between carbon losses and gains. Losses occur through the leaching of SOC with water and erosion, while gains come from the addition of plant above- and below-ground biomass (Blanco-Canqui et al., 2015). For instance, in an experiment between 2007 and 2016 on sandy loam with 3.8% measured SOC (LOI) to a depth of 15 cm in Ridgetown cover crops (Chahal and Van Eerd, 2020), retaining crop residues significantly enhanced soil carbon and nitrogen storage. Oilseed radishes particularly had the highest biomass with 4850 kg C ha^{-1} and 159 kg N ha^{-1}. Retaining crop residues increased SOC by 0.0538 mg C g^{-1} and total nitrogen (TN) by 0.7065 mg N g^{-1} compared to residue removal. Cover crops increased labile fractions associated with microbial biomass carbon and nitrogen and had positive soil health and nutrient cycling effects.

A 36-year old study conducted in Elora on silt loam soil within a humid continental climate explored the combined effects of tillage, cover crops, and 14 different crop rotations (Laamrani et al., 2020). Findings revealed that incorporating red clover as a cover crop into a NT corn-corn-oats-barley (C-C-O-B) 4-year rotation led to an 11% increase in total carbon (TC) concentration compared to NT C-C-O-B without cover crops. Additionally, the study also noted that the highest TC increases were observed in plots where red clover was planted following winter wheat and oats and barley. Overall, the incorporation of a cover crop enhances TC storage better than solely diversifying crop rotations.

- **Tillage**

In a metaanalysis on the effects of NT practices on SOC across various conditions in Gleyic and Orthic Luvisols in southern Ontario, authors found a common increase in SOC in the top 15 cm of soil at 24 of 38 sites (VandenBygaart et al., 2004). However, deeper layers (15-30 and 30-45 cm) generally experienced a decrease in SOC. This trend was most notable in soils with initially higher SOC or thicker Ap horizons, which often showed losses. The study also highlighted the limitations of using single soil cores for SOC measurements, given the variability in SOC changes and the challenges associated with capturing the variability (VandenBygaart et al., 2004).

Further individual studies supported these findings. In a 25-year study on a silty loam farm in Elora, researchers indicated that ZT enhanced SOC storage by 11-16% in the surface layer (0-5 cm). However, considering deeper depths of 0-40 cm, ZT had lower SOC storage compared to spring MP. Spring MP plus secondary tillage had the highest SOC storage for both the 0-40 and 0-60 cm soil depth, which is 6-24% higher than the SOC concentration of other treatments of Spring MB, Fall MP plus secondary tillage, and Fall chisel plow plus secondary tillage (Deen and Kataki, 2003). In another long-term field trial within a humid temperate region of Woodslee, Ontario on a corn and soybean production system, the studies consistently demonstrated higher SOC concentrations in the surface layer by 18-32% on a clay loam soil under NT (Yang et al., 2008a). Similar to previous studies, subsurface SOC levels were significantly lower under NT compared to MP. This was attributed to the reduced burial of crop residues and lower root inputs in NT systems. Another long-term study of 29 years in southwestern Ontario on a Brookston clay loam uncovered similar findings – NT resulted in higher SOC on the surface (0-5 cm) by 56.5% but lower SOC in the subsurface by 7.9% compared to MP. Researchers also studied ridge tillage, a middle-ground between MP and NT, performing slightly worse than NT with 12.4 and 5.9% lower SOC at 0-5 and 10-20 cm, respectively. However, ridge tillage had slightly higher SOC than NT at the subsurface 20-30 cm depth, following the trend of previous studies (Shi et al., 2012).

A long-term study in Ridgetown, Ontario explored the effects of combined tillage and crop rotations at two sites – 11 and 15 years in a humid temperate climate on Brookston clay loam. Findings contradicted previous studies, where NT had 21 Mg ha^{-1},14% higher SOC than CT with MP up to a depth of 100 cm. The researchers mentioned this could be due to a reduced rate of SOC mineralization, as opposed to SOC sequestration, along with the contribution of earthworms (Van Eerd et al., 2014). Additionally, CT in maize-soybean rotations resulted in a

lower deficit of maximum SOC potential of 2.95 g C kg^{-1} soil compared to 8.97 g C kg^{-1} under NT conditions. Maize-soybean rotations had the smallest deficit of all rotations under CT and the largest deficit of all rotations under NT. Researchers hypothesized that this is due to higher yields and rates of residue return under maize-soybean CT (Wepruk et al., 2023).

- **Agroforestry**

In southern Ontario, a region with a temperate climate and a mix of soil types, agroforestry practices have shown promising results in enhancing SOC sequestration. Particularly, a quantitative analysis over medium sandy and silty loam soils in Huron and Oxford counties in Ontario revealed that rehabilitated tree buffers achieve notably higher SOC sequestration rates than natural forest buffers (Ofosu et al., 2022a). More specifically, the study shows that at shallower soil depths (0-20 cm), rehabilitated tree buffers sequestered SOC at an average rate of 6.4 Mg C ha^{-1} yr^{-1} compared to 5.2 Mg C ha^{-1} yr^{-1} in natural forest buffers.

Another study showed that tree age matters in the amount of carbon sequestration. For instance, 99-year-old tree buffers captured 334.10 Mg C ha^{-1} compared to 35-year-old grass buffers (121.11 Mg C ha^{-1}) (Ofosu et al., 2022b). Tree types were compared based on deciduous versus coniferous growth, with 103-year-old coniferous buffers sequestering 357.62 Mg C ha^{-1} and 94-year-old deciduous buffers retaining 310.59 Mg C ha^{-1}. However, on an annual basis, these respective tree types sequestered 3.37 Mg C ha^{-1} yr^{-1} (coniferous) versus 4.47 Mg C ha^{-1} yr^{-1} (deciduous), compared to 3.14 Mg C ha-1 yr-1 for natural forest buffers and 4.71 Mg C ha^{-1} yr^{-1} for rehabilitated buffers in their study. For trees versus grass, respectively, the annual gain in SOC was 3.92 Mg C ha^{-1} yr^{-1} (trees) versus 3.62 Mg C ha^{-1} yr^{-1} (grass).

Studies comparing tree species of deciduous versus coniferous tree types in Guelph's 21-year-old TBI system found that hybrid poplar (57.0 Mg C ha^{-1}) had greater SOC content than Norway spruce (50.9 Mg C ha^{-1}), which was insignificantly greater than the conventionally managed agroecosystem (50.8 Mg C ha^{-1}) (Bambrick et al., 2010). From 1993 to 1995, there was no significant change in SOC within three zones: close to the tree row, middle of the crop alley, and area furthest from the tree row. As trees matured and grew taller, there was a 35% relative increase from 1995 in SOC close to the tree-rows by 2002, given that 80% of the leaves fell within 2.5 m from the tree row (Thevathasan and Gordon, 2004). There was also a reduction of N$_2$O emissions by ~0.7 kg ha^{-1} yr^{-1}, enabling a corresponding fertilizer reduction by the same amount. In total, a gain of 12% of SOC compared to the conventional system can be attributable to litterfall from older trees as well as potentially to shading that slows decomposition (Bambrick et al., 2010).

- **Crop Rotations**

Crop rotations, as a sustainable agricultural practice, have demonstrated significant benefits in enhancing SOC storage, particularly in Ontario's diverse climate and soil conditions. A metaanalysis highlights that incorporating crop rotations, especially combined with NT practices and the use of nitrogen fertilizers, leads to greater SOC storage compared to continuous corn cultivation (Congreves et al., 2014). This finding was seen across various soils, ranging from

Podzolic to Brunisolic and Gleysolic, with textures varying widely from heavy clay to silt loam, and across different sites such as Alfred, Delhi, and Elora in Ontario.

In a previously mentioned study at Ridgetown, Ontario of combined RT and crop rotations on Brookston clay loam, the research found enhanced soil health, SOC, and TN in NT plots specifically in rotations with winter wheat across the 0-100 cm soil profile (Van Eerd et al., 2014). Researchers hypothesized that SOC concentrations at deeper levels were enhanced with winter wheat, known to have deeper roots, due to higher root density, distribution, and exudation. The authors recommended growers on clay loam soil in southwestern Ontario to incorporate winter wheat combined with NT practices (Van Eerd et al., 2014).

In a previously mentioned long-term study conducted at the Elora Research Station in Ontario, 14 crop rotations in silt loam topsoil at depths of 0-15 cm were investigated (Laamrani et al., 2020). Notably, the highest TC concentrations were observed in rotations of corn-corn-oats-barley (C-C-O-B) that incorporated red clover cover crops during both cereal phases. C levels followed in descending order of rotations: corn-corn-alfalfa-alfalfa (C-C-A-A), corn-corn-soybean-winter wheat (C-C-S-W) with 1 year of seeded red clover, and corn-corn-corn-corn (C-C-C-C). The lowest TC concentrations were recorded in corn-corn-soybeans-soybeans (C-C-S-S), C-C-O-B without cover crops, and corn-corn-soybeans-winter wheat (C-C-S-W). Over the course of the study, TC for all investigated plots, regardless of the crop rotations, increased and TC was higher in NT compared to CT. NT C-C-O-B, with cover crops exhibiting the most significant rise in TC content. Additionally, continuous corn rotations under NT had higher TC than rotations involving combinations of soybeans and corn or soybean-winter wheat. Rotations incorporating two consecutive years of soybeans consistently showed lower TC levels compared to other systems (Laamrani et al., 2020). In contrast, continuous alfalfa rotations showed the lowest carbon deficit compared to potential SOC of 7.25 g C kg^{-1}, emphasizing efficacy in SOC retention compared to maize-soybean rotations, which exhibited the highest deficit of 12.07 g C kg^{-1} soil at the same depth (Wepruk et al., 2023).

3.2. GHG Modeling

- **Cover Crops**

Cover crops were not a common practice among farmers, with only 11 out of 31 (35%) incorporating them. The most common cover crops consisted of oats, rye, and red clover, with some planted in the winter and later harvested as a cash crop or used for silage. Cover crop yields were greatest for oats and then rye (**Table 2**). Of the cover crops, oats were associated with more SOC and GHG emissions than rye. By comparison, winter wheat (winter crop) had the lowest yields, but the most SOC and highest GHG emissions. On average, based on Holos results, total emissions per hectare (kg CO_2e) were 36% higher in fields with cover crops than in those without (note: total emissions do not include carbon sequestration from SOC storage). This increase was driven by higher direct N_2O emissions from soil processes such as nitrification and denitrification. Despite the use of cover crops, farmers in the study did not reduce their nitrogen fertilizer inputs. On average, fields with cover crops received 127 kg N ha^{-1} compared to 103 kg N ha^{-1} for farms without cover crops. Research suggests that cover crops

like red clover can offer opportunities to reduce nitrogen fertilizer inputs, indicating that these farms may be missing out on fertilizer savings (Yang et al., 2024).

Table 2. Mean outputs for some of the more commonly appearing cover or winter crops based on Holos modeling.

Cover Crop/ Winter Crop	Yield (kg ha^{-1})	SOC (kg C ha^{-1})	GHG (kg CO$_2$e)
Oats	7083	57,339	965
Rye	6300	42,281	758
Winter wheat	5461	62,851	1237

On average, based on Holos modeling, fields with cover crops experienced higher yields per hectare of 1%, 28%, and 26% in clay, sand, and silt loam soils, respectively. Moreover, corn, soybeans, and spring wheat had higher yields per hectare in a cover cropped setting by 3%, 10%, and 60%, respectively. Although these yield improvements might be partly driven by increased fertilizer usage or different management practices, these findings align with recent studies from Ridgetown, Ontario (Chahal and Van Eerd, 2018; Kerr et al., 2023).

- **Tillage**

RT or NT were common practices among the farmers surveyed. 10 farmers implemented NT, 11 practiced RT, and five used CT. Additionally, three farmers combined NT and RT across their fields, while two incorporated both CT and RT. On average, total emissions for NT per hectare across all soil textures were 4% lower than CT. Surprisingly, RT had the highest total emissions at 1393 kg CO$_2$e, 8% higher than CT. This is likely driven by individual management practices and greater rates of fertilizer application. The slight decrease in emissions for NT was attributed to lower farm energy CO$_2$ emissions due to less equipment use for tillage. Additionally, there was a reduction in direct N$_2$O as NT diminishes the intensity of microbial processes responsible for N$_2$O production in well-drained, coarse-textured soils (e.g., sandy loam) compared to heavier, poorly drained clays (Soil Science Society of America, 2008). This was true in the data, as NT in clay loam performed the worst and experienced an increase in total emissions compared to CT.

Average crop yield per hectare in clay and sandy loams followed an expected trend: CT (intensive tillage) had the highest yield by far, followed by RT, and then NT (**Table 3**). Interestingly, CT had the highest SOC too and nearly the highest GHG emissions. Conversely, RT had the lowest SOC and GHG emissions. While NT had middling SOC, it had the highest GHG emissions associated with it. When examined by crop, corn yield suffered the most under a NT system compared to wheat and soybeans. Similarly, a long-term study in Ottawa found that CT corn yields were ~20% higher than NT corn across all rotations, while wheat and soybean yield remained the same (Morrison et al., 2018). Our results suggest a higher proportion of 54% across crops and soils.

Table 3. Yields for different types of tillage based on Holos modeling.

Type of Tillage	Yield (kg ha^{-1})	SOC (kg C ha^{-1})	GHG (kg CO$_2$e)
Intensive	13,767	96,208	1689
Reduced tillage	7746	54,755	1298
No-tillage	6356	62,671	1693

- **Crop Rotations**

Out of the 31 farms, 29 (94%) included crop rotations as a practice, mainly consisting of corn, soybeans, and winter wheat, highlighting the widespread adoption of grain crop rotations in southern Ontario used to boost productivity and enhance soil health. The type of crop in rotation influences SOC modeled in Holos (**Figure 2**). Although restrained by small sample size (e.g., corn silage), high values for tame mixed, silage corn, and canola can be attributed to a combination of grass and legume species that can improve forage quality, increase yields, and enhance soil health. Legumes in the pea or bean family (Fabaceae) fix nitrogen from the atmosphere into the soil, enriching it for plant growth. For example, canola's deep roots can sequester more carbon than many other crops.
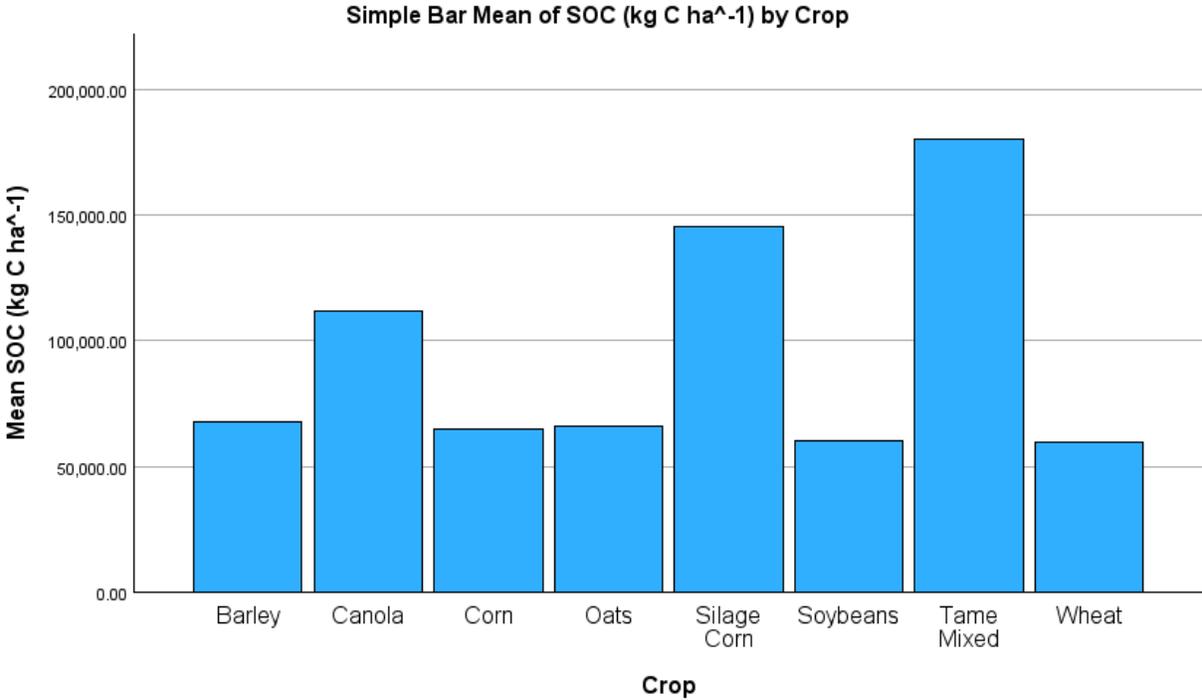
Figure 2. Crops affecting mean SOC data generated in Holos.

The two farmers that have a continuous rotation rely on intensive tillage, manure, and a moderate fertilizer application rate to maintain an adequate amount of crop yield. It should be noted, however, that due to the small sample size for continuous rotation fields (for all crops except corn, soybeans, wheat) and lack of diverse rotations, the validity of yield and emissions analysis when comparing continuous and rotational fields is limited.

4. Broader North American Context

The findings in the previous section specifically conveyed information for Ontario. This section supplements this with a broader view of Canadian and some American research. More topical breadth is also provided here for Northeastern climate and seasonality, as it affects soil biota and species mixtures that can be supported and are currently being investigated in the literature.

It is important to consider the climate where soils and crops are situated (**Figure 3**). A report for Canada, for example, found for wet conditions that soils were sensitive to compaction (Blois, 2024). This applies to soils located in eastern Canada (including Ontario, Quebec, New Brunswick) and BC's Fraser Valley, that are worked under very wet conditions. These wet soils are more susceptible to compaction than where there are more water deficits. Agricultural practices considered by this report included NT, low-till, cover cropping and intercropping. Blois (2024) reported that since 1991 NT practices in Canada have increased from 7% to over 60%. Accordingly, adopting NT farming has improved soil health in Canadian soils, where there are increased carbon stocks. Cover cropping has also been used to promote carbon sequestration among other reasons. Similar considerations are evident for Manitoba rotations, including perennial rotation and intercropping (Curtis et al., 2024). Growing conditions that become hotter and drier would benefit from growing more water use efficient crops, including Fall rye, corn, sunflower, and corn/soybean intercrops.

More water deficits
NT farming improving soil health
Increased carbon stocks
Cover cropping to promote carbon sequestration

Hotter and drier growing conditions benefit from growing more water use efficient crops, e.g. Fall rye, corn, sunflower, corn-soybeans intercrops

Wet soils sensitive to compaction
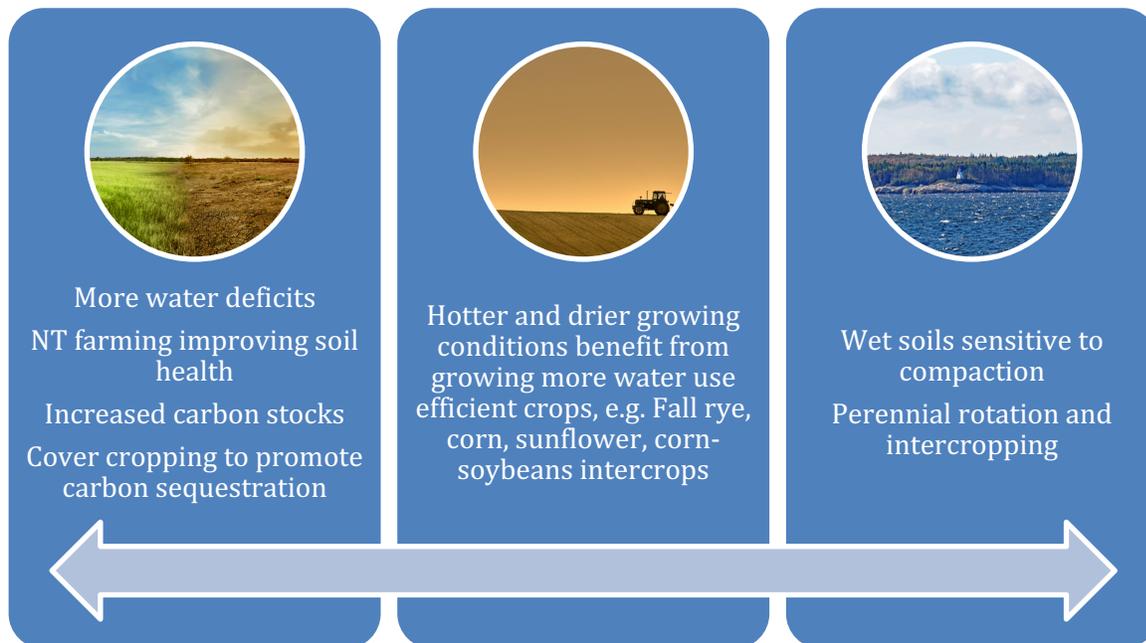Perennial rotation and intercropping

Figure 3. Cross-geography lessons for different Canadian climates.

NT also affects seedbed warmth. A study for a modified NT system found this to be the case in the spring and led to improved wheat production in all crop rotations as well as higher yields of

canola and peas (Arshad et al., 2002). This was evident for an Albright silt loam (Mollic Cryoboralf) located in a cold semiarid region in Beaverlodge (Alberta, Canada).

A global metaanalysis found fewer publications on tillage and crop rotation than on fertilization practices (Audette et al., 2021). However, these authors found the distribution of carbon functional groups to be influenced by crop rotation and tillage practices more than fertilization management. For comparison, whereas fertilization practices increased O-alkyl groups, tillage resulted in increases in the SOC of aromatic and carbonyl groups and crop rotations, especially legume-based rotations, increased the proportion of aromatic groups (Mesgar et al., 2024).

Although some research has found no significant differences in soil bacterial diversity (Rolhauser and Isaac, 2024), other studies for a NT irrigated Mediterranean ecosystem found higher microbial abundance and diversity when compared to CT in a Panoche clay loam (Typic Haplocambids) (Schmidt et al., 2018). NT plots had increasing bacterial diversity with depth, whereas it decreased with depth in standard tillage. It has also been discovered that by introducing three types of bacteria as key candidates found in highly productive land (~20 t ha^{-1}), it is possible to enhance biological soil health and productivity of average-yielding soils (Kandasamy et al., 2019). However, a review focused on designing optimized crop rotations based on niche complementarity (Dias et al., 2015); and these authors espoused that identifying specific key organisms or consortia, rather than assessing soil microbial diversity, is critical for predicting crop productivity and soil health. To this end, soil feedback studies and developing soil biotic community databases were recommended by them to optimize crop rotations.

Research studying SOC changes from cover crops in Ontario is still in its early stages. To supplement the findings from Ontario, a comprehensive review of cover crops in temperate soils in North America highlighted that carbon sequestration depends on numerous factors outlined in **Figure 4**.
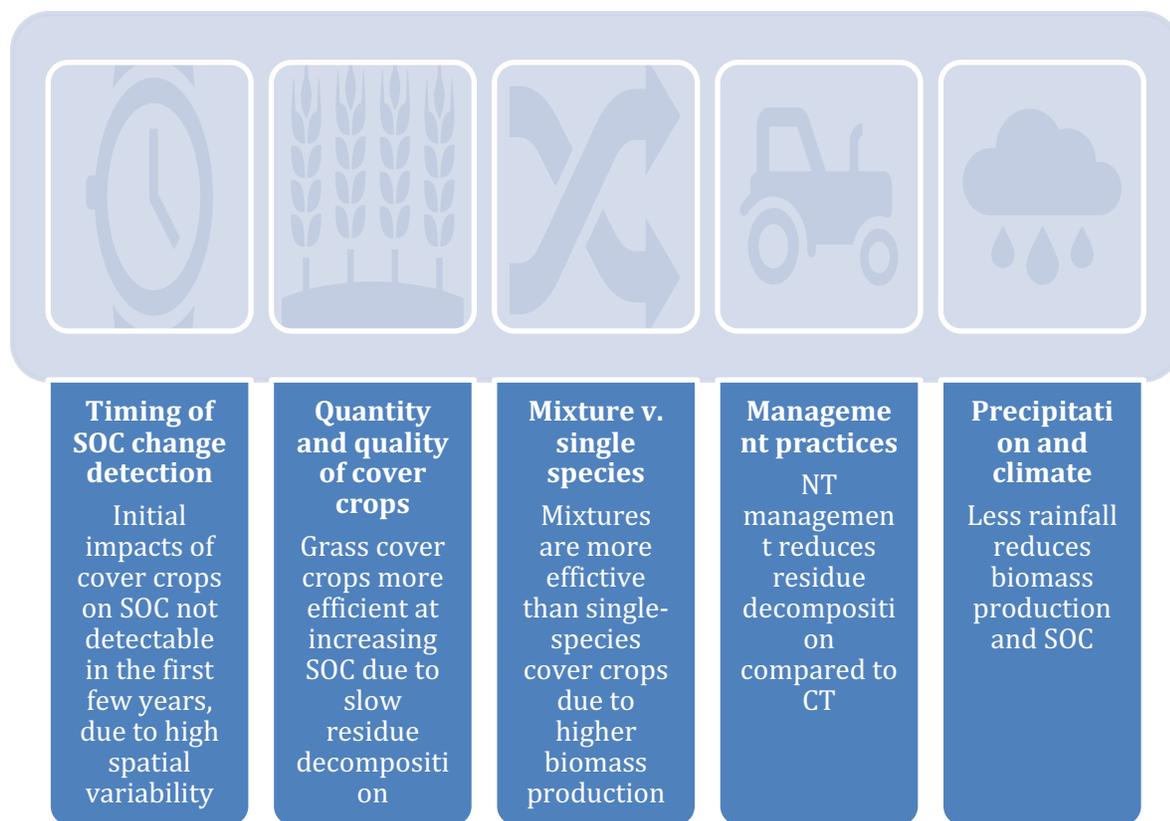
Figure 4. Factors affecting carbon sequestration (after Blanco-Canqui et al., 2015).

Additionally, while NT by itself increases SOC primarily near the surface, it can lead to deeper SOC accumulation when combined with deep-rooted cover crops. However, further research is needed on specific cover crop species and their effectiveness in improving SOC at deeper soil depths (Blanco-Canqui et al., 2015).

According to a recent review assessing cover crop multimixes, there is a trend towards objectively selecting cover crop species based on their complimentary functionality (Chapagain et al., 2020) (**Table 4**). An objective procedure involved in such a selection process has been focused on temperate North America, where different species mixtures can be applied. These include species such as cereal rye, oats, buckwheat, sorghum/Sudan grass, red clover, crimson clover, hairy vetch, forage peas/Austrian winter peas, alfalfa, forage radishes, purple top turnips, canola, sunflowers, annual ryegrass, and perennial ryegrass. Interestingly, these authors specified temperature, moisture, and soil type as defining the context for environmental compatibility. Regenerative agricultural practices such as cover cropping as well as using crop rotations and organic amendments have been reported to improve soil health and build yield resilience in Ontario farms (Potter et al., 2024). Although, there are barriers to its adoption such as financial and regulatory challenges plus the rising input costs, which pose barriers according to farm size and management practice.

Table 4. Functionality of cover crop species relevant to SOM (source: https://www.ontariosoilcrop.org/soil-health-resources/).

Cover Crop Species	SOM Function	Ontario Source(s)
Grasses - fibrous roots that hold soil in place and improve soil structure; fast-growing and easily winter-kill; can accumulate nitrogen from the soil		
Barley	If planted early enough in the fall, there will be sufficient biomass to increase soil organic level	(Hargreaves et al., 2019)
Corn	Best used as a green manure crop; biomass return depends on planting date, seeding rate, and first frost	-
Oats	High biomass produced if well established	(Chahal et al., 2020); (Chahal and Van Eerd, 2018, 2019, 2020); (Hargreaves et al., 2019); (Kerr et al., 2023)
Pearl millet	Biomass return depends on planting date and first frost	(Hargreaves et al., 2019)
Rye	Large volumes of plant biomass returned to soil	(Chahal et al., 2020); (Chahal and Van Eerd, 2018, 2019, 2020); (Kerr et al., 2023)
Ryegrass	Forms a dense sod and lumpy seedbed	-
Sorghum Sudan	Can produce massive amounts of dry matter (4000-5000 lb ac^{-1})	-
Winter wheat	-	-
Legumes - provide nitrogen to succeeding crops; protects the soil from erosion; and add SOM		
Red clover	Adds considerable biomass; improves conditions for soil microbes	(Agomoh et al., 2021); Chahal et al. 2021); (King et al., 2020); (Laamrani et al. 2020); (Mesgar et al., 2024); (Yang et al., 2021); Yanni et al., 2021)
Hairy vetch	Can add 2000-5000 lb ac^{-1} of dry matter	(Yang et al., 2021)
Sweet clover	-	-

Cover Crop Species	SOM Function	Ontario Source(s)
Soybeans	Residue readily breaks down	(Hargreaves et al., 2019)
White/Crimson clover	Both have a C:N of 10:1	(Yang et al., 2021)
Field peas	Add considerable biomass to soil from the seed and stubble; crop residue readily breaks down	(Hargreaves et al., 2019)
Nonlegume broadleaves – can absorb large quantities of nitrogen from the soil; most are not winter-hardy		
Buckwheat	Not a big biomass producer, especially if planted in late summer; easily decomposable residue	-
Oilseed radishes	Residue has low lignin content resulting in rapid decomposition; return moderate amounts of organic matter to the soil; can produce 1.5 t yr^{-1} dry matter if residual nitrogen levels are high	(Chahal et al. 2020); (Chahal and Van Eerd, 2018, 2019, 2020); (Kerr et al., 2023)
Other brassicas	Biomass production varies greatly with species and growing conditions; residues have low lignin content = rapid decomposition; returns moderate amounts of organic matter to the soil	-
Marigold	-	-

Not all potential cover crops are being deployed in Ontario. For example, some crops like grain corn, soybeans, and winter wheat are preferred as rotational crops. Others such as red clover are popular cover crops. More published studies are needed to relay testing of different varieties (and mixtures) of cover crops in Ontario. A survey of Ontario farmers, for instance, conveyed that 70% of respondents used cover crops and 93% of them plan to continue using cover crops (Shah et al., 2022). Accordingly, farms where cover crops are adopted tend to be larger, with mean acreage of 590 than 439 ac by nonadopters. Of the latter group, crop producers represent 80% while livestock producers make up 14%; conversely, the adopted group had 60% crop producers and 35% livestock producers.

5. Key Points and Takeaways

In addressing sustainability, management practices must also consider soil texture and type as key factors, as soils respond differently to disturbance and management intensity.

By minimizing soil disturbance, a core principle of regenerative agriculture, it is possible to retain soil carbon. This has been supported by multiple studies demonstrating impacts on both soil physical properties and biogeochemical processes. For example, bulk density was greater in NT

soils than in CT soils within the 5-10 cm surface layer (Deen and Kataki, 2003). These findings highlight the need for a broader perspective that considers soils as integrated systems (Potter et al., 2024), shaped by multiple components and their complex interactions. Tillage is therefore a critical consideration for soil health, as RT improves soil structure, lowers erosion risk, and enhances carbon sequestration. Additionally, reducing fuel-intensive tillage operations limits SOM losses to the atmosphere (Singh, 2023).

The literature also demonstrates the role of cover crop mixtures in enhancing carbon sequestration and soil health. For instance, long-term use of cover crops resulted in significantly higher tomato yields compared to isolated management practices (Kerr et al., 2023), supporting the conclusion that cover crop mixtures improve soil health. In this case, soil health was inferred using crop yield as a proxy. Other studies have assessed soil health using composite indices that integrate multiple soil attributes such as the OSHA framework (Congreves et al., 2015; Van Eerd et al., 2014; Wepruk et al., 2023). Under multispecies cover cropping, greater particulate organic carbon (POC) and nitrogen were observed to a depth of 15 cm, along with approximately 10% higher cumulative carbon mineralization and increased soil-test biological activity at the 0-5 cm depth (Franzluebbers et al., 2021). Similarly, research conducted in Ridgetown showed that a mixture of winter cereal rye and oilseed radish was the most effective cover crop for enhancing SOC levels (Chahal and Van Eerd, 2018).

Diverse crop rotations are also well recognized for their benefits to carbon capture and soil health. Research from experimental plots in southern Ontario, including Ridgetown and Elora, showed that rotations incorporating winter wheat or alfalfa achieved higher OSHA scores (Congreves et al., 2015; Laamrani et al., 2020). Rotations that included corn and winter wheat as cereal crops produced the highest soybean yields, while positively influencing soil health, as cereal crops contributed to increased soil carbon (Agomoh et al., 2021). These authors further reported that residues from corn, winter wheat, and red clover contributed more to soil carbon accumulation than soybeans residue. These findings align with other studies advocating for diversification of corn-soybean rotations and monocultures through the inclusion of cover crops, perennials, and small-grain cereals to improve soil health and crop productivity (Chahal et al., 2021; Janovicek et al., 2021).

Compared to the management strategies discussed above, agroforestry research related to soil health in Ontario remains limited. Existing studies (at the time of this literature review) have primarily focused on forested riparian buffers for carbon capture through new biomass growth (Ofosu et al., 2022a, 2022b). Quantitative analyses indicate that rehabilitated tree buffers achieve significantly higher SOC sequestration rates than natural forest buffers (Ofosu et al., 2022b). Vegetation type is also an important factor, as fast-growing tree species such as poplar and willow tend to sequester more carbon due to their higher growth rates.

5.2. Recommendations

Researchers studying the impact of soil textural groups on four soil health indicators measured in diverse agricultural systems across Ontario found significant effects of three textural groups (fine, medium, and coarse) (Chahal et al., 2023). Fine soils had more concentrated SOM

compared to coarse soils, reflecting soil carbon retention in fine-textured soils. This could be indicative of a greater microbial activity with the fineness of soil texture. The researchers recommended using these three soil textural groups (fine, medium, coarse) over the five soil textural groups clay, clay loam, loam, sandy loam, and sand to measure soil health.

The literature on soil health further supports that the physical attributes of soils influence their biogeochemistry. For example, it has been shown that coarser soils have less SOM (Chahal et al., 2023). Adding fines to soils (e.g., clays, liming) is known to improve soil aggregation and pH, among other factors – although the focus here has been on variables affecting SOC content. Another study found that SOC accumulation, including labile carbon, occurs with more water regulation (Driscoll et al., 2023). This is an important consideration, since active carbon has been found to account for 45% of the variation in soil health scores based on textural groups of fine, medium, and coarse soils (Fine et al., 2017).

The focus on Ontario has removed variability attributed to climate, although there remains some variety in soil textures. Researchers working in Ontario have evidently recommended the use of three soil textural groups (fine, medium, coarse) used to encompass the different soil types (Chahal et al., 2023). The findings have focused on loam (medium-textured soils) according to the three (clay, silt, sandy) loam groups appearing in Ontario publications. The recommendations that follow, therefore, are presented according to soil textural groups for loam soils (**Figure 5**). This has been reiterated along with other recommendations, adding that four key indicators of soil health be employed, including active carbon, penetration resistance, respiration, and wet aggregate stability (Fine et al., 2017).
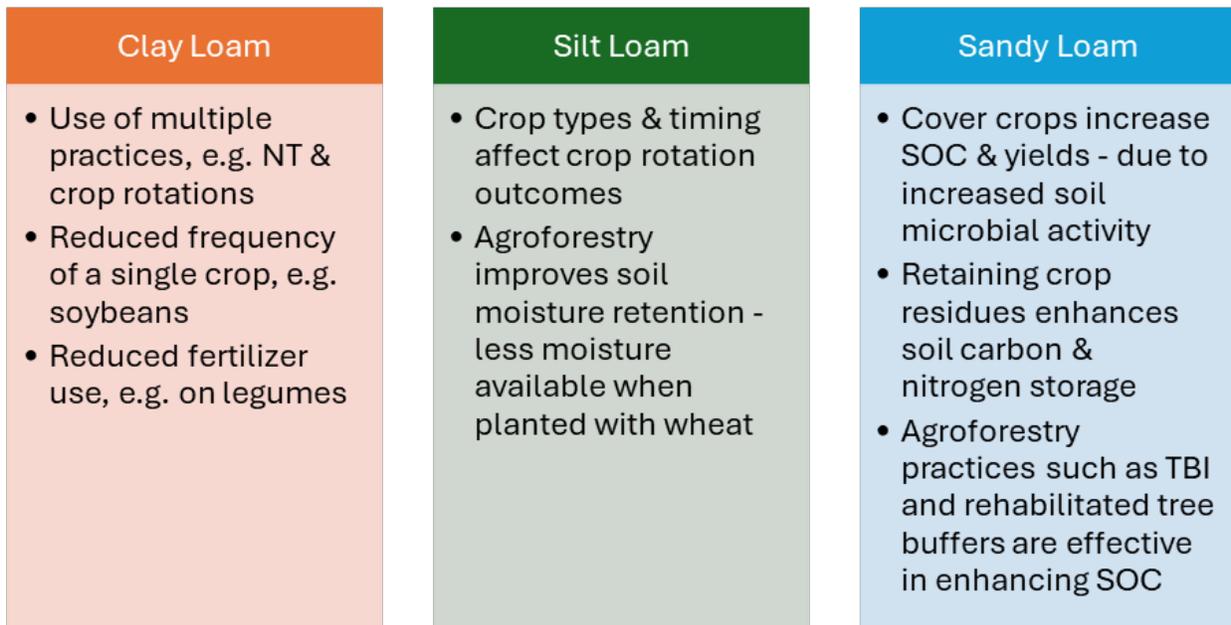
Clay Loam	Silt Loam	Sandy Loam
• Use of multiple practices, e.g. NT & crop rotations • Reduced frequency of a single crop, e.g. soybeans • Reduced fertilizer use, e.g. on legumes	• Crop types & timing affect crop rotation outcomes • Agroforestry improves soil moisture retention - less moisture available when planted with wheat	• Cover crops increase SOC & yields - due to increased soil microbial activity • Retaining crop residues enhances soil carbon & nitrogen storage • Agroforestry practices such as TBI and rehabilitated tree buffers are effective in enhancing SOC

Figure 5. Recommendations for differently-textured Ontario loam soils.

There is a temporal influence of the findings. A study based on two silt loam soils from Elora and Burlington and a sandy loam from Guelph investigating perennial biomass crops found that long-term research (>10 years) was missing (Vijayakumar et al., 2023). The implementation of regenerative agriculture compares changes to a baseline over initially short time spans. It takes time for measurable change to occur, however, as evident for NT and rotation farming after 10 years (Van Eerd et al., 2014), for Brookston clay loam.

It should be noted that some 20% of Ontario farmers already test their soils, with half testing every 3 years (Shah et al., 2022). These authors relayed that a predominance of Ontario farmers already employ at least four BMPs to bolster soil health, with the most common combination including more than two crops in rotation (corn, soybeans, winter wheat) under NT. For Elora silt loam (and Ridgetown clay loam), it was found that diversifying crop rotations enhances soil microbial activity as well as surface SOC sequestration and crop productivity in the long term (Chahal et al., 2021). Authors have recommended that long-term farming system trials be implemented to compare conventional and regenerative agricultural practices to move forward and build knowledge at regional scales (Khangura et al., 2023).

5.2.1. Clay Loam (Ridgetown, Woodslee)

From the literature review, studies show that NT on its own does not improve soil carbon at depth (Yang et al., 2008b; Shi et al., 2012). Authors conducting research on Ridgetown, Ontario clay loam instead recommended the use of winter wheat (cereal crop) and/or alfalfa (legume) in rotations alongside NT (Van Eerd et al., 2014). The recommendation can also be derived from other studies, seeing improved soil carbon storage, microbial activity, and increased crop yields when the frequency of soybeans was reduced in rotations (Agomoh et al., 2021). A broader recommendation for clay loam from Quebec has been that nitrogen fertilizer not be applied to soybeans (St. Luce et al., 2022), at least not at the rates in their study. Additionally, NT is not as beneficial for SOC levels as CT in maize-soybean rotations on clay loam (Wepruk et al., 2023).

5.2.2. Silt Loam (Burlington, Dundalk, Elora, Guelph, Lucknow)

For maximizing SOC sequestration, a study at the Elora Research Station demonstrated that the best crop rotation was continuous alfalfa, whereas rotations incorporating two consecutive years of soybeans showed lower TC levels (Laamrani et al., 2020). Red clover cover crops were most effective following winter wheat and oats and barley. Generally, incorporating cereals and cover crops enhanced SOC further than diversifying crop rotations solely (Laamrani et al., 2020).

Agroforestry also improves soil moisture retained in soils (Williams and Gordon, 1995), which affects young trees early in the growing season. Less soil moisture was available when wheat was grown, although wheat did protect tree seedlings earlier in the season than soybeans.

5.2.3. Sandy Loam (Delhi, Dunville, Grand Valley, Guelph, Ottawa, Ridgetown, St. Thomas)

Cover cropping augments average SOC concentrations and crop yields (Chahal and Van Eerd, 2018), as evident in Ridgetown sandy loam. Increased soil microbial activity was observed for cover crops, and improved SOC concentration over time (Chahal and Van Eerd, 2019), as in medium- to long-term studies. When crop residues were retained, both soil carbon and nitrogen storage were improved between 2007 and 2016 (Chahal and Van Eerd, 2020). Oilseed radishes were found to have the most above-ground biomass production, contributing to carbon inputs to soils (Chahal et al., 2020), whereas below-ground biomass (roots) contributed towards improved soil fertility and carbon stocks. Therefore, the fibrous roots of cereal crops (e.g., rye, oats), both in mixtures and singly planted, denoted the highest SOC increases. Other work has supported that 6 years of planting radishes and mixed radish-rye produced higher tomato yields (Kerr et al., 2023).

Additionally, incorporating specific agroforestry practices such as TBI and rehabilitated tree buffers were effective in enhancing SOC on sandy loam soils (Ofosu et al., 2022a, 2022b; Bambrick et al., 2010; Thevathasan and Gordon, 2004). For two soil textures (sandy loam, loam soils), an experiment performed at the University of Guelph (Ntayombya and Gordon, 1995), found that tree crops improved the nitrogen of arable crops and helped to sustain crop yields with less nitrogen fertilizer. Using legume cover crops such as red clover has been shown to increase both the soil's capacity to supply nitrogen and nitrogen use efficiency (NUE), through the reduction in the amount of nitrogen fertilizer that must be applied (Gaudin et al., 2015). Leaf nitrogen inputs helped to counteract reduced water infiltration and a reduced tree seedling growth rate attributed to soil compaction due to foot traffic by cattle (Bezkorowajnyj et al., 1993), although a reduced potential for productivity was still implicated with reduced seedling growth rates. It should be noted that livestock grazing was not addressed in this report and should be explored in the future.

6. Soil Health Gains

This review paper has focused on regenerative agricultural practices as reflective of BMPs for agriculture. The authors have considered four main types of conservation agricultural practices (cover crops, tillage, agroforestry, crop rotations) to improve soil health and sequester carbon in loam (clay loam, silt loam, sandy loam) soils. The farming practices in **Figure 6** have shown to retain SOC and improve the physical structure of soil, contributing to soil health.
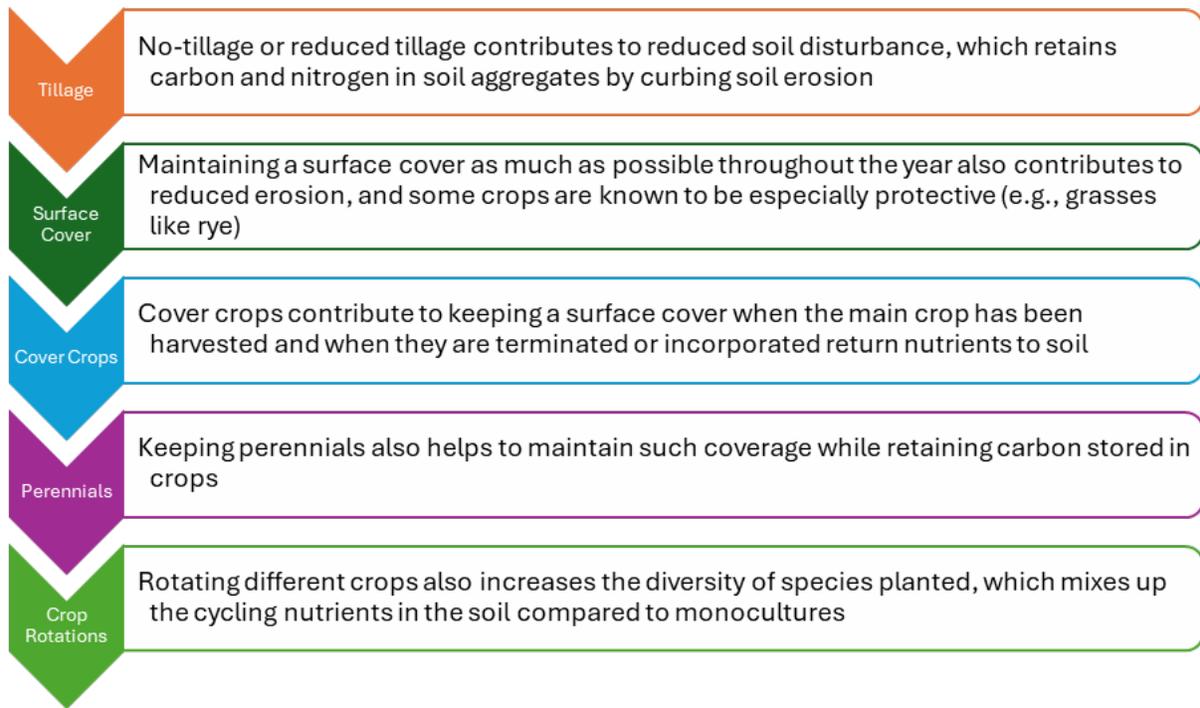
Figure 6. Farming practices that promote soil health.

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Appendix - Regenerative Agriculture Studies in Ontario

Note: Numerous studies may refer to the same field experiment sites

Reference	Location	Soil Texture &Type	Soil Depth (cm)	Crops	Practice	Experiment Duration
(Agomoh et al., 2021)	Woodslee, Ontario	Brookston clay loam soil (Mesic Typic Argiaquolls)	0-15	Soybeans, corn, winter wheat, and red clover	9 soybean rotations	2002-2018
(Bambrick et al., 2010)	Guelph, Ontario	Sandy loam (Gray Brown Luvisol)	0-20	Maize, soybean, winter wheat, and barley rotation	TBI	1987-2007
(Bezkorowajn yj et al., 1993)	Grand Valley, Ontario	Sandy loam	30	Tree seedlings, including poplar	Silvopasture	5 months
(Chahal and Van Eerd, 2018)	Ridgetown, Ontario	Sandy loam (Orthic Humic Gleysol)	0-15	Crop rotation typical of processing vegetable production in SW Ontario, including grain and oilseed crops	Cover crops of oats, winter cereal rye, oilseed radishes and oilseed radish and rye mix	2007-2016
(Chahal and Van Eerd, 2019)	Ridgetown, Ontario	Sandy loam (Orthic Humic Gleysol)	0-15	Crop rotation typical of processing vegetable production in SW Ontario, including grain and oilseed crops	Cover crops of oats, winter cereal rye, oilseed radishes and oilseed radish and rye mix	2007-2016
(Chahal and Van Eerd, 2020)	Ridgetown, Ontario	Sandy loam (Orthic Humic Gleysol)	0-15	Crop rotation typical of processing vegetable production in SW Ontario, including grain and oilseed crops	Cover crops of oats, winter cereal rye, oilseed radishes and oilseed radish and rye mix	2007-2016
(Chahal et al., 2020)	Ridgetown, Ontario	Sandy loam (Orthic Humic Gleysol)	0-15	Crop rotation typical of processing vegetable production in SW Ontario, including grain and oilseed crops.	Cover crops of oats, winter cereal rye, oilseed radishes and oilseed radish and rye mix	2007-2016
(Chahal et al., 2021)	Ontario	Ridgetown: clay loam soil (Orthic Humic Gleysol); Elora: silt loam (Gleyed Melanic Brunisol)	0-15	Corn, soybeans, winter wheat, red clover, alfalfa, oats, and barley	Two tillage system treatments (NT and CT full inversion tillage) and 7-8 crop rotations	2016
(Chahal et al., 2023)	Ontario	Not specified	0-30	Not specified	Not specified	2019-2020
(Congreves et al., 2015)	Ontario	Ridgetown: clay loam (Orthic Humic Gleysol); Delhi: sandy loam (Brunisol; Gray Brown Luvisol); Elora: silt loam (Gleyed Melanic Brunisol); Ottawa: sandy loam (Melanic Brunisol)	0-15	Corn, soybeans, winter wheat, rye, tobacco, alfalfa, oats, barley	At each site, there were four replicates, two tillage practices (NT and CT), 3-8 crop rotations	Since 1980 (Elora), 1988 (Delhi), 1995 (Ridgetown), and 1992 (Ottawa)
(Congreves et al., 2014)	Ontario	Forested area Podzolic soils; cultivated soils including Brunisolic and Gleysolic soils; forested soil from Edwards, Elora, Exeter, Plainfield, Ste. Anne, Winchester, and Woodslee included soil great groups of mainly the Gray Brown	10-120	Corn, grains, oats, alfalfa, cereal, forage, beans, tobacco, peach, annual ryegrass, and red clover (Table 1, pp. 319-320)	Metaanalysis for Ontario based on land use (forest versus agriculture land), tillage systems (NT or minimal-tillage versus CT, and cropping systems (continuous corn versus corn in rotation)	Experiments since 1800 (see Table 1, p. 319) or spanning 195 years

Reference	Location	Soil Texture &Type	Soil Depth (cm)	Crops	Practice	Experiment Duration
		or Luvisol and Humic Gleysol, soil textures of silty loam or silty clay				
(Deen and Kataki, 2003)	Elora, Ontario.	Silt loam (Typic Hapludalf)	0-60	Continuous corn from 1976 to 1990 to corn-soybeans 1991 onwards	ZT, Spring MP, Spring MP plus secondary tillage, Fall MP plus secondary tillage, Fall chisel plow plus secondary tillage	1976-2001
(Hargreaves et al., 2019)	Southweste rn Ontario	St. Thomas: loam to sandy loam (Brunisolic; Gray Brown Luvisol); Dundalk: silt loam (Podzol; Gray Brown); Lucknow: loam to silt loam (Podzol; Gray Brown)	15	St. Thomas cover crop mix in 2015 of oats/barley/peas, followed by soybeans/millet/sunn hemp/sunflowers, then the field was split into three sections of daikon radishes, oats/barley/peas, and winter cereal rye/hairy vetch for the fall and winter; 2013: mustard followed by one section of buckwheat and another section of winter cereal rye undersown with red clover)	3 organic growers, including mixed cover crops	2016
(Islam et al., 2015)	Dunville, Ontario	Mostly sandy loam	10-30 (root zone)	Corn/maize and soybeans	Strip-row farming, including NT	2012-2013
(Janovicek et al., 2021)	Southern Ontario	Elora: Woolwich silt loam (Typic Hapludalf; FAO taxonomy: Gleyed Melanic Brunisol); Ridgetown Campus: Brookston clay loam (Typic Hapludalf; FAO taxonomy: Orthic Humic Gleysol)	Not specified	Elora: Prior to trial establishment, the site had been in continuous corn production with annual application of 50 kg ha^{-1} of liquid dairy cattle manure for 13 years (1967-1979); crops currently include corn, soybeans, red clover, and winter wheat. Ridgetown: Prior to establishment, the trial site had a history of corn, soybean, wheat, and alfalfa production using CT. Current crops include corn, soybeans, red clover, and wheat	CT, NT, and RT, with 5 rotations and 4 fertilizer N rate treatments	Since 1982, analysis in 2017
(Kandasamy et al., 2019)	Dunnville, Ontario	Not specified	Not specified	Wheat used as an indicator crop in growth room experiments	Not specified	Not specified, used 8 years of unpublished A&L data

Reference	Location	Soil Texture &Type	Soil Depth (cm)	Crops	Practice	Experiment Duration
(Kerr et al., 2023)	Ridgetown, Ontario	Sandy loam (Orthic Humic Gleysol)	Not specified	Peas, sweet corn, spring or winter wheat, tomatoes, grain corn, squash, and soybeans; cover crop experiment included oats, cereal rye, radishes, and a radish-rye mixture	Crop rotation with cover crops; wheat crop residue and nitrogen fertilizer treatments were tested	Initiated in 2007
(Laamrani et al., 2020)	Elora, Ontario	Silt loam (Gray Brown Luvisol)	0-15	Corn, soybeans, and wheat are the main crops, with diversified rotations including red clover cover crops in some rotations	Tillage, cover crops, and 14 crop rotations	1982-2018
(McGrath et al., 2023)	Ontario	Not specified	Not specified	Field trees	Not specified	Summer 2020
(Mesgar et al., 2024)	Elora, Ontario	Woolwich silt loam (Gray Brown Luvisol)	0-15	Corn, alfalfa, cereals, soybeans, and a red clover cover	14 crop rotations and two types of tillage (CT and NT)	Initiated in 1980
(Ntayombya and Gordon, 1995)	University of Guelph, Guelph, Ontario	Sandy loam and loam soils	Not specified	Barley, trees	Intercropping as an agrosilvicultural practice	1988-1990
(Ofosu et al., 2022)	Huron and Oxford counties in Ontario	Medium, sandy, and silty loam	0-60	Corn, soybeans, wheat	Riparian buffer systems	2017-2019
(Potter et al., 2024)	Ontario	Not specified	Not specified	Not specified	Cover cropping, crop rotations, and organic amendments	2022-2023
(Price and Gordon, 1998)	Southwestern Ontario at the University of Guelph's Agroforestry Research Station, Guelph, Ontario	Sandy loam with an Ap horizon ranging in depth from 28 to 53 cm	40	10 different tree species intercropped with maize, wheat, and soybeans on yearly rotations	Rotations and tree intercropping	11 year old site tested in Spring and Summer 1997
(Rolhauser and Isaac, 2024)	Southern (southwestern) Ontario	Not specified	6	Dominant crops in the area are corn (*Zea mays*) and soybeans (*Glycine max*), with smaller contributions of winter wheat (*Triticum aestivum*), rye (*Secale cereale*), tobacco (*Nicotiana tabacum*), and American ginseng (*Panax quinquefolius*), among others	3 cover types: cropland, restored grassland, and forest	July 2022
(Shah et al., 2022)	Ontario	Not specified	Not specified	Predominantly soybeans, corn, and winter wheat in crop rotations	Cover crops, crop rotations, NT, conservation buffers, and organic amendments	January-April 2020

Reference	Location	Soil Texture &Type	Soil Depth (cm)	Crops	Practice	Experiment Duration
(Shi et al., 2012)	Southwestern Ontario, Canada	Clay loam (Orthic Humic Gleysol)	0-60	Corn-soybean rotation	Ridge tillage, NT, and MP	1982-2012
(Thevathasan and Gordon, 2004)	Guelph, Ontario	Sandy loam (Gray-Brown Luvisol)	0-20	Maize (corn), soybean, winter wheat, barley rotation	TBI	1987-2007
(Van Eerd et al., 2014)	Ridgetown, Ontario	Brookston clay loam (Orthic Humic Gleysol)	0-120	Corn, soybeans, and winter wheat	Crop rotations for NT and CT	1991 tillage (11 years) trial and 1995 (15 years) tillage-rotation trial
(Wepruk et al., 2023)	Delhi, Elora, Ottawa, and Ridgetown Ontario	Delhi: loamy sand; Elora: silt loam; Ottawa: sandy loam; Ridgetown: clay loam	0-20	Not specified	Crop rotations, NT versus CT	Spring 2009 in Elora; Spring 2010 for Delhi and Ottawa; spring 2016 in Ridgetown, resulting in sampling at 29, 22, 18, and 21 years after establishment
(Williams and Gordon, 1995)	Agroforestry Research Site at the Guelph Research Station, Guelph, Ontario	Imperfectly drained silt loam with an enriched clay horizon (argillic) horizon at 40 cm depth that was partially impervious to water	12-40	Barley, winter wheat, soybeans, corn; black walnut, poplar, and other tree seedlings	Crop rotations with intercropping	1988-1992
(Yang et al., 2008a)	Woodslee, Ontario	Clay Loam (Typic Argiaquoll).	0-60	Corn-soybean rotation	NT and MP	1983-2004
(Yang et al., 2008b)	Elora, ON; Woodslee, ON; Urbana, IL	1. Maryhill fine-silty loam (Typic Hapludalf); 2. Brookston clay loam (Typic Argiaquoll); 3. Thorp silty loam (Argiaquic Argialboll)	0-60	Corn-soybean rotation/continuous corn	NT and MP	23-year tillage study with continuous corn; 16-year second trial on a corn-soybean rotation; and 11-year third tillage experiment
(Yang et al., 2021)	Woodslee, Ontario	Brookston clay loam (Orthic Humic Gleysol)	0-60	Corn, soybeans, and winter wheat/cover crop rotation	Crop rotations, with cover crops	2018-2020
(Yanni et al., 2018)	Ontario	Not specified	Not specified	Corn	Cover crops, crop rotations = diversification, tillage, etc.	2011-2016
(VaandenBygaart et al., 2004)	Ontario	Not specified	Not specified	Not specified	NT and CT	Not specified