ONFARM Soil Health Technical Report

March 31, 2023

Prepared by:

SRG SOIL RESOURCE GROUP

Executive Summary

The ONFARM soil health monitoring program has established a network of cooperator sites that represent predominant soil landscape conditions and agricultural crop management across Ontario. The 25 sites of paired BMP trials have equal representation from five distinct regions across the province based on regional climate, geology, and physiography as well as soil conditions and cropping systems. Candidate farms put forward were selected by considering the predominant soil type, landscape and soil drainage class, enterprise type, and management systems within a region. Cooperator selection was based on an interview questionnaire that included information ranging from current management practices to outreach experience to available equipment.

The ONFARM program focused on three types of BMPs to evaluate over three field seasons that would promote improvements in soil health: cover crops, organic amendments, and reduced tillage. The majority of cooperators were interested in testing various kinds of cover crops as well as organic amendments in their crop management system as most were already following some form of conservation tillage.

Field site plot design was developed that reflected major physiographic features by selecting three general slope/site positions or soil landscape zones. The upper, middle, and lower soil landscape zones chosen best characterized natural groupings of soil features, hydro-geological properties, and the locating of key types of degradation found in the field. The soil landscape zones at a site were overlain by side-by-side field-scale BMP treatment strips down the field. Benchmark sampling locations were centred within each of the treatment plots so that there was a benchmark consistently across each of the soil landscape zones. At most BMP trial sites, there were four treatments comparing BMP1, BMP2, a BMP combination, and a check strip across each landscape zone for a total of 12 benchmarks per field.

Soil health assessment at a site included a pedological assessment for the soils baseline condition at all benchmark locations for the purposes of classifying the soil series, determining the nature and extent of soil degradation (water, wind and tillage erosion, or compaction), and interpreting crop performance. A comprehensive high-level sampling of soil health indicators (SHI) at each benchmark location in triplicate included both in-field and laboratory analyses parameters. In-field soil health parameters included surface water infiltration, soil temperature, compaction using a penetrometer, soil moisture and bulk density. Laboratory analyses included: soil organic matter (SOM), active carbon (AC, POxC), Solvita CO_2, Solvita Labile Amino-Nitrogen (SLAN), potentially mineralizable nitrogen (PMN), aggregate stability (AggStab), nematode counts (2020 only), autoclaved citrate extractable (ACE) protein (2022 only), and fertility including nutrients (macro and micro) and pH.

Agronomic monitoring at each benchmark location involved observations of treatment crop and soil conditions through the season. Crop development was monitored from planting, emergence, in-season crop scouting, and yields from hand harvesting and combine yield monitor data when available.

Annual partial budgets were developed for each site on the basis of costs of implementing the specific BMPs that were different from the control treatment. The net costs or net revenues from the BMP use each year were calculated by comparing the difference in yield revenue from the check treatment.

The impacts of BMPs on soil health indicators were analyzed using statistical comparisons (multivariate analysis; Spearman and Pearson correlations, ANOVA) at several levels including individual sites, soil texture category, and region. In particular, multivariate analysis comparing the Year 3 results with Year 1 as the baseline examined the influence of soil landscape position on SHI, impact of different BMPs on SHI, and interaction effect of both landscape and BMP on SHI. The relationship between SHIs (correlation), the variability of SHIs around a benchmark, the responsiveness of each SHI to changes in organic matter, were examined in order to determine which SHIs might best reflect changes in soil health in response to BMP implementation. The paired BMP trials were conducted over three field seasons, which often equated to one crop rotation cycle. Therefore, dramatic changes in soil health as measured by a range of SHIs were not expected.

Findings of the baseline pedological assessment identified degradation by historic tillage erosion as the most severe form followed by near surface compaction as the most abundant. The reduction in the soil condition in upper landscape positions most affected by past tillage erosion was often reflected by the various soil health indicators tested.

The impact of BMPs on SHIs in the short term were measurable. Use of organic amendments were somewhat more effective than cover crops in driving a change in carbon based indicators. The impact was shown more frequently on coarse textured soils and they proved adaptable for a number of cropping systems. Pairing cover crops with an organic amendment frequently improved SHI responses compared to cover crop treatments alone. Cover crop use was more often effective in a significant change in SHI on finer textured soil, a benefit that would be weighed with the additional cost of cover crop use. When harvested for feed, the BMP combination of a cover crop and organic amendment was shown to be a significant economic benefit.

In evaluating the practical use of a SHI, to represent a soil function, be responsive and consistent, the SHIs did differ. Considering SOM as the fundamental core indicator, AC and SLAN appeared to be the most responsive to differences in SOM. Solvita CO_2 respiration was slowest to respond but in contrast showed low variability, and paired well with AC to better understand how carbon might be cycling in the soil. Aggregate stability and bulk density should be considered longer term indicators. Other indicators such as PMN, water infiltration and nematode counts showed high variability, and thus less promising as SHIs. ACE soil protein shows promise as a relatively sensitive indicator and ties together carbon and nitrogen cycling in the soil, but was only monitored in 2022. Its responsiveness to BMP implementation has yet to be determined.

The ONFARM results are encouraging for the use of several indicators to show impacts from the BMPs tested. However, BMP treatment effects cannot be expected to result in consistent measured change in many of the SHIs in the timespan of the study. With two field seasons of BMP implementation completed, conclusions drawn from the SHI results should be considered preliminary. At least another three years are recommended to compare results over a minimum of two crop rotations to determine the longer-term stability of these changes. What is also clear is that there is no one best indicator. Identifying a group of indicators that best reflect soil health conditions in Ontario should continue to be a research goal.

The range of results across the various ONFARM sites should be interpreted based on site details since response of SHI to specific BMPs can be influenced by pre-existing conditions and/or external factors including the type and degree of soil degradation at various landscapes, inherent soil capabilities, region (SOM level), climate (moisture related), soil type, and management history. Overall, the results demonstrate the need for continued monitoring of the ONFARM cooperator sites to further improve the understanding of indicator variability in developing a long-term dataset.

To learn more about how ONFARM plans to continue sharing results and engage the agricultural community, please visit the ONFARM website and the ONFARM Data Dashboard to directly interact with all the soil health data. Please also visit our news page or OSCIA's twitter to stay up to date on project information and future activities.

Acknowledgements

The On-Farm Applied Research and Monitoring (ONFARM) program was a four-year, applied research initiative delivered by the Ontario Soil and Crop Improvement Association (OSCIA) on behalf of the Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA) to support soil health and water quality research across farms in Ontario. This program is funded by the Canadian Agricultural Partnership, a five-year federal-provincial-territorial initiative. OSCIA would like to acknowledge the support of several organizations and members of the agricultural community for their contributions to the program:

- Soil health data was collected, compiled, and analyzed by The Soil Resource Group (SRG) located in Guelph, Ontario. SRG played an instrumental role working directly with ONFARM cooperators to organize and execute the soil health trials, and collect soil health data for the edge of field sites.
- Five partnering Conservation Authorities (CAs) implemented the Priority Subwatershed Project (PSP) component of ONFARM. They worked in six PSPs to collect key water quality, water quantity, and land-use data to achieve the program objectives. CAs also provided technical advice and worked directly with cooperators to carry out ONFARM outreach activities. Partnering CAs include: Ausable Bayfield Conservation Authority (ABCA), Essex Region Conservation Authority (ERCA), Maitland Valley Conservation Authority (MVCA), Lower Thames Valley Conservation Authority (LTVCA), and Upper Thames River Conservation Authority (UTRCA).
- The Watershed Evaluation Group at the University of Guelph conducted the modelling component of the program using the water quality, soil health, and economic data gathered as part of ONFARM to create a representative watershed model for each of the priority subwatersheds using the Integrated Modelling for Watershed Evaluation of BMPs (IMWEBs) model and Ecosystem Services Assessment Tool (ESAT).
- Representatives from Agriculture and Agri-Food Canada (AAFC), Environment and Climate Change Canada (ECCC), and OMAFRA who sat on the ONFARM Technical Working Group provided valuable input on several technical aspects of the program, such as data management and collection.
- OSCIA would like to highlight the critical role of the participating ONFARM Cooperators in accommodating the research program’s objectives on their respective farms. ONFARM is an applied research program that is being implemented on working farms across the province. ONFARM would not be possible without the dedication of cooperating farmers and the agricultural community.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

1.1 Report Overview

The 2022 Technical Report has been prepared to summarize data collected across three field seasons of the On-Farm Applied Research and Monitoring (ONFARM) Program, beginning with baseline data collected in 2020 and ending with trials completed in 2022. The objective of the Technical Report is to summarize the ONFARM research program and the best management practices (BMPs) being monitored at soil health trial sites, describe the data that was collected and analyzed, highlight technical achievements, and present conclusions from the first two years of BMP treatments.

1.2 ONFARM Program Description

ONFARM is a four-year initiative funded by the Canadian Agricultural Partnership. It was announced on December 5, 2019, by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). ONFARM is delivered by the Ontario Soil and Crop Improvement Association (OSCIA) with the support from various organizations, including OMAFRA, Agriculture and Agri-Food Canada (AAFC), five Conservation Authorities (CAs), The Soil Resource Group (SRG), and the Watershed Evaluation Group from the University of Guelph. ONFARM is also supported by a network of cooperating farmers who are essential to the success of the program.

ONFARM builds on work completed under the Great Lakes Agricultural Stewardship Initiative's (GLASI) Priority Subwatershed Project (PSP), supporting Ontario's Soil Health and Conservation Strategy and helping the industry meet commitments under the Great Lakes Water Quality Agreement. The three pillars of ONFARM designed to support Ontario's agricultural industry are:

- Continuation of the monitoring and modelling established in the PSPs;
- Establishment of on-farm trials in-field to identify soil health indicators and test the effectiveness of best management practices in cooperation with farmers;
- Enhanced engagement opportunities with stakeholders and farmers to foster a network of demonstration farms.

1.3 Soil Health Overview and Program Goals

The ONFARM's Soil Health Research and Monitoring component established a network of on-farm side-by-side trials across Ontario to investigate management practices and their impact on soil health. Candidate sites were selected to represent the high variability of soils found across the province and the variability of soils which may be found within a field. Differences in soils captured differences in landscape features that represented predominant soil landscape combinations used for broader regional interpretation. Soil health baselines also varied between farms depending on past management practices, and the types and extent of soil degradation often associated with different soil types.

Soil health monitoring sites were established at 33 farm cooperator fields under two components of the ONFARM program: the water quality pillar included 8 edge-of-field sites embedded within the previously established priority sub-watershed project (PSP) areas under GLASI, and the soil health monitoring and research pillar included 25 field scale sites forming a network of paired BMP trials to represent the regions across the province from Southwestern to Eastern Ontario. The PSPs of the Lake Erie, Lake St. Clair, and Lake Huron watersheds are found within the Conservation

Authorities (CA) of Maitland Valley, Ausable-Bayfield, Upper Thames River, Lower Thames Valley, and Essex Region. Upper Thames River Conservation Authority also monitored the Kettle Creek PSP.

A detailed and consistent soil health testing approach was conducted at all sites over 3 years, including initial pedological sampling and soil degradation risk assessment at existing or new edge-of-field (EOF) monitoring locations in the PSPs in collaboration with each of the CA's, as well as at the BMP trial farm sites established by SRG and the ONFARM Technical Working Group (TWG).

Through detailed soil health and pedological sampling and soil risk assessments, a greater understanding was gained of how soil degradation types and soil health conditions vary with landscape and site position, soil type, climatic region, management system and management history. Soil health management practices or BMP treatments were implemented on each farm and the soil was monitored to assess the applied practice's influence on key soil health parameters at benchmarked sampling locations within each benchmark treatment. A control strip was also established and monitored in tandem with the treated strips. It was anticipated that the evaluation of data from a series of soil health testing methods will help further investigation to identify key soil health indicators for an Ontario soil-landscape context.

2.0 Methods

2.1 Site Selection

2.1.1 EOF PSP Site Establishment

Edge-of-field locations within the PSPs were monitored by 5 CA's at a small number of locations but were expanded to 8 in total with the ONFARM initiative. SRG provided input into the suitability of sites for runoff monitoring feasibility and cooperator experience for BMP comparison at each site as well as soil health sampling requirements. Runoff monitoring locations and management proposed by the individual CA and selected by OSCIA added to the diversity of farming operations, cropping systems, climatic conditions, topographic features and soil types studied in the soil health project across Ontario. These cooperator managed field sites were reviewed for their existing site databases and soil sampling activities along with project partners, extension personnel and the TWG to avoid possible duplication. Soil health sampling results were reported in the ONFARM Water Quality Technical Report.

2.1.2 BMP Trial Site Establishment

2.1.2.1 Regional Framework

The establishment of the BMP trial site network required a significant process for selection. A key goal was to describe soil degradation and to determine the efficacy of BMPs for soil health on Ontario cropland. A realistic number of properties to participate in the study that could also represent a good range of the soil and crop conditions in the agricultural regions of southern Ontario was proposed to be 25 sites. This portion of the province south of the Canadian Shield was divided into 5 distinct regions in which to find the most suitable and most representative 5 sites. Each geographic region was based on a distinct combination of factors related to regional climate, geology, and physiography as well as soil conditions and cropping systems. The establishment of the 5 regions by SRG with input from the OMAFRA Soil Team (a group of soil management specialists, agricultural engineers, soil fertility specialists, pedologists, sustainability specialists and environmental specialists) also reflected the intensity of agricultural activity in the Lake Erie basin (Table 1).

Table 1. . *Distribution of BMP Trial Region by counties and regional municipalities*

BMP Trial Region	Counties
Lake Erie West	Essex, Chatham-Kent, Lambton, Middlesex, Elgin
Lake Erie East	Oxford, Norfolk, Brant, Hamilton, Haldimand, Niagara
Western	Huron, Perth, Bruce, Grey, Waterloo, Wellington, Dufferin
Central	Halton, Peel, Simcoe, York, Durham, Victoria, Peterborough, Northumberland
Eastern	Hastings, Prince Edward, Lennox & Addington, Renfrew, Frontenac, Lanark, Leeds & Grenville, Ottawa-Carleton, Stormont, Dundas & Glengarry, Prescott & Russell

2.1.2.2 Soil Matrix Approach

A key selection criterion for candidate fields for the BMP trial considered the representativeness of the range and central tendencies of soil types in each region. An approach was developed using a soil matrix ranking to determine the most representative cropland soil types in each region. Soils were grouped in a 12-cell matrix by texture (4 texture types: fine, fine loamy, coarse loamy, coarse) and moisture (3 drainage classes: well, imperfect, poor) for the key soil series mapped in the counties of each region. The acreages of soils were then aggregated for each matrix cell to provide a total acreage of each soil type (textural group x drainage class) in the region. The soil types with the top 5-6 total acreages within a region were considered the most representative. A list of combined soil type, landscape and soil drainage recommendations was developed specific for a region and was used as key criteria for selecting 5-6 candidate farm operations for the region.

2.1.2.3 Cooperator Selection

A list of close to 100 possible farm cooperators to consider for the BMP trial study was initially provided to SRG by the OMAFRA Soil Team and other OMAFRA field specialists. Discussions were held with the OMAFRA specialists across the province to narrow the list down to about 40 potentially suitable cooperators for the study and ensure there were enough candidates to choose from in each of the study regions. Candidates considered had most often demonstrated experience from participation in other on-farm applied research projects in the past and had knowledge of soil health-related BMPs. OMAFRA staff contacted the 40 potential cooperators they knew to gauge their interest in participating in the project

To best determine the final list of cooperators, a detailed set of selection criteria was developed by SRG with input from the OMAFRA specialists and the TWG that was used to develop an interview questionnaire. A set of 53 interview questions included a candidate's cropping and tillage, cover crop use, soil health challenges and BMPs implemented on the farm, interest in soil health, plot work history, record keeping, interest/experience in hosting tours, communication/outreach experience/comfort and equipment availability and width dimensions. A scoring grid for the questions was developed to allow for the ranking of cooperators. Further criterion developed with the soil matrix approach was an important consideration for the final selection and distribution of sites within each region.

Interviews conducted with the 40 candidates were initially on-site. This also allowed opportunities for some field reconnaissance; however, COVID restrictions implemented halfway through the site selection process required the remainder be completed by phone. The interview information was compiled into the scoring grid; and where it was close between potential cooperators, further discussion was held with an OMAFRA specialist familiar with them to help finalize the selection. The top 5 cooperator candidates in each region were contacted to confirm their interest and the final list of 25 BMP trial cooperators was presented to the TWG and OSCIA for approval. The geographic distribution of the network of soil health monitoring sites is shown in Figure 1.

The intent of the site selection process was to objectively assess and find the most suitable cooperators for the study. Time constraints and pandemic restrictions brought a level of difficulty to fully evaluate candidate sites prior to the spring establishment of field sites. What was observed over the course of the study was that these were good cooperators who were also good soil managers, so that despite targeting sites with a range of soil quality, many of the sites chosen were perhaps better than expected overall.

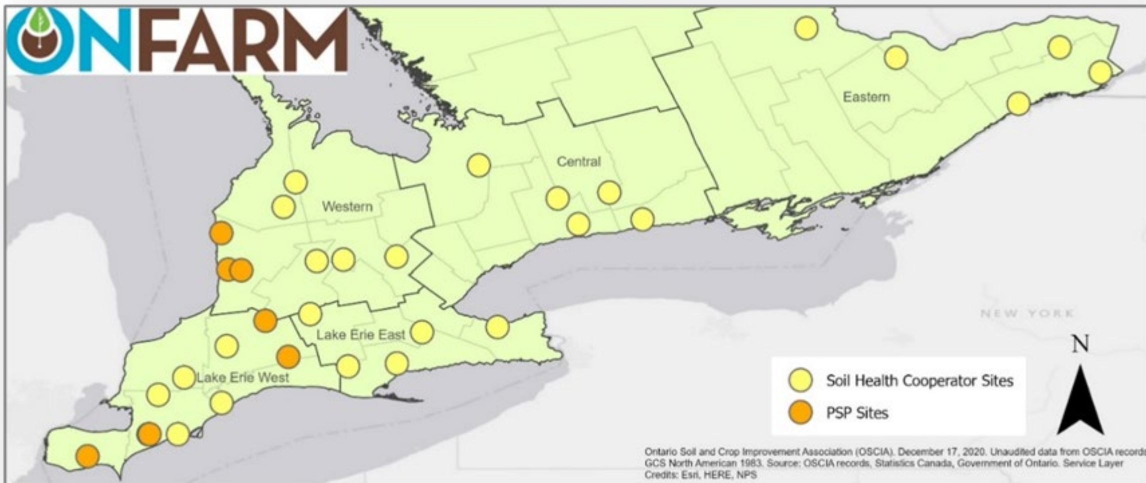


Figure 1. *Map of ONFARM soil health monitoring activities at BMP trial cooperator sites and PSP water quality monitoring sites*

2.2 Field Site Establishment

2.2.1 Soil Reconnaissance

The soil health evaluation of the 33 selected EOF and BMP trial sites required the development of a method and protocol to identify sampling locations that considered field characteristics such as topographic variability and soil features that were deemed representative for a site. An initial field site reconnaissance was undertaken as a ground-truthing exercise to determine topographic, soil and other site properties for the purpose of verifying the suitability of the field to lay the groundwork for BMP trial plot layout. Reconnaissance of a field site required several considerations prior to visiting:

- Ownership, site history and past management
- Current crop rotation, point in rotation and current BMPs in place
- Observations regarding overall and site-specific soil degradation and yield variability
- Soil and slope characteristics based on county soil map
- Field access

Field reconnaissance to confirm soil types and conduct a soil degradation assessment included a series of soil auger holes across predominant landscape features. BMP trial field plot layout included locating key upper, middle and lower slope positions, where topographic features followed this pattern, and sufficient width to permit the desired number of management practice treatments on similar slope positions. The soil and site reconnaissance and collected data included the following:

- Field location and ownership
- Selection of key landscape positions along a field-length transect
- Description of key soil and site properties of a full soil profile at each selected point along the transect (e.g., slope, profile data, drainage, series, location)
- Identification of surface and soil profile-based evidence of degradation (e.g., depth to free carbonates)

2.2.2 Soil Landscape Sampling Design

Field site plot design developed following the field site reconnaissance, reflected major physiographic features by selecting three general slope positions or soil landscape zones. The upper, middle, and lower soil landscape zones chosen best characterized natural groupings of soil features, hydrological and hydro-geological properties, and probabilities of locating key types of degradation found in the field.

The design approach was first employed at the EOF sites embedded within the PSP watersheds where distinct drainage basins or micro-watersheds were selected within a field in which to monitor runoff. This watershed context, further gave rise to the opportunity to select soil sampling benchmark locations that considered three general slope/site positions. This set of three soil health sampling locations by landscape position was established within each treatment micro-watershed identified by a cooperator to be either a BMP treatment area or a control treatment area.

For the paired BMP trials outside the PSP areas, the major physiographic features at a site were overlain by side-by-side field-scale management treatment plots or strips of different management down the field most often perpendicular to the predominant slope to ensure that soil and agronomic features were observed on consistent sampling sites across landscape positions. Monitoring and sampling locations or benchmark locations were centred within each of the management treatment plots so that there was a benchmark per treatment plot on each of the soil landscape zones. At most BMP trial sites, there were 4 treatments comparisons and a control or check treatment across each landscape zone for a total of 12 benchmarks per field on average.

This approach of 3-5 adjacent treatment strips across 3 soil landscape zones was transferable in most fields where there was one major (gentle or steep) slope in the proposed plot; however, in very gently sloped fields such as on a clay plain, there was often little difference in elevation to correlate with depth to water table, soil drainage class and differences in soil texture, so that the 3 soil zones were distinguished by distance to a water feature and a separation of at least 100m. Established sampling benchmark locations were georeferenced and returned to throughout the monitoring study period using a high accuracy GPS device.

2.2.3 BMP Trial Design

The ONFARM program focused on three types of soil management BMPs that would promote improvements in soil health: cover crops (CC), organic amendments (OA), and reduced tillage. During the initial interview process of the list of candidates, cooperators were asked which BMPs they were interested in testing in their crop management system. The majority were interested in various kinds of CCs as well as OAs. Most were already following some form of conservation tillage, with many in no-till, so there was little interest in assessing the impact of more conventional tillage compared with the reduced tillage management system they were already in. Further support for limiting the number of variables to consider between sites and to encourage adoption of CCs and OA BMPs across as many sites as possible was recommended by provincial specialists and supported by the TWG.

The BMP trial plot design relied on each cooperator to manage side-by-side treatment strips that in most cases were the length of the field excluding the headland. The ease of management at this scale also provided the opportunity for some to carry out field length yield monitor comparisons of the treatments. Treatment strip width was determined in collaboration with the cooperator to accommodate equipment width for implementing the BMPs as well as matching the width of two or more pieces of equipment such as combine passes, to better facilitate field operations and assist with unique treatment data collection. Where there was sufficient field width and consistent landscape features, some cooperators were willing to add a second or third replication of treatments for their own field strip yield comparison. SHI soil sampling was not conducted in these additional strips.

Each cooperator was provided the flexibility to consider and select the project BMPs they were interested in implementing and comparing within their crop management system. Support was made available from the consultation of the OMAFRA Soil Team to implement innovative and new practices to the cooperator. A minimum comparison of two BMPs along with a control or check treatment strip of business-as-usual management were planned. Most sites had a plot layout of 4 strips; a CC BMP, an OA BMP, a combination or suite of both BMPs, and the check strip (Figure 2). Seven sites elected to compare only CC treatments with 3 of those having 3 treatment strips total. Two sites had 5 treatment strips where a second OA treatment was included. Discussion of the proposed BMP treatments and how they would fit within the cooperator's crop management was finalized with input from the Soil Team. A three-year plot plan document was sent to each cooperator prior to the initial field season. Each year-end, the plan for the plot was reviewed and discussed with the cooperator before an updated plan was sent prior to the following season.

Regular communication with the cooperator prior to and during the season ensured the logistics of establishing the treatment strips and implementing the BMPs was successful. The choice of CCs and seeding rates were either the cooperators choice or with a recommendation by SRG staff. Organic amendments were generally sourced by the cooperator if not available on farm, with the application rate generally determined by the cooperator. If needed, assistance was provided in sourcing CC seed or OAs. The establishment and management of each of the BMP treatments by the farm cooperators at preplant (CC or OA), during the crop season (CC interseeding), and post-harvest (CC and OA) were documented and recorded annually by each of them using crop input and management information data sheets developed for the project.

Figure 2. *BMP treatment strips and benchmark sampling locations example at Site 20*

2.3 Field Benchmark Sampling

2.3.1 Pedology Sampling

Pedological descriptions were conducted for the soils baseline condition at all benchmark locations of the EOF and BMP trial sites for the purposes of:

- classifying the soil series
- determining the nature and extent of soil degradation
- interpreting crop performance

Two types of pedological descriptions using soil pits and soil auger checks were utilized for the ONFARM soil benchmarks to: ensure detailed information was captured on the most representative benchmark sites; and balance the labour, monitoring and data analyses costs per field location (Figure 3).

Detailed soil pedology information was obtained from small shovel excavations or pits (50cmx50cmx50cm depth) and deeper soil auger (50-100cm) investigations to include: horizon data (type, depth, thickness, texture, porosity and structure, density (bulk density on compacted sites), colour, rooting characteristics); profile data (depth to water table, bedrock, pore-size discontinuity, compacted or other root restricting layers, mottles, gley colours, parent materials); and pedon data (drainage class, soil series, CLI class, HSG group). Laboratory data of pedology parameters sampled from an average of three horizons at benchmark locations included: particle size and coarse fragment, pH, organic matter, and calcium carbonate.

Soil pits were described for a subset of representative benchmarks at the EOF sites and for 6 of the BMP trial benchmarks at the upper, middle and lower landscape zones for the control and combined BMP treatment plots. General soil pedology information was gathered from the remaining benchmark locations using soil auger (0-100cm) investigations. These descriptions of the horizon and pedon data were completed for the full soil profile but did not include separate laboratory analysis.

Baseline assessment of soil degradation indicators identified the location of contributing factors such as water, wind and tillage erosion processes, or compaction. The degree and distribution in a field of a risk indicator were used to further characterize varying production systems and soil-landscape conditions across all the various sites.

Figure 3. *Photos of soil characterization, auger and pit investigations to determine presence and level of degradation*

2.3.2 Soil Health Assessment

Soil health assessment at a site included a comprehensive high-level sampling of soil health indicators at each benchmark location. The package of recommended indicators included laboratory soil health tests and in-field soil health measurements or observations (Table 2). Soil health related parameters measured directly in the field included surface water infiltration rates, soil temperature, and penetration resistance using a penetrometer. Soil core samples (5 cm diameter) taken from the 0-5 cm depth were analyzed for soil moisture content and soil bulk density. Soil profile information was completed in the pedology characterization of the baseline or year 1 assessment. Soil surface samples (composite 0-15 cm cores) taken for laboratory analysis were tested for soil organic matter (SOM), active carbon (AC, POxC), Solvita CO_2, Solvita Labile Amino-Nitrogen (SLAN), potentially mineralizable nitrogen PMN), aggregate stability (AggStab), and fertility including nutrients (macro and micro) and pH. Composite 5-20 cm samples were also taken for nematode analyses. A reduced package of indicators with potentially more sensitive responses to a management change was recommended in year 2 to sample at all benchmark locations that included laboratory analysis tests for SOM, AC, Solvita CO_2, and SLAN. In the third and final year, the original package of tests were completed to compare to the baseline year to determine the impact of BMPs on soil health indicators. Autoclaved Citrate Extractable (ACE) protein analysis was added in the final year as an SHI for measurement from the composite 0-15 cm samples. Nematode counts were not conducted in the final year because of the extreme variability in results observed in year 1.

Table 2. *Soil Health Indicator measurements used in ONFARM and their description*

Soil Health Indicator Measurements	**Description of Measurement**
Physical	
Bulk Density (BD)	Density (g cm^{-3}) of a known soil volume. Samples were taken from the top 5 cm of soil, oven dried and weighed. High bulk density numbers can be an indicator of soil compaction.
Soil Hardness	Penetration resistance of a soil by depth (soil compaction) was measured using a field penetrometer.
Infiltration Rates	Rate of added water infiltrating the soil surface. A 2.5 cm depth of water was added to a 12.5 cm diameter ring and the time for it to infiltrate was measured. It was repeated a second time to determine the saturated infiltration rate. Poor infiltration rates can be an indication of soil compaction or surface soil slaking.
Aggregate Stability (AggStab)	Resistance of soil aggregates to break apart following rapid wetting and agitation. Soils with low aggregate stability are prone to crusting and wind and water erosion.
Moisture Content	Moisture content of the soil. The bulk density samples were weighed, oven dried and re-weighed to determine soil moisture.
Temperature	Temperature of the surface soil. Soil temperatures were taken at a 7.5 cm depth.
Chemical	
Fertility Levels	Measure of plant available nutrients (phosphorus, potassium, calcium, magnesium, zinc, manganese).
pH	A measure of soil acidity.
Biological	
Soil Organic Matter (SOM)	A measure of organic carbon (living and dead plant and animal materials) in the soil.

Active Carbon (AC)	An indicator of the fraction of soil organic matter that is readily available as a food source for soil life; also referred to as Permanganate Oxidizable Carbon (POxC).
Solvita CO_2 Burst	The CO_2 burst is a rapid measure of microbial biomass respiration and reflects the size and activity of the microbial biomass.
Potentially Mineralizable Nitrogen (PMN)	PMN measures the ability of the microbial population to mineralize (convert) organic nitrogen into plant available nitrogen.
Solvita Labile Amino Nitrogen (SLAN)	SLAN estimates organic nitrogen reserves present by measuring readily mineralizable amino-sugars in soil.
Nematodes	Parasitic soil nematode species numbers and total nematode numbers are counted to give an indication of overall soil life.
Autoclaved Citrate Extractable (ACE) Protein	An indicator of the amount of protein like substances that are present in the soil organic matter (organically bound nitrogen in the soil organic matter).

Many of the soil health laboratory indicators analyzed were based on microbiological activity in the surface soils. Timing of sampling was therefore an important consideration in capturing the potential expression of a soil's health when microbiological activity was near its peak. Recommendations of provincial soil specialists and university soil specialists advised the project team that late spring or early summer was the optimal period when testing should be done consistently across all farm field sites each year. As a result, sampling of soil health indicators occurred over the month of June in each of the 3 years in a consistent sequence of sites from the furthest southwest toward the east. In Eastern Ontario where heat unit ratings are higher than Central Ontario, sites were sampled ahead of Central Ontario sites.

2.3.3 Spatial Sampling Design

Representative soil surface sampling around each benchmark for soil health laboratory testing required sufficient material to complete the full package of analysis. For the majority of parameters, approximately 24 surface cores at 0-15 cm depth were composited, homogenized by hand, bagged as a single sample and stored until lab submission within 24 hours (Figure 4). Separate composite sampling and handling was required for nematode count and PMN samples that were packed in coolers with freezer packs until submitted and refrigerated within 24 hours.

The BMP trial sampling for soil health testing was conducted in triplicate from 3 separate areas within a 2m radius around each benchmark (a "trillium" design), down each treatment and across each soil zone (Figure 5) to allow for statistical comparison of the benchmark results for three areas of analysis:

- influence of soil landscape position on SHI
- impact of different BMPs on SHI
- interaction effect of both landscape and BMP on SHI

The number of soil samples collected for SHI analysis across the ONFARM study in each of 3 years were:

- 8 EOF cooperator sites represented by 16 treatments and 3 soil landscape zone benchmarks that total 48, and
- 25 BMP trial cooperator sites of 99 treatments and 3 soil zone benchmarks and 3 triplicates that total 891.

In addition, each of the 33 cooperator sites had a SHI composite soil sample collected from a non-disturbed native location (woodlot, grassland, fenceline) of comparable soil and middle slope landscape position to use as a reference of a soil type's potential soil health level but not as a comparable goal or yardstick.

Figure 4. *Field staff conducting SHI sampling*

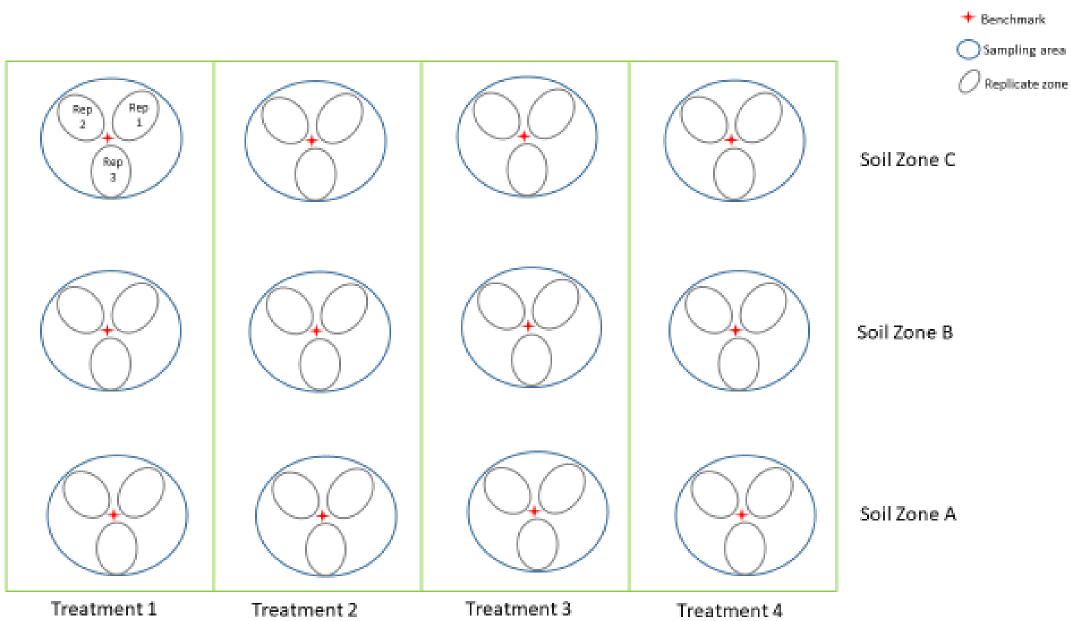


Figure 5. *Conceptual field treatment and sampling design for BMP trial sites*

2.3.4 Agronomic Monitoring

The monitoring of agronomic information is critical to the evaluation of treatment effects of the BMP trials on crop performance, separate from any unplanned effect (e.g. crop pest). Verification of detailed treatment management practices with on-site monitoring, management input data, and crop data as well as field and soil conditions and crop residue ground cover were recorded for each treatment benchmark location. Monitoring of crop development from planting included: population counts after emergence, crop scouting for growing conditions pre-harvest (including pest and weed pressure differences), harvest data from hand harvesting and crop yield monitor data when available, as well as grade quality for the one horticultural crop.

Crop yield monitoring for the BMP trials used hand harvest techniques to sample the grain or forage plant portion from a standard plot size of 1/1000th of an acre. As with the SHI sampling, triplicate samples were harvested around each benchmark. To improve representativeness of the samples, rows from the 3 sample plots of a benchmark were not the same, and corn ears from alternative plants were removed from 2 rows instead of just one row. Length of row sampled was a function of crop and row spacing. Samples were placed in a mesh bag with identification tag and stored in a dry enclosed environment such as a crop research facility until the crop samples were processed. Grain was weighed and moisture content was measured to determine standard moisture content and yield weights extrapolated from the harvest area to determine a yield estimate.

2.3.5 BMP Implementation Monitoring

Field monitoring subsequent to crop harvest assessed the growth of CC treatments by surveying the plant surface cover of the ground as well as the biomass amount accumulated prior to termination by harvesting CC plant samples in a unit area at each benchmark. When an OA treatment was included in a cooperator's plan, a representative sample was obtained for nutrient analysis to ensure suitable and accurate rates of inputs were applied. Application of a liquid or solid OA treatment was monitored and calibrated with the purpose of meeting a target nutrient application rate. Spread material was intercepted in several 1m wide containers across the spread pattern and weighed to determine a volume and nutrient application rate across the plot and at the benchmark location.

2.3.6 BMP Economic Analysis

BMP treatment information and field management data including input costs were recorded by each of the 25 cooperators annually in crop input and management information data sheets. The BMP CC (seed type, rate, method, timing, termination, etc.) or OA application information (type, nutrient content, rate, method, timing, etc.) and the cooperator's actual input costs of each BMP were compiled for economic analysis. An annual partial budget analysis on a per acre basis of the costs of implementing the specific BMP(s) different from the control treatment was applied to the crop year that followed BMP implementation. Actual equipment operation costs were used when provided or custom rates were used from the OMAFRA Survey of Ontario Custom Farm Work 2018 rates. When considering an OA application, the reduction in the cost of available nutrients was applied. The significant change in fertilizer prices over the project years was reflected by using average annual spring fertilizer prices in the calculation. The overall net cost or net revenue from the BMP use was calculated by comparing the difference in yield revenue from the control or check treatment using an average annual crop price taken from the Grain Farmers of Ontario website or personal communication with cooperators. Crop yields were averages of the hand harvest yield estimates of each BMP treatment. Hand harvest yields may be different than combine monitor yields but there was not a complete set of combine yields available.

2.4 Laboratory Analysis

Laboratory analysis of the soil health indicators was carried out by SGS Agri-Food Labs, Guelph, Ontario; with the exception of nematode counts and ACE protein tests which were conducted by the Agriculture & Food Laboratories, University of Guelph, Guelph, Ontario.

2.4.1 Soil Sample Processing

Soil samples collected from the field were stored at 4°C until processing. Soil samples were air dried (35°C) and ground to pass through a 2 mm sieve for the following analyses: particle size, soil organic matter, wet aggregate stability (Eijkelkamp), Solvita CO_2-burst, Solvita Labile Amino Nitrogen (SLAN), Active Carbon (POxC), ACE protein, and standard fertility package (SGS AFL pkg III). Fresh soil samples, sieved and stored at 4°C, were used for potentially mineralizable nitrogen. Fresh soil samples, stored at 4°C, were used for nematode enumerations (microscopic).

2.4.2 Soil and Soil Health Indicator Test Methods

Physical Tests were completed using the following methods:

- Soil particle size: analysis mineral soils (SOM<8%) for the distribution (% by weight) of sand silt clay. The method is based on differential settling rates of sand/silt/clay particles (Black 1965, Carter 1993; Land Resource Science 1984)
- Sand fractionation (for sandy sites): analysis of mineral soils for the distribution of various particle size groups by sieving (USGA 1993, Black 1965, Carter 1993; Land Resource Science 1984)
- Wet aggregate stability determinations were carried out using the Eijkelkamp wet sieving apparatus for disturbed samples, according to the supplier procedures (https://www.royaleijkelkamp.com/media/0v3hahtq/m-0813e-wet-sieving-apparatus.pdf)

Chemical Tests were completed using the following methods:

- Calcium carbonate determinations were based on weight loss following application of HCl to an oven dried sample (Gohl & Mermut 2008, NAPT 1997).
- Fertility: the nutrient package used was SGS AFL III which included organic matter, pH (includes buffer pH, if pH is less than 6.5), phosphorus, potassium, magnesium, zinc, manganese, calcium, base saturation, cation exchange capacity. Procedures were carried out as described in OMAFRA Publication 611, online)

Biological Tests were completed using the following methods:

- Soil organic matter determinations for mineral soils (SOM 0%-8%) were conducted using the Walkley Black colorimeteric method (McKeague, ed. 1978).
- Soil organic matter determinations for soils with organic matter greater than 8% were conducted using the Loss on Ignition method (OMAFRA Protocol).
- Active carbon (Permanganate Oxidizable Carbon; POxC) determinations were conducted using the colorimetric method of Weil et al (2003) described in the Cornell CASH SOP Handbook (2016)
- Respiration (Solvita CO_2 burst) determinations were carried out according the Solvita Manual (https://solvita.com/product/solvita-soil-co2-burst-manual/ ; hard copy available).
- Solvita Labile Amino Nitrogen (SLAN) determinations were done according to the Solvita Manual (https://solvita.com/product/slan-manual/; hard copy available).
- Potentially Mineralizable Nitrogen (PMN) determinations were done using the 7-day anaerobic incubation method described in the Cornell soil-health manual procedures (Cornell, 2016)
- Nematodes were enumerated microscopically (University of Guelph Agriculture and Food Laboratories). The following groups were assessed: root lesion, pin, cyst, root-knot, stunt, spiral, dagger, ring, lance, stubby-root, sheath, bulb & stem, sting, Ditylenchus, total parasitic, total nematodes, and % parasitic (calculated).

2.5 Statistical Analysis

Soil health indicator data were analyzed across the in-field measurements and laboratory tests. As laboratory tests were completed and data received, an initial data quality control check was completed. Any samples that were deemed significant outliers, such as a single value of a triplicate at a benchmark, were queried and a laboratory recording check or repeat analysis was completed. All statistical analysis data generated as well as all field and laboratory data collected was compiled by SRG and stored in the ONFARM database management system by OSCIA.

The predominant focus of the soil health indicator data analysis was significant differences within a site between soil landscape zones and/or BMP treatments. Data analysis across sites considered regional differences (Lake Erie West, Lake Erie East, Western, Central, and Eastern) and soil texture group categories (fine, fine loamy, coarse loamy, and sandy) by indicator and to investigate relationships between indicators. Because of inherent soil variability coupled with the short time frame of the study in which to see a high level of significant change, a statistical confidence level of $p<0.10$ was used in order to better able to detect trends.

2.5.1 Univariate Statistical Analysis

Descriptive statistics were performed at each site for each of the 3 years. Microsoft Excel 2013 was used for computing the mean, standard deviation and coefficient of variation for each set of benchmark triplicate samples, landscape positions and treatment strips at each site.

Data was tested for normal distribution in SAS® OnDemand for Academics before the correlation coefficient of the SHI tests were selected. A Spearman (non-normal distribution) or Pearson (normal distribution) correlation coefficient was computed for each pair of SHIs and yield for each year (2020, 2021, 2022) to create year specific correlation matrices across all sites. Correlation of SHIs were also generated from all sites, then sites were grouped into the regions and soil categories to investigate the presence of regional and soil category trends.

2.5.2 ANOVA Statistical Analysis

Single factor analysis of variance (ANOVA) was completed in SAS® OnDemand for Academics on each SHI at each site in the baseline year of 2020. This was used to determine if there were any differences between the treatment strips at a site before a BMP was implemented. The Proc GLIMMIX procedure was used to investigate the effects of treatment strip and landscape. A Type III Test of Fixed Effects was considered significant at $p<0.10$ and mean differences were computed using the Tukey-Kramer Grouping for Least Square Means. The same ANOVA determinations were completed for the 2021 and 2022 SHI data and yields after BMP implementation.

2.5.3 Multivariate Statistical Analysis

Multivariate statistical analysis using an ANOVA analysis was completed on the 2022 SHI data and computed using SAS® OnDemand for Academics using the 2020 SHI data as a covariate to account for the pretreatment variation at each site. The model effects were the 2020 covariate, BMP treatment strip, landscape position and the interactions. A Type III Test of fixed Effects was considered significant at $p<0.10$ and mean differences were computed using the Tukey-Kramer Grouping for Least Square Means. Differences of the BMP treatments from the check treatment, and lower landscape position from the more degraded middle and upper slopes were reported as BMP treatment effect or landscape position effect, respectively.

3.0 BMP Trial Sites

3.1 Site Characteristics

The BMP trial sites were first characterized by their soil landscape variability to better understand the nature and extent of soil degradation on Ontario cropland to help interpret the impact on SHIs. Soil variability and soil moisture differences were observed to relate to landscape variability such that: soils in lower to level site positions with active water tables in the rooting zone were classed as poorly and imperfectly drained; sands on upper site positions with no water table activity were classed as rapidly drained; and loamy soils on crest and upper slope positions with no water table activity were classed as well-drained. The distribution of soils and landforms found by region and at the sites are summarized below.

Lake Erie West - dominant soil types and slope ranges included: level, stone-free, imperfectly to poorly drained clays and clay loams (e.g. Brookston - Site 1); imperfect to poorly drained, level to moderately sloping to rolling clay loam soils with some stoniness (e.g. Brantford, Gobles - Site 4, Site 5); undulating, stone-free imperfectly drained sandy loam (e.g. Normandale - Site 2); and rapidly to poorly drained sandy soils of fine to very fine sand content (e.g. Plainfield Site 3).

Lake Erie East - dominant soil types and slope ranges included: rolling to undulating, imperfectly drained clays and some clay loams on heavier textured sites (e.g. Haldimand, Chinguacousy - Site7, Site 8); gently-sloping, imperfectly drained sandy loams, and sands on coarse-textured sites (e.g. Berrien, Normandale - Site 9, Site 10); and moderately well drained stoney loam soils on moderately sloping landscapes (e.g. Guelph - Site 6).

Western - dominant soil types and slope ranges included: steeply sloping, well to imperfectly drained loamy tills (e.g., Harriston - Site 11); stony loamy and sandy to gravelly soils on rolling landscapes (e.g., Hillsburgh - Site 12); and undulating to gently sloping clay loam to clay soils (e.g., Perth - Site 13 and Site 14, Kemble - Site 15).

Central - dominant soil types and slope ranges included: steeply sloping, well to imperfectly drained loamy tills (e.g., Bondhead - Site 18, Otonabee - Site 20); imperfectly drained, variable medium textured, eroded complex topography (e.g., Percy - Site 17); stony loamy and sandy soils on rolling landscapes (e.g., Pontypool - Site 16, Guerin - Site 19).

Eastern - dominant soil types and slope ranges included: level to undulating, poorly drained, marine clay plains (e.g. North Gower - Site 23, Bearbrook - Site 24); undulating, mostly poorly drained clay (e.g. Ste. Rosalie - Site 21); moderately sloping, moderately well to poorly drained, stony loam tills (e.g. Eamer - Site 25); and, undulating imperfectly to poorly drained, loamy to fine loamy textured marine origin soils (e.g. Bainsville - Site 22).

Key soil degradation types found were: tillage erosion, surface compaction, subsurface compaction, and more limited evidence of wind and water erosion. Site conditions lent themselves to certain degradation types. Tillage erosion was most often found on rolling, hummocky and undulating landscapes of sandy and coarse loamy soils but also on some fine-loamy till sites, especially where convex slope curvature dominated. There was a substantive impact on crop yield on moderate and severely eroded sites where reductions of 50% were observed on severely eroded sites. Site observations suggested tillage erosion can be quite spotty across upper landscape positions and that compensating factors such as drainage hesitation layers, and thick, rich topsoil can offset expected yield impacts on sites showing evidence of tillage erosion.

Surface compaction observed at benchmark sites was most often found on middle and lower site positions; and, on imperfect to poorly drained loams, clay loams and clays with very little evidence on sandy sites. Regionally, there were more surface compacted sites found in the Western region than in other regions. The extent of severe surface compaction across all sites was observed at less than 5% of all benchmarks but was also associated with yield loss. In general, surface compaction was more prevalent on poorly drained sites, on a wide variety of textures and had a significant impact on yield.

Subsurface compaction was the most frequently observed of the 3 key types of degradation. However, there was little evidence of impact on yield as very few benchmark sites were observed to be severely compacted. The Lake Erie East region had the most sites recorded with this form of degradation, although two of the sites in this region were prone to natural compaction by glacial advance.

3.2 Field Management and BMP Implementation

Field management by cooperators at the BMP trial sites were field crop based, typically comprised of the predominant Ontario field crops of wheat, corn and soybean (Figure 6). Regional differences were captured with one site in the Lake Erie West region including a horticultural field crop of sugar beets in the rotation, and with spring wheat grown in Eastern Ontario compared with winter wheat planted elsewhere. Other cereals represented across sites were cereal rye, oats and spring barley. The soybean category included adzuki beans grown at two cooperator sites. Corn crop management saw two dairy farmers include silage corn in the rotation. Row spacing was another management variable with one cooperator planting corn in 20in rows, and soybeans or beans being planted at 7.5 in., 15 in., 20 in., or 30 in. row widths. The selection of as many field sites in cereal crops at the beginning of the 3-year project met two goals. This provided cooperators with the opportunity to implement a BMP in the window of late summer and fall of the first year of the study to establish a CC BMP and apply an OA, and best to exploit the two-year period to test the impact of BMP use on SHIs.

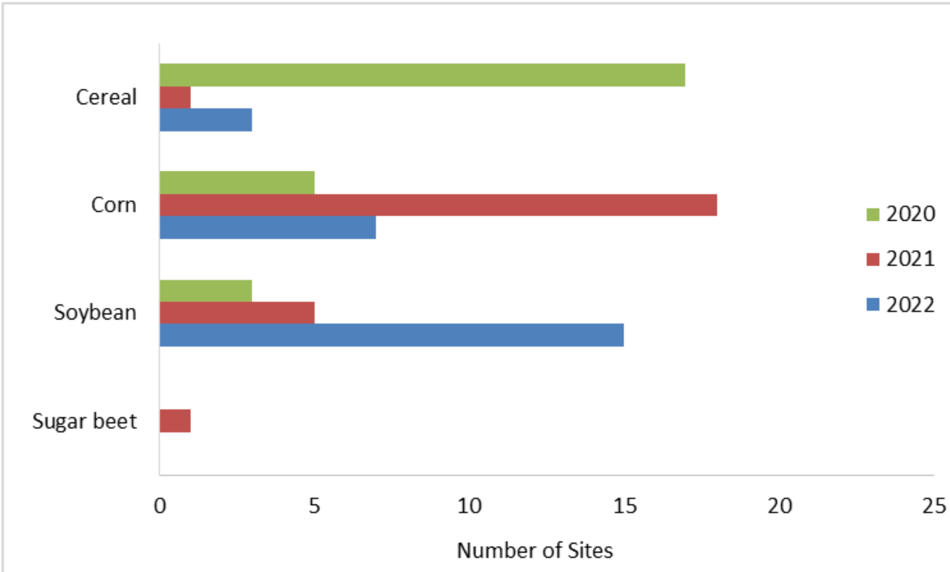


Figure 6. *BMP Trial annual crop distribution*

BMPs established across the 25 BMP trial sites were based on the individual soil health and management goals of the cooperator. As a result, differences between operational practices include crop, fertilization, and pest management, and in the incorporation of a wide variety of BMPs over the period of implementation (Table 3). Consistent among almost all sites was reduced tillage management systems of complete no-till, row crop strip tillage, minimal tillage, or combinations thereof, although 2 organic operators relied on multiple seasonal tillage passes for weed control.

Cover crop treatments were included at all 25 sites. These CC treatments, however, differed by species and blend complexities, timing of planting, and termination practices depending on the BMP intent. Single species such as cereal rye seeded in the fall allowed for additional growth in the spring. Oats after winter wheat at a dairy farm were harvested late in the fall for feed. Multi species mixes ranged from 2 to 14 species and were often seeded in the fall with a drill or broadcast. Benefits such as retaining nutrients or fixing nitrogen, compaction reduction as well as soil organic contribution were intended goals. Interseeding of CCs was done in corn at one site with a cultivator and nitrogen side-dress unit (Figure 7), or broadcast at side-dress or later in soybeans at leaf drop at other sites. An interest at one site in improving the stand and growth of an interseeded CC on heavier textured soil was tested in 60in corn rows as a means of increasing light and reducing moisture competition with the CC. Crop herbicide selection was always a necessary consideration with CCs. Organic managers considered CCs an important weed control practice while some other cooperators were able to observe the same effect for the first time. Biostrips were tested at two sites where there was a concern regarding excess CC residue the following spring. Soil type was a factor for one cooperator on sandy soils where a wheat crop was not a viable option. An interest in interseeding led to arranging a custom application of annual ryegrass in corn that allowed for overwinter grazing by the cooperator's sheep followed by the testing of a drone applicator to interseed oats in the next soybean crop. Experience was gained by the ONFARM cooperators on the many application options within a system.

The selection of cooperators included 9 livestock farmers from the dominant livestock sectors in the province (beef, dairy, poultry, swine) with at least one livestock operation in each region that was able to utilize their manure as an OA treatment. Three of these livestock cooperators along with an additional 8 cash crop cooperators sourced various types of OAs, such as off-farm manure or biosolids to also test alongside CC treatments. Liquid non-agricultural source material (NASM) included anaerobic digestate and municipal biosolids, and solids included municipal green bin compost, mushroom compost, and municipal biopellets. The OAs were all applied either after previous crop harvest in the fall or before spring planting (Figure 7). As with a CC BMP, the best opportunity for cooperators to apply an OA BMP was in the window that followed a cereal crop mostly in year 1 of this study, for the benefit of a corn crop in year 2. At several sites where significant nutrients were applied with the OA, the cooperators managed fertilizer applications in the other strips to even out the nutrient application across the treatments. Rates of OA application varied but many applied at a rate to meet the crop nutrient requirements. Material purchased off-farm tended to be lower in application rate due to the cost of the product. Solid compost application ranged from around 4 to 10 tons/ac, biosolid pellets were 2 to 4 tons/ac, and off-farm manure was applied from 3 to 10 tons/ac. Liquid manure was applied around 3000 to 3500 gal/ac, anaerobic digestate rates and municipal biosolid rates were applied close to 4000 but were as high as 9000 gal/ac.

Where an OA was applied as a treatment, there were 15 cooperators that included a combination suite BMP treatment of both CC and OA together. With the addition of an OA application after CC establishment (Figure 7), CC performance measured greater biomass accumulation compared to a CC treatment alone in all comparisons.

***Figure 7**. Examples of selected BMPs: cover crops, organic amendments, cover crop and organic amendment*

Table 3. *BMP trial site BMP and crop year after implementation*

Region	BMP Site	Study Crop Rotation	Single species CC	Multi species CC	Liquid Manure OA	Solid Manure OA	Liquid Biosolid OA	Solid Biosolid OA	Suite of CC and OA
Lake Erie West	1	W-C-S		2,3					
	2	S-SB-C		2		1			
	3	S-C-S	2	3				2	2
	4	W-C-S	2			2			2
	5	C-S-C	2,3					2,3	2,3
Lake Erie East	6	W-Cs-C	2,3		2,3		2,3		2,3
	7	W-C-S	3	2					
	8	BW-C-A	3	2,3					
	9	S-C-S		2,3					
	10	C-C-C	2,3			2,3			2,3
Western	11	W-C-S	2	2				2	2
	12	W-S-C	3	2				2,3	2,3
	13	C-C-B		2,3					
	14	W-C-S		2	2		2		2
	15	W-C-S		2,3				2	2
Central	16	CR-CR-CR		2		2,3		2,3	2
	17	W-C-A		2		2			2
	18	W-C-S	2	2					
	19	B-S-S		2				2	2
	20	C-S-O	3	2			2	3	2,3
Eastern	21	W-C-S	2,3					2,3	2,3
	22	SW-C-S	2	2					
	23	SW-Cs-S	2,3	2	2				2
	24	SW-C-S	2		2				2
	25	S-C-S	2,3						

Note: table of site information indicates project crop rotation, BMP used and crop year following implementation; CC-CC, OA-OA, W-winter wheat, SW- spring wheat, C-corn, Cs-silage corn, S-soybeans, SB-sugar beets, BW-buckwheat, A-adzuki bean, B-spring barley, CR-cereal rye, O-oats

4.0 Soil Health Indicators

4.1 Overview of SHI Data 2020-2022

4.1.1 Provincial Wide SHI Site Data Overview

An overview of the soil health indicator dataset from all site benchmarks over the 3 years provides an indication of the significant range of values that were measured (Table 4). Levels of the different SHIs vary in the relative scale of unit measurement. Essential to the characterization of the data is the mean organic matter value of 3.9% that would be considered a good overall level. Relative differences in how SHIs relate to organic matter provide context as SOM is considered the foundational measure of soil health. Data from one Eastern site, 21, at its lower landscape position (b) was excluded from the analysis as it was a uniquely organic soil type with greater than 30% SOM that tended to skew upward the remainder of the results, particularly the maximum measured SHI values. The min PMN value of 0 ppm represents sample results where the levels were below the detection limits of the laboratory equipment. Solvita CO_2 and PMN have the smallest and highest range of values, respectively, across the 25 ONFARM shown by the coefficient of variation (CV%). The range of results grouped by region and soil type are discussed in the sections that follow.

Table 4. *Summary values of the ONFARM SHI dataset over all sites and all 3 years (n=2673).*

		Soil Organic Matter (%)	**Active Carbon** (ppm)	**Solvita CO_2** (ppm)	**PMN** (ppm)	**SLAN** (ppm)	**ACE Protein** (2022) (ug/g)	**Aggregate Stability** (%)	**Bulk Density** (g/cm3)
All Site Data*	Mean	3.9	530	62	14	101	6528	65	1.20
	StdDev	1.1	144	8	11	48	1890	15	0.15
	Min	1.1	95	27	0	4	2246	7	0.59
	Max	11.5	1194	99	70	315	16002	99	1.64
	CV%	28	27	13	79	48	29	23	13

*Organic soils from Site 21b benchmark (SOM>30%) and all native soil samples not included

4.1.2 Regional SHI Data Overview

Results of the site SHI analysis when grouped into the 5 regions across southern Ontario indicate differences particularly in the Eastern region compared to the others. Organic matter levels were substantially greater on average in Eastern sites along with the range of values shown in Figure 8, even with the removal of Site 21b benchmark values from the analysis. Lake Erie West was the next highest while the remaining regions measured more similarly. Greater SOM values in Eastern Ontario may be attributed to historically mixed farming with livestock populations being maintained longer and with land in less time under cultivation, combined with a cool climate and a significant amount of clay soils resulting in slower soil carbon decomposition. Several of the other SHIs tended to follow a similar trend with the highest means and maximum values occurring in the Eastern Region (Table 5), along with more favourable lower bulk density.

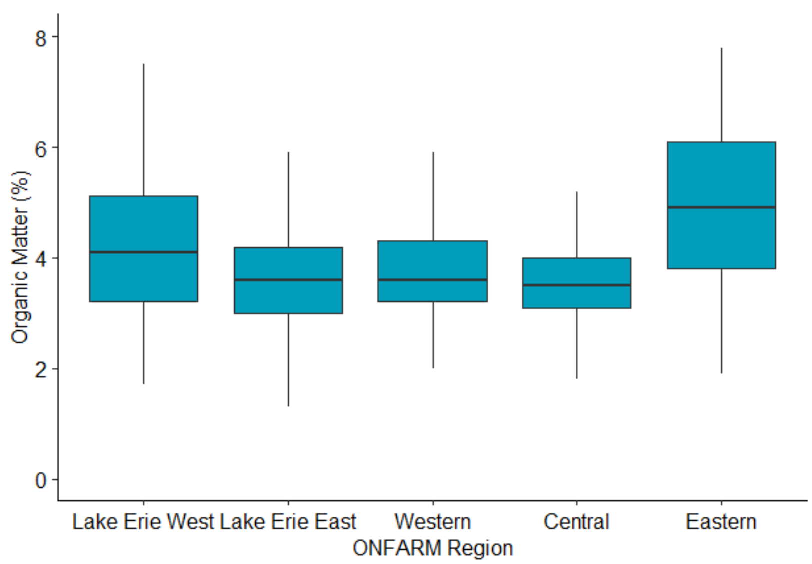


Figure 8. *Organic matter median, interquartile range, and range over 3 years from benchmarks across the 5 regions*

***Table 5**. Soil Health Indicator values over 3 years by region*

Region (n=5)		**Soil Health Indicator***							
		Soil Organic Matter (%)	**Active Carbon** (ppm)	**Solvita CO_2** (ppm)	**PMN** (ppm)	**SLAN** (ppm)	**ACE Protein** (2022) (ug/g)	**Aggregate Stability** (%)	**Bulk Density** (g/cm^3)
LEW	Mean	4.2	488	59	17	101	6452	60	1.22
	SD	1.2	139	9	12	41	2226	18	0.13
	Min	1.7	95	29	0	12	20	7	0.93
	Max	7.5	1056	86	65	221	14208	89	1.64
LEE	Mean	3.6	517	62	16	87	6159	68	1.25
	SD	1.0	146	9	11	36	1254	15	0.13
	Min	1.1	116	33	0	18	2859	16	0.78
	Max	6.5	924	86	47	224	10081	96	1.58
Western	Mean	3.8	526	64	15	98	6226	66	1.22
	SD	1.0	122	7	13	47	1655	14	0.13
	Min	2.0	168	42	0	4	3349	16	0.81
	Max	7.6	978	99	70	277	12300	101	1.58
Central	Mean	3.5	519	62	10	88	6070	63	1.30
	SD	0.7	106	7	9	37	1229	15	0.11
	Min	1.7	201	35	0	14	2579	24	0.98
	Max	5.2	791	89	43	312	9881	90	1.61
Eastern	Mean	4.8	610	63	13	136	7897	68	1.08
	SD	1.3	176	8	8	62	2684	9	0.14
	Min	1.9	140	27	0	25	4422	18	0.59
	Max	11.5	1194	94	44	315	16002	99	1.50

* Site 21b benchmark (SOM>30%) and native locations not included

4.1.3 Soil Texture Group SHI Data Overview

Organic matter levels measured across the study years and grouped by the soil texture categories indicated similar differences in mean values and ranges found in Ontario literature (OMAFRA, Pub 811, 2017). As expected, the organic matter levels are highest at sites in the finer textured soil categories and lower in the coarse, sandy textured soil categories (Figure 9). Other SHIs values presented in Table 6 follow a similar trend as the relative differences in SOM. The fine loamy soil category that was the highest and slightly above the fine (clay) soil category in SOM, was highest on average in AC, Solvita CO_2, SLAN, ACE protein, AggStab and had the most favourable and lowest BD. The coarse loamy and coarse (sandy) textured soil categories were less favourable on average in all indicators, with the exception of ACE protein which by contrast was the lowest on fine clay soils. Bulk density measurements were lower and better on the finer soils highlighting the inherent risk of compaction on some coarse textured soils but may also reflect the resilience and strength of peds in the high SOM fine and fine loamy soils, and the good cropping and tillage management of those project cooperators managing heavier textured soils.

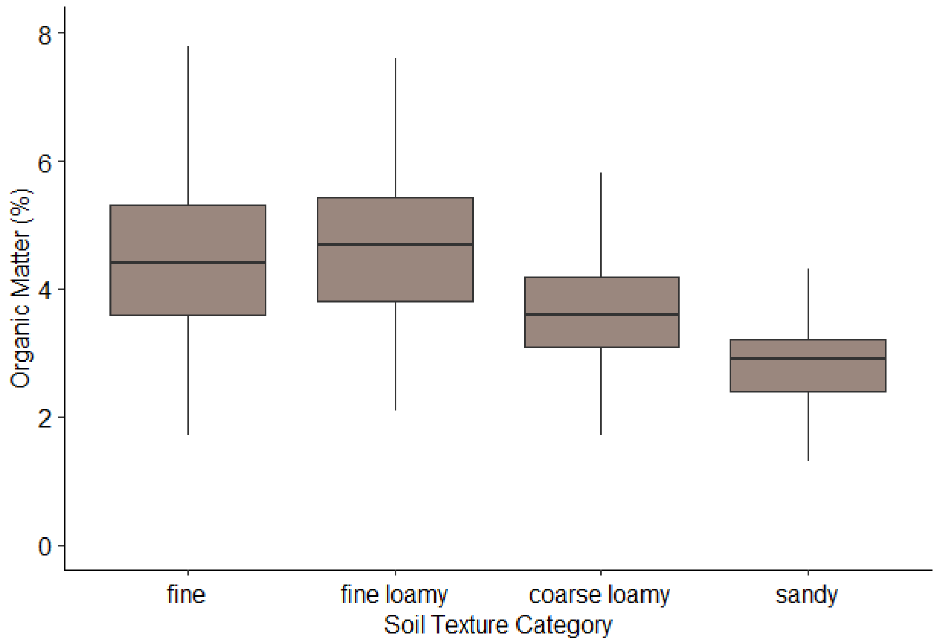


Figure 9. *Organic matter median, interquartile range, and range from benchmarks across 4 soil categories. Soil Texture Category: fine=clay; fine loamy=clay loam; coarse loamy=loam, silt loam, sandy loam, very fine sand; sandy=sands and gravels*

Table 6*. Range of Soil Health Indicator Values over 3 years by Soil Category*

Soil Category		Soil Health Indicator*							
		Organic Matter (%)	**Active Carbon** (ppm)	**Solvita CO_2** (ppm)	**PMN** (ppm)	**SLAN** (ppm)	**ACE Protein** (2022) (ug/g)	**Aggregate Stability** (%)	**Bulk Density** (g/cm3)
Fine (n=6)	Mean	4.4	550	63	21	96	6103	67	1.20
	SD	1.1	146	8	13	39	1745	9	0.16
	Min	1.7	116	27	0	25	2246	41	0.68
	Max	11.5	1194	86	70	245	16002	99	1.58
Fine Loamy (n=4)	Mean	4.7	567	64	17	138	7865	73	1.14
	SD	1.1	159	9	9	55	2726	8	0.13
	Min	2.1	140	29	2	25	3933	50	0.59
	Max	7.6	998	94	51	315	15373	101	1.50
Coarse Loamy (n=13)	Mean	3.7	531	61	12	97	6336	64	1.24
	SD	1.0	133	8	10	45	1676	16	0.14
	Min	1.7	95	35	0	12	2579	7	0.66
	Mean	7.5	1087	99	45	312	14208	96	1.64
Coarse (n=2)	Mean	2.8	398	59	6	66	6250	51	1.23
	SD	0.7	95	8	6	34	1579	17	0.15
	Min	1.1	177	33	0	4	3349	16	0.78
	Max	5.0	609	75	28	186	10081	86	1.58

* Site 21b benchmark (SOM>30%) locations not included

4.1.4 Landscape SHI Data Overview

Landscape position was an important consideration of the project design to highlight the effects of soil degradation on soil health measurement and to determine potential BMP effects on varying levels of degradation. Figures 10 and 11 illustrate the effect of landscape position on organic matter levels measured across the sites in the 5 regions and grouped in the 4 soil texture groups over the 3 years of the project. Typically, SHI values at lower landscape positions were greater than at middle landscape positions, which were greater than at upper landscape positions. Observations across the province at sites with physiographic differences noted the occurrence of degradation on many upper and middle slope benchmarks where erosion processes had reduced soil profile depths, impacted structure, pH and nutrient levels, and as a result impacted SHIs. The differences between the SHI values at upper and lower landscape positions at a site within any given year were often statistically different (data not shown).

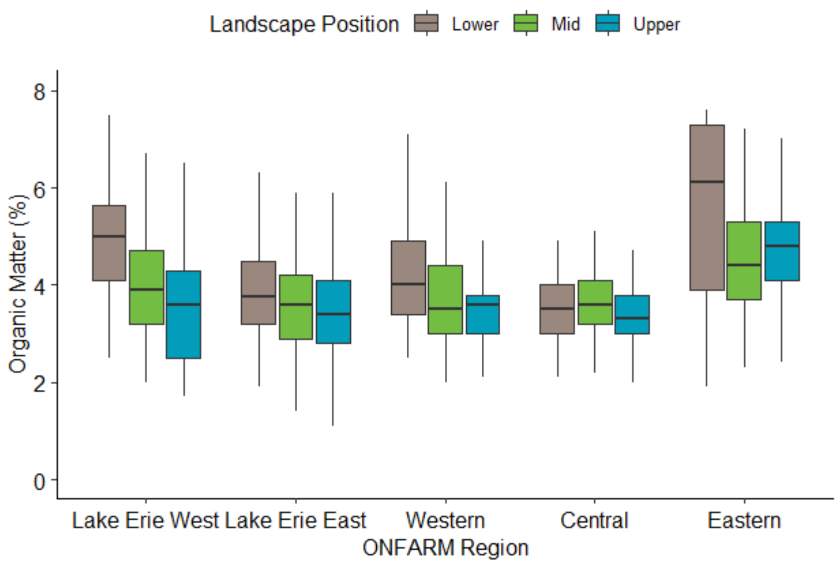


Figure 10. *Organic matter median, interquartile range, and range from benchmark data grouped by 5 regions across landscape positions*

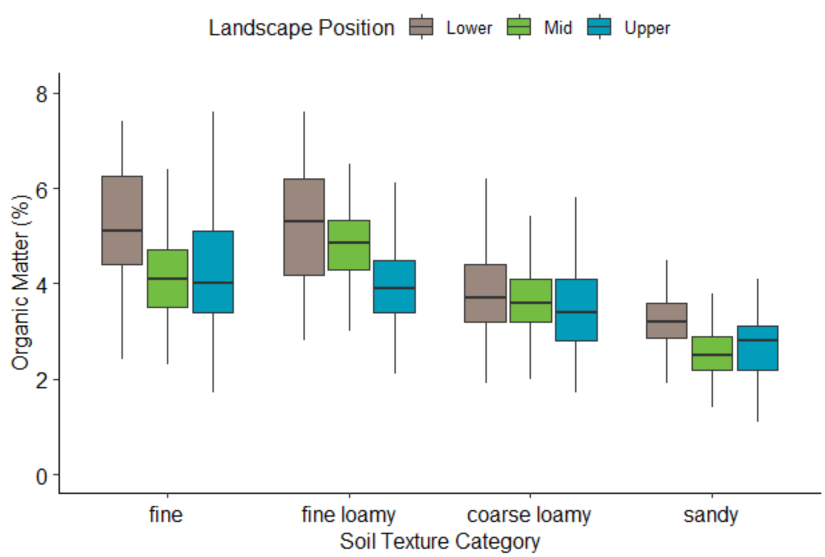


Figure 11. *Organic matter median, interquartile range, and range from benchmark data grouped by 4 soil categories across landscape positions*

4.2 Evaluation and Interpretation of 2020 SHI Results

The 2020 mean values for the SHIs at each of the 25 BMP sites are given in Table 7 below. To further evaluate and interpret the sampling results across the sites, the range of values were compared to available rating schemes for each SHI (see Appendix 1). The SHI means from a site were rated and colour coded to reflect a class of category that follow a low to high ranking. Published Ontario ratings are available for SOM (OMAFRA 2017, Pub 811) by soil texture suggesting soils with adequate organic matter levels will be more productive and more resilient to the forces of degradation. In the absence of Ontario soil health general ratings for the remaining SHI tests, the Comprehensive Assessment of Soil Health (CASH) framework of Cornell University rankings for AC, PMN, and AggStab were used (Cornell 2016) that also distinguishes values by soil texture category. For BD, ratings by texture were taken from the USDA Soil Quality Test Kit Guide (USDA 1999). In the case of Solvita CO_2 and SLAN, the ratings provided on the Solvita company website were used and are the same for all soil texture groups. It should be noted that the Solvita CO_2 burst test is not the microbial respiration protocol used in the CASH, though the same methodological principles are applied.

Applying the SHI category rankings to the data gathered in the ONFARM study found the majority of the 25 sites across Ontario ranked: high to very high for SOM, AggStab, infiltration and BD; medium for Solvita CO_2 and SLAN; low to very low for PMN, while values of AC were distributed across the range of classes (Table 7). ACE protein data, which is only available for 2022, is also included in the table, and shows a distribution across the range as well.

Table 7. *ONFARM BMP Trial: 2020 site averages for Soil Health Indicators and their relative ratings*

Site	Soil Texture*	Soil Organic Matter	Active Carbon	Solvita CO_2	SLAN	PMN	Aggregate Stability	Infiltration	Bulk Density	ACE protein (2022)
		%	ppm	ppm	ppm	ppm	%	mm/hr	g/cm^3	ug/g
1	CL	4.87	383.6	65.8	116.8	17.4	80.1	3.4	1.19	6460
2	vfSL	3.02	410.8	69.3	80.4	3.3	53.0	18.1	1.41	5609
3	fS	3.89	442.9	51.9	68.4	1.2	37.0	16.5	1.24	7306
4	SiCL	4.81	475.2	65.2	97.0	11.0	71.7	12.1	1.31	5422
5	L	5.47	406.7	63.2	105.7	12.6	70.4	7.9	1.18	7462
6	SiL	3.82	610.1	74.9	194.8	11.8	72.8	34.6	1.30	6395
7	SiCL	4.61	447.0	67.2	78.3	25.1	74.4	29.5	1.36	5697
8	SiCL	5.39	474.2	67.7	78.7	14.3	66.2	31.7	1.32	5543
9	SL	2.96	734.2	54.5	63.4	1.3	76.0	5.9	1.09	6021
10	S	2.86	373.4	58.1	38.6	1.3	36.5	5.8	1.19	7046
11	SiL	2.93	501.4	72.0	86.7	5.5	56.5	27.3	1.24	5384
12	SL	3.36	451.0	63.4	51.1	5.3	47.9	11.2	1.38	5453
13	SiCL	3.64	482.6	62.4	77.1	24.4	54.4	6.3	1.10	6259
14	SiL	3.63	527.5	61.4	89.9	4.2	66.5	32.0	1.24	6033
15	SiL	4.91	580.8	70.5	132.6	14.1	72.3	14.9	1.21	8007
16	SL	3.45	453.4	64.7	54.8	1.9	39.9	17.0	1.33	6211
17	L	3.16	429.6	65.8	72.3	4.8	55.1	32.9	1.38	5675
18	SiL	3.72	616.3	67.8	96.7	8.0	50.4	18.3	1.28	7038
19	SL	3.33	434.0	57.5	53.2	3.8	75.6	24.0	1.33	5849
20	L	4.39	547.6	60.3	60.8	2.0	59.5	16.8	1.35	5512
21	SiCL	15.03	728.2	73.1	271.5	23.2	66.8	4.4	0.92	8118
22	SiL	3.96	528.6	70.3	106.7	10.3	59.1	7.1	1.10	6532
23	CL	5.36	619.3	49.5	90.0	1.8	57.2	8.7	1.16	6287
24	L	5.11	622.1	69.4	173.6	17.2	64.7	4.1	1.02	10844
25	L	4.48	695.5	66.1	153.1	4.8	67.9	19.0	1.15	7579
Mean (not Site 21)		4.05	510.3	64.1	92.5	8.6	61.0	16.9	1.24	6484.4
Native Mean		7.80	710.7	72.7	187.3	46.0	72.2	3.2	0.87	–
Very high										
High										
Medium										
Low										
Very low										

* Soil Texture: C=Clay, Si=Silt, L=Loam, S=Sand, v=very, fine=fine

The disparity between the category ratings of the various SHIs found across all sites, and also within a site, would indicate that a refinement of these categories is required for Ontario soils. In the case of the ratings for both of the Solvita tests, the class ranges are very broad (Solvita CO_2: medium 40-140 ppm; SLAN: medium 10-150 ppm) indicating there is almost no differentiation between the wide range of ONFARM sites. For Solvita CO_2, even the relatively high average value of the native samples (those taken off-field from fence lines, bush or grassland) is not rated high and falls well within the medium category. Taken together, this interpretation across the tests provides inconsistent and contradictory information for a producer in terms of soil health targets. Relating on-the-ground observations and SHI data from ONFARM along with other SHI project information being gathered in Ontario (e.g., OMAFRA Topsoil project) may allow for some refinement of these categories to improve their utility for Ontario producers wanting to evaluate BMP effects and the state of their field's soil health.

Site-specific assessments or report cards were generated for each property. These reports depicted by benchmark – slope characteristics, soil descriptions, physical soil degradation interpretations and ratings, yields and SHI results and ratings. The intent was to illustrate and interpret key correlations between these key attributes. An example of a report card and site assessment is given for Site 12 in Section 6 (Case Study) below. This furthered the understanding of the effect of soil capability and degradation on SHI results and yield.

4.3 Year 1 Baseline Analysis (2020)

4.3.1 Single Factor ANOVA (2020 variability)

The variability of the SHI values at each site prior to BMP implementation was investigated to help characterize the baseline condition in 2020. Both the statistical difference between landscape position and between the treatment strips were analyzed to better relate comparisons of any BMP effect in year 2 and 3.

Landscape or contrasting soil zones particular to each site representing upper, middle and lower positions had baseline SHI results compared in an ANOVA (Table 8). Most of the sites had significant differences in laboratory SHI values - SOM, AC, Solvita CO_2, SLAN, PMN, and AggStab - that were influenced by landscape position. The lower landscape position had higher indicator levels due likely to greater levels of SOM and more favourable topsoil conditions (e.g. higher moisture content), including from topsoil redistribution from upper to lower positions by tillage and water erosion. Results of indicators like infiltration and nematodes did not suggest they were as frequently affected by landscape as the other SHIs; however, higher variability of the measurement reduced the number of statistically significant findings.

***Table 8**. 2020 ANOVA Summary of SHI that showed significant ($p<0.1$) differences by landscape position (n=25)*

SHI Test	Organic Matter	Active Carbon	Solvita CO_2	SLAN	PMN	Aggregate Stability	Infiltration	Bulk Density	Nematodes	Yield
Total Sites	17	16	18	17	13	16	6	11	2	12

Differences in SHI values between the pretreatment strips in Year 1 were also measured using an ANOVA (Table 9). For most of the SHIs, there were a small number of sites that had pretreatment differences between treatment strips. Of the 10 sites that had pretreatment strip differences, one site was a side-by-side comparison of long-term soil health practices and conventional practices. These pretreatment differences occur more frequently on level to very gently sloping clay textured sites and sandy texture sites where the range of SHI values were smaller. Nematode data showed that typically the populations were present in a localized area of the field generally in the direction of tillage which is likely why there were a larger number of sites with pretreatment strip differences.

***Table 9**. 2020 ANOVA Summary of SHI that showed significant (p<0.1) differences by Treatment (n=25)*

SHI Test	Organic Matter	Active Carbon	Solvita CO_2	SLAN	PMN	Aggregate Stability	Infiltration	Bulk Density	Nematodes	Yield
Total Sites	10	9	4	7	5	8	3	6	10	6

To address the differences found in the pretreatment landscape and BMP treatment strip analysis, covariate analysis was utilized using the 2020 SHI data as a covariate when analyzing the 2021 and 2022 data for BMP treatment and landscape position effect. Differences within the 2021 and 2022 data were also analyzed using single factor ANOVA.

4.3.2 Year 1 (2020) SHI Correlation Analysis by Region and Soil Texture Group

Correlation analysis was completed for the 2020 baseline pre-treatment data to create correlation coefficients for all SHI and yield comparisons. The paired SHI coefficients were summarized in correlation matrices created for data from all sites (Table 10). The analysis was completed for each of the 5 regions, as well as for each of the 4 soil categories. Coefficients between SHIs or yield over 0.7 were considered a 'strong' relationship. In 2020, the results indicate one strong correlation between SOM and SLAN.

***Table 10.** 2020 Spearman or Pearson correlation coefficients matrix for SHI at all sites (n=891)*

	SOM	AC	Solvita CO_2	SLAN	PMN	AggStab	Infiltration	BD	Nematodes	Yield
SOM										
AC	0.5120									
Solvita CO_2	0.2406	0.3066								
SLAN	**0.8003***	0.5351	0.4153							
PMN	0.4568	0.2146	0.3980	0.4677						
AggStab	0.2296	0.2474	0.2798	0.3753	0.3920					
Infiltration	0.0840	-0.0513	0.0559	0.0621	0.1806	0.1844				
BD	-0.5095	-0.4412	-0.1366	-0.4798	-0.3325	-0.1894	-0.1562			
Nematodes	-0.0376	-0.0794	-0.1960	-0.0992	-0.1227	-0.1712	0.0243	-0.0050		
Yield	-0.0403	-0.0687	-0.0977	-0.0747	-0.0352	-0.0388	-0.0299	-0.0935	0.0473	

*Correlation coefficients >0.7 are considered strong relationships

Data separated into regional categories for 2020 correlation analysis indicated few strong correlations between indicators as two regions (Lake Erie West and Central) did not have any, while Eastern Ontario had the most with four (Table 11). In the Western region, a decrease in BD was related to an increase in yield. The SHI having the most frequency of strong correlations was SOM. All the regional 2020 correlation matrices are in Appendix 2.

Table 11. *Summary of strong correlation coefficients by region in Year 1 (2020)*

Region	**Strong correlation coefficients**
Lake Erie West	no strong correlations
Lake Erie East	SOM and yield (negative)
Western	SOM and SLAN, yield and BD (negative)
Central	no strong correlations
Eastern	SOM and AC, SLAN and SOM, SLAN and AC, SLAN and PMN

Correlation analysis completed for the 4 soil categories for 2020 data determined there were very few strong relationships between the SHIs along with yield under different soil texture environments (Table 12). The fine loamy soil was the only category to have any strong correlations between 2020 SHIs, with three. All the soil categories correlation matrices for 2020 are in Appendix 2.

Table 12. *Summary of strong correlation coefficients by soil category in Year 1 (2020)*

Soil Texture Category	**Strong correlation coefficients**
Fine	no strong correlations
Fine Loamy	SOM and SLAN, AC and SLAN
Coarse Loamy	no strong correlations
Coarse	yield and BD (negative)

4.4 Year 2 Analysis by Region and Soil Texture Group (2021)

Soil health indicator measurements in 2021 included a smaller package (6 tests) than year 1 or year 3 (10 tests). When grouped across all sites, there were no strong correlation coefficients found between the indicators (Table 13).

Table 13. *2021 Spearman or Pearson correlation coefficients matrix for SHI at all sites (n=891)*

	SOM	AC	Solvita CO_2	SLAN	BD	Yield
SOM						
AC	0.55025					
Solvita CO_2	0.40966	0.46269				
SLAN	0.64681	0.60127	0.4865			
BD	-0.321	-0.45656	-0.11026	-0.23408		
Yield	-0.06442	-0.02894	0.03191	0.18516	0.06221	

When the dataset from 2021 was grouped by region, a small number of strong correlations between indicators were determined, mostly relating to SOM (Table 14). Lake Erie East and Eastern regions had the most frequent strong correlation coefficient results between SHIs.

Table 14. *Summary of strong correlation coefficients by region in Year 2 (2021)*

Region	Strong correlation coefficients
Lake Erie West	SOM and SLAN
Lake Erie East	SOM and Solvita, Solvita and AC
Western	SOM and SLAN
Central	no strong correlations
Eastern	SOM and AC, SLAN and Solvita

Analyzing the 2021 data by soil indicated SOM and SLAN were again strongly correlated, this time in the two medium textured categories (Table 15). Again, SOM was most frequently correlated to other indicators. Detailed regional and soil category correlation matrices are in Appendix 2.

Table 15.*Summary of strong correlation coefficients by soil category in Year 2 (2021)*

Soil Category	Strong correlation coefficients
Fine	yield and BD
Fine Loamy	SOM and SLAN
Coarse Loamy	SOM and SLAN
Coarse	SOM and Solvita $CO_{2\ (2022)}$

4.5 Year 3 Analysis by Region and Soil Texture Group (2022)

The correlation analysis in 2022 with the full set of indicators, as was found in Year 1, determined that only SOM and AC showed a strong correlation with each other when all the site data was analyzed together (Table 16).

Table 16. *2022 Spearman or Pearson correlation coefficients matrix for SH Indicators at all sites (n=891)*

	SOM	AC	Solvita CO_2	SLAN	PMN	AggStab	BD	Yield	ACE
SOM									
AC	**0.73322**								
Solvita CO_2	0.38182	0.45519							
SLAN	0.64349	0.56183	0.47909						
PMN	0.32482	0.21588	0.22355	0.12336					
AggStab	0.31064	0.27773	0.39999	0.42455	-0.05565				
BD	-0.36116	-0.26234	-0.01338	-0.2875	-0.21229	-0.02713			
Yield	-0.00674	0.09072	-0.16908	0.01278	0.02156	-0.12297	-0.25178		
ACE	0.6455	0.60451	0.37879	0.61582	0.21757	-0.19838	-0.46179	0.17456	

*Correlation coefficients >0.7 are considered strong relationships

With the correlation analysis of 2022 grouped by region, the number of strong correlation values increased significantly (Table 17). As found in 2020, the Eastern Ontario region had the most findings of strong correlations (6) followed by Lake Erie West (4) that had none in Year 1. The SOM and AC were strongly correlated in 4 of the 5 regions and SOM and ACE protein were strongly correlated in 3 of the 5 regions.

__Table 17.__ Summary of strong correlation coefficients by region in Year 3 (2022)

Region	Strong correlation coefficients
Lake Erie West	OM and AC, SOM and SLAN, SOM and ACE protein, AC and ACE
Lake Erie East	no strong correlations
Western	SOM and AC, SOM and ACE, AC and ACE
Central	SOM and AC
Eastern	SOM and AC, SLAN and AC, SLAN and AggStab, SOM and ACE, AC and ACE, ACE and SLAN

Strong SHI correlations were also higher in number in Year 3 across the 4 soil categories (Table 18). As was found across the regions, SOM and AC were most prevalent across all 4 soil categories. The SOM and ACE protein indicators were strongly correlated in 3 of the 4 soil categories of which the remaining soil category had a strong correlation with ACE protein and AC, suggesting the 3 indicators are closely associated with each other. The fine-loamy soils had the highest number of strong correlations (5) as in year 1 though the coarse soils had a relatively high number (4) as well in year 3. Detailed regional and soil category correlation matrices are in Appendix 2.

__Table 18.__ Summary of strong correlation coefficients by soil category in Year 3 (2022)

Soil Category	Strong correlation coefficients
Fine	SOM and AC, SOM and ACE
Fine Loamy	SOM and AC, SOM and SLAN, SOM and ACE, AC and ACE, SLAN and ACE
Coarse Loamy	SOM and AC, SOM and ACE
Coarse	SOM and AC, Yield and BD (negative), AC and ACE, PMN and ACE

Analyzing the strength of the relationships between SHIs indicates SOM is most frequently associated with other indicators of soil health. ACE protein was only measured in 2022 but it had a high frequency of strong correlations with SOM and AC. The Eastern region of the province and the fine loamy soil category had the most frequency of strong correlations. Overall, the correlations demonstrate the need for SHI samples to be evaluated against related samples, i.e., regional groupings or results from similar soil textures to best evaluate soil health within the larger context of an Ontario wide monitoring program. Furthermore, contextualizing how SHIs relate to each other should be considered on a site-specific basis, being dependent on physical site characteristics like soil texture and topography, but also historical and current management practices.

Data analyses results from the 3 years of study indicates that yield did not correlate well with the SHI laboratory results and the respective rankings. The exceptions to this general observation (for certain SHIs) were found on severely degraded benchmarks. On these benchmarks, yields were substantially lower and some SHIs were in the low to very low category. Yield differences may not be a good indication of soil health over a landscape as crop performance may respond to inputs or timely moisture conditions that mask soil degradation issues, as was observed at Site 10 in 2020 where a sandy soil with some 'low to very low' SHI ranges was able to produce, on average, a 200 bu/ac corn crop, with the well managed fertility and irrigation. Yield limiting factors are often associated with available soil moisture and fertility limitations which are not captured by SHIs but can greatly influence crop growth potential. Some locations observed where SHIs values were within a 'good' range had areas where yields were reduced due to poor growing conditions and premature crop senescence (Figure 12), typically on sites with extreme soil degradation.

Figure 12. *Aerial photograph of Site 12 showing a soybean crop reaching maturity prematurely on degraded hilltops*

5.0 Soil Health Indicator Impacts

5.1 Overall Effects of BMPs on SHIs Across Sites

The impact of BMPs on the soil health indicators was investigated within sites and across sites within the 2-year time period of implementation using an ANOVA analysis with a covariate to account for the 2020 site variability. This assessed whether a BMP treatment resulted in statistically significant changes in the 2022 SHI within a landscape position compared to the check treatment from the same landscape position (a BMP treatment*landscape position interaction effect). Findings indicated that it was common for SHIs to have these interactions occurring at most BMP trial sites. With the majority of sites having significantly different landscape position SHI results from the baseline year ANOVA, it was expected that BMP effects on SHIs would vary with landscape position. The number of significant positive or negative changes for each 2022 SHI at a benchmark, at each BMP strip and each landscape position, were summed up to determine the proportion of significant responses for each BMP*landscape position combination.

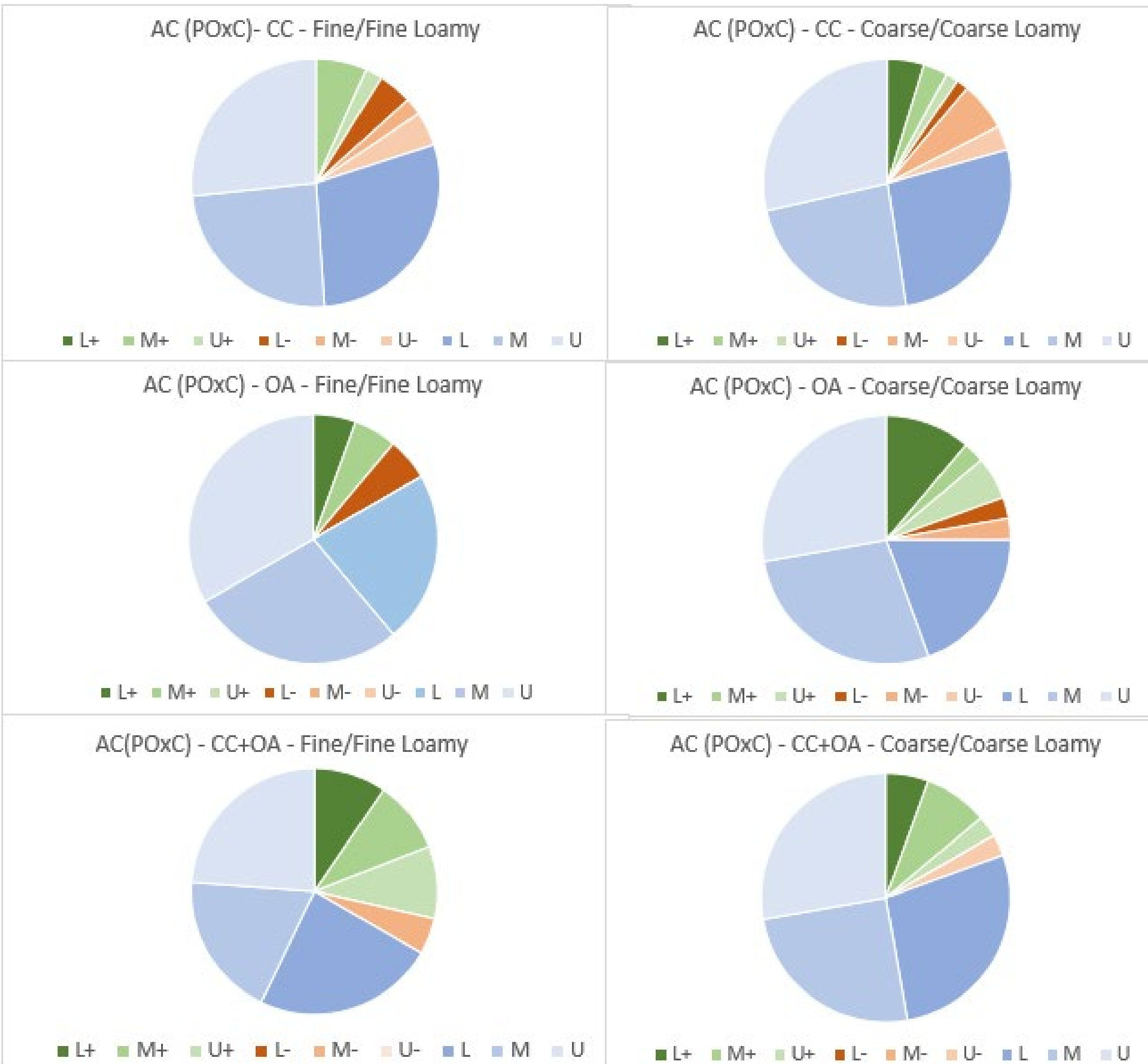
Further distinction of the interaction results grouped sites into soil texture differences with two high level categories of the Fine/Fine Loamy sites and Coarse/Coarse Loamy sites. It should be noted that the total number of each of the 3 types of BMP treatment (n) varied across the soil groupings such that for Fine/Fine Loamy soils: CC n=15, OA n=6, CC+OA n=7, and for Coarse/Coarse Loamy soils; CC n=21, OA n=12, CC+OA n=12. The difference reflects a greater number of sites with Coarse/Coarse Loamy soils. Therefore, the positive, negative or no response data are presented in the example below as a proportion of the respective treatments in each soil grouping (Figure 13). The full set of analysis for SOM, AC, Solvita CO_2, SLAN, PMN and AggStab are presented in Appendix 3.

The results for AC (Figure 13) provide an illustration of an indicator that is relatively more responsive and/or less variable than some other SHIs (see Section 7 below). It should be noted that, when compared to the check treatment, the majority of benchmark locations results showed no significant effect of the interactions between BMP treatment and landscape position on the SHI AC. This finding was consistent for all of the other SHIs. This low level of significant

BMP*landscape position interaction is expected because of the limited time of BMP implementation compared to the check condition over the short 2-year time frame of the study.

A comparison of the effects of BMPs on AC showed the use of a CC resulted in a lower proportion of positive responses than the use of an OA by itself for both soil categories. There were also more responses that were negative or a statistical decrease in level with CC use compared to the check. However, when the CC and OA combined treatment was analyzed within the Fine/Fine Loamy soil sites, the proportion of positive responses increased substantially, and the proportion of negative responses decreased. In the Coarse/Coarse Loamy soils, the proportion of positive response with a combined CC and OA treatment did not increase from the OA by itself, though the negative responses decreased with the use of a combined CC and OA treatment when compared to the OA by itself and CC by itself.

The pattern of response illustrated with AC was very similar for the SOM levels measured when compared to the check (see Appendix 3). For most SHIs, the proportion of negative responses or statistically lower values was reduced at benchmark locations where CC and OA were combined. The Solvita CO_2 burst indicator had the fewest significant positive or negative responses of all the SHIs, particularly on the finer soil textures, indicating that it may be slower to respond to BMP implementation than the other SHIs. Overall, the sites with finer textured soils tended to have a higher proportion of statistically positive responses across the SHIs with the use of a CC, whereas coarser textured soils tended toward more statistically positive responses with the use of an OA.



Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

Figure 13. *Multivariate covariate analysis of change in active carbon (AC) as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks*

Where a BMP trial site did not show a significant landscape position and BMP treatment interaction effect, the landscape position only (section 5.2) and BMP treatment only (section 5.3) effects were investigated separately.

5.2 Landscape Position Effect

For those SHIs with landscape effects consistent across treatments, changes in a SHI were noted only when the indicator was significantly different, either positively or negatively, from the lower landscape position (Figure 14). In this way, the lower landscape position was used as the reference for comparison purposes, similar to how the check treatment was used for BMP comparison.

The upper landscape position most frequently resulted in statistically lower SHIs than the lower landscape position. This is most likely due to the observed moderate to severe tillage erosion which has visibly impacted the soil condition in those landscape areas. The middle landscape position was also found to have statistically lower SHIs than the lower landscape areas. At sites with rolling and/or undulating landscapes the middle and upper landscape positions, the damage from historical erosion was evident at most of these sites when compared to the lower landscape. However, the SOM in the upper and middle positions were not often statistically different than at the lower landscape position. This was unexpected but may be due to the ranges in SOM across field sites due to natural variability or recent BMPs used by landowners prior to ONFARM. The Solvita CO_2 indicator showed the greatest landscape difference amongst the SHIs, particularly its distinction between upper and lower positions, which may be a reflection of its apparent stability and low variability across sites (often less than 10ppm). In general, the indicators measuring carbon were most affected by landscape position.

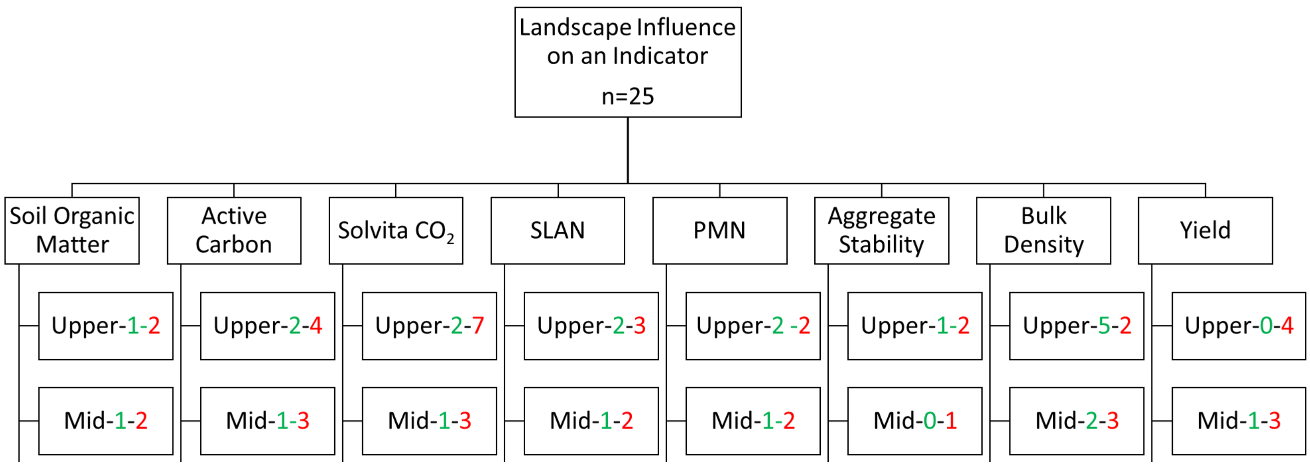


Figure 14. *Positive (green) and negative (red) SHI change from landscape position effect after 2 years of BMPs (p<0.1)*

5.3 BMP Effect

The number of times a BMP treatment statistically influenced a SHI, either positively or negatively, from the check strip across the 3 landscape positions was summed and is shown in Figure 15. An important note to consider when viewing the results is that the BMP categories of CC, OA, and combination represent various types and methods of implementation that are not consistent between sites. Additionally, while there were two years between the baseline and the 2022 soil sampling events, the timing and frequency of BMP implementation also varied over the 2 years.

Of the 3 groups of BMP treatments, the CC treatment most frequently resulted in a SHI being statistically lower than the check, particularly for AC. An important note was that in some cases, the CC treatment, such as overwintering cereal rye, was terminated with little growth (<10cm) and little accumulated biomass carbon would have been added to the soil. It is unclear from the range of site results whether there was a significant management effect or what may be contributing to a CC effect. A recent meta-analysis has indicated both positive and negative CC effects on SHI and crop yield with initial implementation (Bourgeois et al. 2022). The number of significant effects is relatively small across the treatment strips but an unexpected result showed 2 CCs treatments with statistically higher bulk density levels, a negative soil condition result (lower pore space) but there were 2 OA treatments that had statistically lower bulk density levels.

The OA treatments, as with CCs, showed limited significant results but indicated increased SHI levels statistically from the check strip, particularly for the Solvita CO_2 and PMN measurements. Soil health improvements from BMPs were expected to occur slowly over a longer period of time than the study (i.e., 5-10 years to see consistent changes), but given the relatively small number of OA treatments (n=17), having up to three sites show positive responses was statistically significant in 18% of the OA treatments. Preliminary observations may also indicate OA treatments tended to increase soil carbon as indicated in the 3 carbon-based measurements.

The combination CC and OA treatment strips statistically increased SHIs from the check strip at a similar occurrence as the OA treatment alone. Again, the highest occurrence was for the Solvita CO_2 and PMN measurements. Further qualification of the results on a site-specific basis reveal that the sites where the combination treatment was significantly different from the check occurred mainly where the OA and CC treatments were applied in both BMP years. This level of implementation was not always possible across intended sites, unfortunately, due to wet weather conditions in the fall 2021, which may explain the lower number of combination results where they might have been expected.

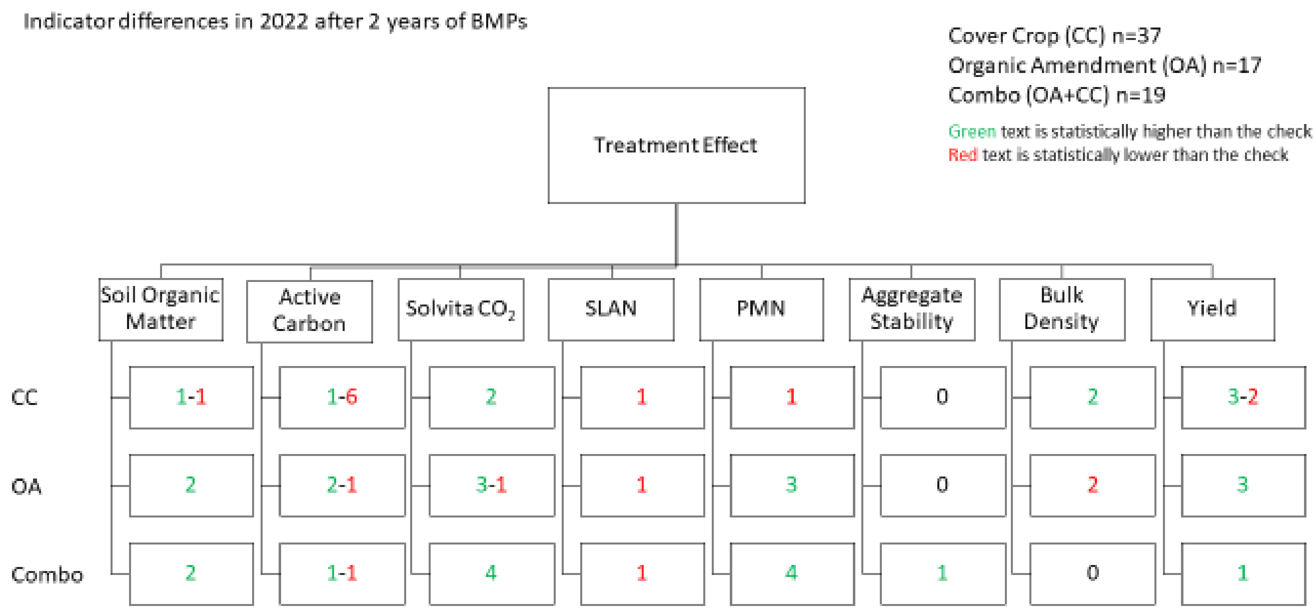


Figure 15. *Positive (green) and negative (red) SHI change from treatment effect after 2 years of BMPs (p<0.1)*

The impact on SHIs statistically analyzed from all 25 sites indicate some positive impact of BMPs and some possible differentiation between types and intensity of BMPs. The SHIs that measure carbon seem to be more responsive in the short period of time of this study. The results, however, are from 2 years of study and more often 1 year of BMP implementation at a site. It remains to be seen whether the observed trends will be consistent, or even amplified, over a longer BMP implementation period.

6.0 Case Study of Site 12

A case study using Site 12 (Figure 16) is presented to illustrate the site assessment and data analysis process that was conducted at all of the 25 ONFARM BMP trial sites based on the data that was collected.

The crop rotation and BMP sequence at Site 12 were:

2020: winter wheat, fall multi species CC, fall compost application
2021: soybeans, fall single species CC
2022: spring compost application, corn

Figure 16. *BMP Treatment strips and benchmark sampling locations at Site 12*

6.1 Site 12 Pedological Survey Summary of Degradation, SHI, and Yield/Crop Productivity

The first form of site assessment was a pedological and topographic description of each sampling benchmark. The findings of the survey and the 2020 SHIs reflect the variable nature of the site due to its geological features of an undulating landscape with a dominance of short, steep slopes and gravelly material at depth. The study plot area demonstrated the most severe examples of tillage erosion of the 25 ONFARM properties, as observed at the upper crest (B) position cluster of benchmarks (Table 19). The mix of topsoil and parent material of high lime, stony and gravelly materials at the surface at these positions were prone to droughtiness, high pH and often compacted at depth. These conditions severely impede plant root growth, reduce available moisture, and potential crop yield. In recognizing these limitations, recent management by the cooperator to improve SOM and topsoil conditions include no-till, crop rotation including CCs plus regular additions of OAs. The BMP implementation may have contributed to improvement at some of the degraded benchmarks, though not on the most severely eroded areas.

Table 19. *Site 12 ONFARM 2020 soil information and Soil Health Indicator summary by benchmark*

BM	Soil Series & Textures	Drainage	Slope	Physical Degradation	Wheat Yield	AC	SOLV	PMN	SLAN	AS	SOM	pH
				AVG	64	381	63	5	51	48	3.4	7.6
1A	CALEDON Sandy loam (fine sandy loam over gravelly-sands)	Well	Lower 6% rolling	**No evidence - auger only***	**78**	481	73	8	100	53	4.2	6.5
2A	EDENVALE Sandy loam (fine sandy loam over gravelly sandy loam)	Imperfect	Lower 6% rolling	**Slight subsurface compaction, Bulk Density (BD) 1.7, platy structure at 23cm**	**76**	520	66	4	58	43	3.7	7.4
3A	EDENVALE Sandy loam (sandy loam over gravelly sandy loam)	Imperfect	Lower 2% rolling	**No evidence - auger only**	**68**	384	64	3	44	40	3.2	7.7
4A	EDENVALE Sandy Loam (sandy loam over gravelly sandy loam)	Imperfect	Lower 3% rolling	Slight to moderate tillage erosion; Moderate surface compaction and subsurface compaction, BD 1.7	71	440	65	4	40	48	3.7	7.7
1B	CALEDON Sandy loam (sandy loam over gravelly-sands)	Well	Crest 4% rolling	No evidence - auger only	61	266	62	2	37	67	2.9	7.5
2B	CALEDON Sandy loam (sandy loam over gravelly-sands)	Rapid	Crest 4% rolling	Slight tillage erosion, Moderate surface compaction BD 1.7, platy structure @ 0-20cm	58	424	69	1	49	52	3.8	7.6
3B	FOX Eroded phase (sands over sands and gravels)	Rapid	Upper 5% rolling	Severe tillage erosion, carbonates @ 0cm- auger only	52	330	58	3	42	44	3.5	7.9
4B	CALEDON Eroded phase (gravelly sands)	Rapid	Upper 5% rolling	**Severe tillage erosion, Slight to moderate surface and subsurface compaction, platy structure**	**38**	292	53	0	38	57	3.2	7.9
1C	CALEDON Eroded phase (gravelly sands)	Rapid	Middle 8% rolling	Severe tillage erosion, carbonates @ 0cm- auger only	52	315	66	3	32	57	3.1	7.7
2C	HILLSBURGH Buried horizon (Fine sands)	Rapid	Lower 6% rolling	**Buried A horizons @ 78cm, Moderate surface and subsurface compaction, BD 1.7, platy structure**	**72**	346	60	0	93	27	2.6	7.6
3C	HILLSBURGH Sand (sands over sands/gravels)	Well	Lower 7% rolling	Slight subsurface compaction, hesitation layer at 70cm -auger only	68	367	57	2	39	40	3.1	7.8
4C	FOX Buried horizon (loamy sands over sands and gravels)	Rapid	Lower 7% rolling	Slight surface and subsurface compaction, BD 1.7, platy surface structure	71	418	69	4	42	48	3.3	7.5

*Auger descriptions are quick checks of soil textures, horizons and 'depth to' type measurements.

Yield 76 is >= 10% above avg 61 is avg +/- 10% 52 is <= 10% below avg

AC= active carbon SOLV = Solvita CO_2 burst

PMN= potentially mineralizable nitrogen AS = aggregate stability

SLAN = Solvita labile ammonium nitrogen SOM = soil organic matter

Ratings: Very Low | Low | Medium | High | Very High

Winter wheat yield measurements in 2020 were lowest (10% below site yield average as indicated by red in Table 19) at the benchmarks with the most severe degradation. Loss of topsoil and organic matter from historic tillage erosion likely resulted in moisture and pH related plant stress. Interestingly, the SHIs measured at those benchmarks in 2020 ranged from a rating of very low to high which does not reflect the variation in crop growing conditions.

The SHI values and ratings in Table 19 indicate some level of poor soil health from degradation at the most severely affected benchmarks with ratings of very low to low for Solvita CO_2, SLAN, PMN. Although not measured in 2020, ACE protein levels at this site were low to very low with the exception of the non-degraded benchmark 1A, which was medium.   Some of the SHIs are rated as high to very high (AggStab and SOM) at benchmarks where moderate to severe degradation and/or yield reductions were observed. It is clear that moisture and pH related plant stress were over-riding influences at this site.   Measuring SHIs within the context of existing soil degradation is important to recognize to assess soil health and the ability of a soil to support a crop.   It could also suggest that, for the purpose of assessing overall soil health and BMP performance, ranges of SHI ratings need to better reflect Ontario SHI measurement ranges.

6.2 Site 12 Single Factor ANOVA Results (2020 variability)

The 2020 SHI data were analyzed to determine background variability at the sites. Tables 20 and 21 show the results of that analysis for pretreatment differences between landscape position and BMP treatment strips. SHI measured at the different landscape positions mostly followed the trend of having higher indicators at the lower landscape position. Due to the degree of variability of the measurements taken at this site, significant differences may not have been indicated at $p<0.1$ but the trend is visible. There were no significant differences in SHI results between BMP treatment strips prior to BMP implementation. Due to the degree of variation that was observed in the data at this site, and nearly all the other sites, an ANOVA analysis with a covariate was performed on the 2021 and 2022 data to account any background variability and to determine BMP effects on SHIs.

Table 20. *Site 12 2020 landscape position SHIs values and analysis for differences (p<0.1).*
Indicators sharing the same letter across landscape positions are not significantly different.

Trt	SOM (%)		AC (ppm)		Solvita CO_2 (ppm)		SLAN (ppm)		PMN (ppm)		AggStab (%)		Infiltration (mm/hr)		BD (g/cm3)		Wheat Yield (bu/ac)	
Upper	3.4	AB	328	A	61	B	42	A	6.8	A	55	A	442	A	1.43	A	52	B
Mid	3.0	B	569	A	63	AB	51	A	4.3	A	43	B	473	A	1.38	AB	66	A
Lower	3.7	A	456	A	67	AB	61	A	4.9	A	46	AB	248	A	1.30	B	73	A

Table 21. *Site 12 2020 BMP treatment strip SHIs values and analysis for differences (p<0.1).*
Indicators sharing the same letter across BMP treatments are not significantly different.

Trt	SOM (%)		AC (ppm)		Solvita CO_2 (ppm)		SLAN (ppm)		PMN (ppm)		AggStab (%)		Infiltration (mm/hr)		BD (g/cm3)		Wheat Yield (bu/ac)	
CC	3.4	A	354	A	66.8	A	56	AB	6.7	A	59	A	97	A	1.3	A	64	A
CK	3.3	A	360	A	59.5	A	67	AB	8.9	A	41	B	115	A	1.3	A	68	A
OA	3.4	A	383	A	62.6	A	42	AB	3.0	A	41	B	105	A	1.4	A	63	A
OA+CC	3.4	A	430	A	64.9	A	40	B	2.7	A	51	AB	232	A	1.4	A	60	A

6.3 Site 12 Single Factor ANOVA Results 2021

To generate landscape position and BMP treatment averages, ANOVAs were completed on the 2021 data as well (Table 22 and 23). As observed across sites, sets of SHI values measured in 2021 shifted from 2020 with some indicators increasing and some decreasing that may be due to soil variability, crop and moisture differences between years, and/or lab variability. In general, the trend of statistically higher SHIs at lower landscape positions in 2021 remained the same as in 2020. In 2021, the single factor ANOVA calculation found there were no differences between BMP treatment strips at this site.

Table 22. *Site 12 2021 landscape position SHIs values and analysis for differences (p<0.1). Indicators sharing the same letter across landscape positions are not significantly different.*

Trt	SOM (%)		AC (ppm)		Solvita (ppm)		SLAN (ppm)		BD (g/cm3)		Soybean Yield (bu/ac)	
Upper	2.9	A	449	A	60	B	53	B	1.28	A	19	B
Mid	2.5	B	453	A	62	AB	53	B	1.23	A	21	B
Lower	3.0	A	464	A	65	A	78	A	1.21	A	31	A

Table 23. *Site 12 2021 BMP treatment strip SHIs values and analysis for differences (p<0.1). Indicators sharing the same letter across BMP treatments are not significantly different.*

Trt	SOM (%)		AC (ppm)		Solvita CO_2 (ppm)		SLAN (ppm)		BD (g/cm3)		Soybean Yield (bu/ac)	
CC	3.0	A	476	A	61	A	62	A	1.27	A	18	A
CK	2.7	A	461	A	60	A	62	A	1.26	A	25	A
OA	2.7	A	486	A	65	A	68	A	1.23	A	27	A
OA+CC	3.0	A	444	A	62	A	65	A	1.20	A	26	A

6.4 Site 12 Single Factor ANOVA Results 2022

ANOVAs were completed on the 2022 data to assess potential differences between landscape position averages and BMP treatment averages (Table 24 and 25). SHI values in 2022 again shifted from 2020 and 2021 for the same possible reasons as previously mentioned. However, the trend of statistically higher SHIs at lower landscape positions remained the same. In 2022, the single factor ANOVA showed that a majority of the indicators tended to be higher, though not necessarily statistically higher, in the OA+CC BMP treatment. The yield measurement in the OA+CC treatment was significantly lower than the check likely reflecting the degree of degradation in that strip.

Table 24. *Site 12 2022 landscape position SHIs values and analysis for differences (p<0.1). Indicators sharing the same letter across landscape positions are not significantly different.*

Trt	SOM (%)		AC (ppm)		Solvita CO_2 (ppm)		SLAN (ppm)		PMN (ppm)		AggStab (%)		BD (g/cm3)		ACE (ug/g)		Corn Yield (bu/ac)	
Upper	3.0	AB	385	B	61	A	85	B	6.5	A	77	A	1.4	A	4805	B	44	C
Mid	2.7	B	297	B	64	A	88	B	5.8	A	55	C	1.3	B	4946	B	163	B
Lower	3.2	A	467	A	64	A	130	A	7.1	A	66	B	1.3	B	6043	A	189	A

Table 25. *Site 12 2022 BMP treatment strip SHIs values and analysis for differences (p<0.1). Indicators sharing the same letter across BMP treatments are not significantly different.*

Trt	SOM (%)		AC (ppm)		Solvita CO_2 (ppm)		SLAN (ppm)		PMN (ppm)		AggStab (%)		BD (g/cm3)		ACE (ug/g)		Corn Yield (bu/ac)	
CC	2.9	AB	387	BC	64	A	111	A	5.3	B	71	A	1.36	A	5583	A	151	A
CK	2.7	B	368	C	60	B	77	A	5.1	B	62	A	1.33	AB	4723	A	139	A
OA	3.0	AB	454	AB	61	B	101	A	6.4	AB	63	A	1.34	AB	5019	A	129	AB
OA+CC	3.2	A	458	A	67	A	118	A	9.3	A	69	A	1.28	AB	5734	A	109	B

6.5 Site 12 SHI Correlations 2020, 2021, 2022

The correlation coefficients for the 2020, 2021, and 2022 SHIs at site 12 are presented in tables 26, 27, and 28. There were no strong correlations between any of the SHIs and/or yield in 2020 or 2021. In 2022, SOM and AC, and SOM and ACE protein were strongly correlated.

Table 26. *2020 correlation coefficient matrix for SH Indicators at Site 12 (n=36)*

	SOM	AC	Solvita CO_2	SLAN	PMN	AggStab	BD	Yield
SOM								
AC	0.6446							
Solvita CO_2	0.5399	0.4938						
SLAN	0.2677	0.4759	0.2454					
PMN	0.3559	0.4378	0.365	0.1197				
AggStab	0.2104	-0.1971	0.1325	-0.2217	-0.2168			
BD	-0.3562	-0.5242	-0.5378	-0.6354	-0.2798	0.0796		
Yield	0.3301	0.6054	0.4606	0.6138	0.4994	-0.2705	0.4819	

Table 27. *2021 correlation coefficient matrix for SH Indicators at Site 12 (n=36)*

	SOM	AC	Solvita CO_2	SLAN	BD	Yield
SOM						
AC	0.07696					
Solvita CO_2	0.33018	-0.04798				
SLAN	0.66152	0.11855	0.71786			
BD	-0.24487	0.00703	-0.2696	-0.41529		
Yield	0.29998	0.00072	0.54772	0.70286	-0.36096	

Table 28. *2022 correlation coefficient matrix for SH Indicators at Site 12 (n=36)*

	SOM	AC	Solvita CO_2	SLAN	PMN	AggStab	BD	Yield	ACE
SOM									
AC	0.73312								
Solvita CO_2	0.49121	0.45595							
SLAN	0.52578	0.43406	0.30298						
PMN	0.67627	0.66028	0.54402	0.39319					
AggStab	0.16258	-0.16188	-0.07044	0.1317	0.1769				
BD	-0.241	-0.26628	-0.12094	-0.17083	-0.10769	0.41271			
Yield	0.05836	0.36708	0.08069	0.2539	-0.16135	-0.57027	-0.39005		
ACE	0.74566	0.63108	0.55078	0.55325	0.80184	0.253	-0.05521	-0.03282	

6.6 Site 12 BMP Effects on SHI

To better understand the effect of BMP treatment, the effect of landscape position and the interaction of BMP treatment*landscape position on the SHIs, an ANOVA analysis was completed using the 2020 baseline data as a covariate to account for some of the pretreatment SHI variability previously mentioned. The statistical model determined which of the design components in the model were significant at $p<0.1$. The results indicated that, at this site, none of the SHIs were affected by the covariate factor in the model. If the interaction between BMP treatment and landscape position was significant then that relationship was investigated to determine, at the benchmark level, where the changes in SHIs at BMP treatments from the check treatment were occurring (Table 29). The SHIs from a BMP treatment that were determined to be statistically higher than the check (within a landscape position) are shown in green and the SHIs that were statistically lower than the check (within a landscape position) are shown in red. The most noteworthy result was that AC, Solvita $CO_2$and AggStab increased from the check in all strips at the middle landscape position.

The pedological survey indicated that the middle landscape position at this site generally had slight to moderate compaction with some indication of effects from tillage erosion. The lower landscape position did not show much degradation and had more medium to high SHIs in the baseline year than the other landscape positions. This may explain why the SHIs in the lower position were not changing significantly from the check with BMP treatments after 2 years. In addition, the SHIs were not different from the check at the upper landscape position either, but that may be because the upper landscape position was greatly impacted from severe tillage erosion and loss of topsoil. The low to medium SHI values measured in the baseline year may require more years of BMPs to see changes in SHIs.

Table 29. *Site 12 Covariate analysis results where interactions were significant at p<0.1*

Landscape Position	Strip 1- CC	Strip 2- Ck	Strip 3- OA	Strip 4- OA+CC
Lower	SOL		PMN	AC
Middle	SOL, AC, AggStab		SOL, AC, PMN, AggStab	SOL, AC, PMN, AggStab
Upper	PMN			PMN

Note: SOL=Solvita CO_2 burst, AC=active carbon, AggStab=aggregate stability, PMN=potentially mineralizable nitrogen; green colour SHI were significantly higher than the check (within a landscape position), red SHI was significantly lower than the check (within a landscape position)

Where there was no BMP treatment*landscape position interaction at the benchmark level, the effects of the BMP treatment only and the landscape position only were investigated. In 2022, after two years of BMPs, the SOM values measured in the OA and OA+CC BMP treatments were significantly higher than the check treatment. A measurable increase in SOM within that short period of time was not expected; however, the increases may be a result of the variability within a stable measurement when taken annually as described in Section 7. The bulk density measured at Site 12 was significantly higher (more compacted) at the upper landscape position which was expected. The SLAN measurements at this site were not affected by BMP treatment, landscape position, or the interaction and may be due to the range of data measured over the entire site and the variability within the benchmark triplicates.

As indicated in the pedology summary, there were cases of severe tillage erosion at Site 12 and the crops at these areas were visibly impacted by moisture and nutrient availability limiting conditions. The 2022 corn yields reflect the substantial yield variability by treatment strip and landscape position. Statistical analysis of the data indicated that the BMP treatment*landscape position interaction effect influenced yield at this site and that the OA+CC treatment at the middle landscape position was significantly lower yield than the check. The lack of significant statistical difference at the benchmarks does not mask the clear difference in the values measured between the landscape positions based on the observed degradation.

Table 30. *Site 12 2022 corn yield differences at benchmark positions*

Landscape Position	Strip 1- CC (bu/ac)	Strip 2- CK (bu/ac)	Strip 3- OA (bu/ac)	Strip 4- OA+CC (bu/ac)	Landscape Average (bu/ac)
Lower	200	178	194	185	189
Middle	171	181	173	124	163
Upper	82	56	19	17	44
Treatment Average	151	139	129	109	

Note: red colour value indicates the yield was statistically lower than the check

Findings from Site 12 and other sites in the ONFARM BMP trial study found the SHI ratings used did not capture the influence of degradation and yield limiting factors. An assessment of SHI ratings at this site would suggest a medium rating of soil health for most SHI measurements, but the yield results from the yield monitoring, particularly in the upper position, would suggest differently. Low moisture and high pH values at this site were very likely overriding limiting factors to crop productivity. SHIs need to be evaluated within the context of underlying soil conditions to assess the overall soil health of a site. In addition, improved moisture related SHIs are needed for more complete soil health assessment.

7.0 Factors in Using Soil Health Indicators

The extensive testing and use of several soil health indicators in the ONFARM project gathered further insight into their assessment of their application for Ontario. A number of factors were considered as part of compiling a set of key attributes. A good soil health indicator needs to be:

- Measurable – able to assess it in a reliable, quantitative manner
- Meaningful – reflective of a physical, chemical or biological capability in a manner that is relatable to soil capability, performance or productivity
- Consistent – without high variability between samples taken in a small area (e.g., triplicates at each benchmark)
- Responsive – able to reflect changes in management, or differentiate between zones with different inherent or baseline soil characteristics (e.g., differences in soil organic matter between degraded areas, soil types, or slope positions)

The objective of this section is to look at the ONFARM SHI data as a whole and identify factors that impact SHI levels, ranges, and responses to a wide variety of conditions. The data shown below are used as examples to illustrate key issues. The full data set can be accessed directly on the OSCIA [ONFARM Data Dashboard.]

7.1 Regional Effects on SHI

The main regional differences appear to relate to baseline SOM levels, where the Eastern sites have generally higher SOM than the rest of the regions; the 2022 AC results by region are shown on the left in Figure 17 below. This regional separation can generally be explained through the combined impacts of 1) inherent differences in the Eastern climate (colder, wetter) resulting in slower SOM degradation, and 2) differences in management history, having more recently been converted from primarily livestock/pasture production systems into cash crop production systems. Site 15, highlighted in the right graph of Figure 17, is a Western region site that also has a more recent history of livestock/pasture production relative to the other sites in this area, and also skews toward the higher SOM category, lending support the theory that the Eastern sites appear as a separate group partly because of historical differences in management.

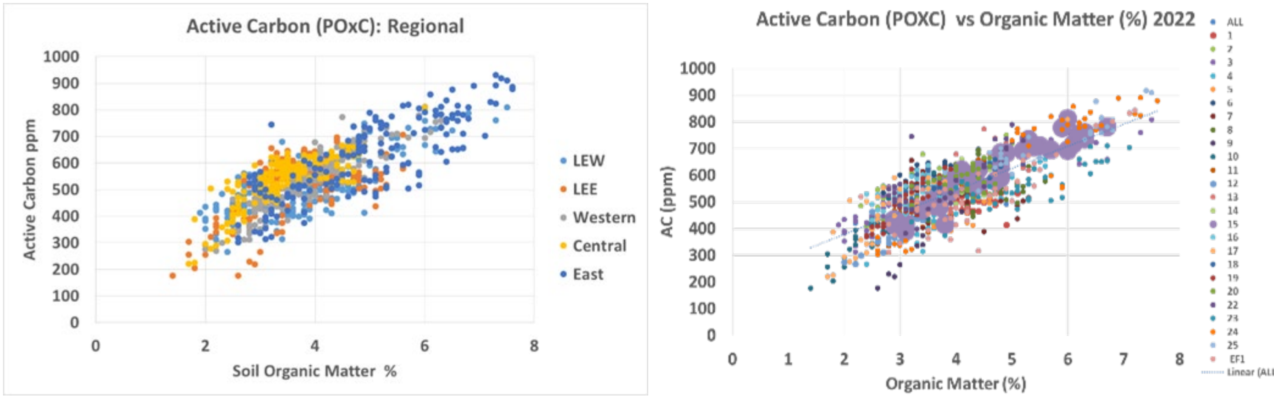


Figure 17. *Regional AC levels relative to SOM, 2022 (left) and Site 15 AC relative to SOM (2022) highlighted in purple.*

7.2 Effect of Soil Texture Group on SHI

Soil texture tended to influence the ranges of various indicators. In general, this resulted in the SHIs for the different soil textures separating out according to the typical range of SOM for that soil texture, such that coarser soils generally had lower levels of the SHI. As an example, the 2022 results for AC are shown in Figure 18 below. The AC tends to increase in a linear fashion to increases in SOM, though the rate of increase in fine soils is slightly lower.

Interestingly, ACE protein (shown on the right in Figure 18 below) behaved slightly differently, such that for a given SOM level, on average, coarser soils had higher ACE protein levels than finer soils. This overall observation is consistent with the CASH rankings from Cornell. The reason for this difference in SHI behavior is not clear but may be related to different microbial populations specific to different soil texture groups and regional conditions. There is currently only one year of data on ACE protein, so its responsiveness to BMP implementation has not yet been examined.

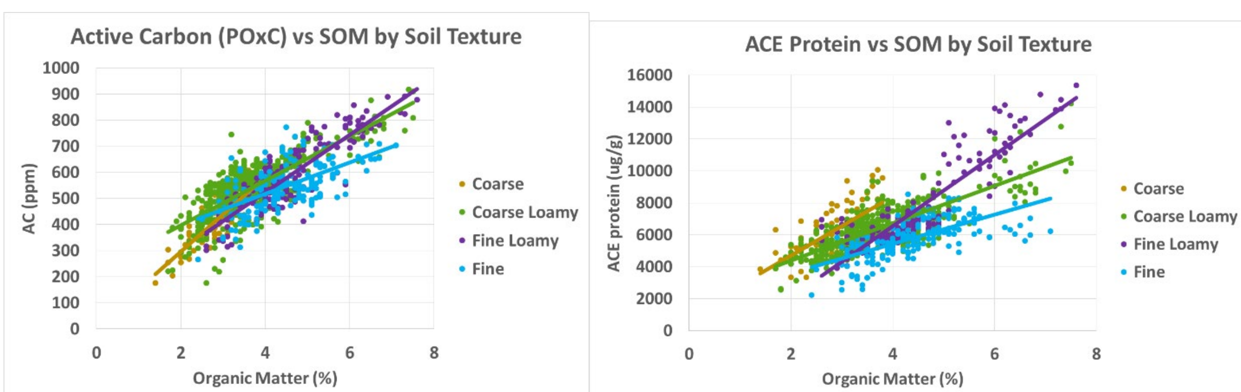


Figure 18. *2022 AC relationship to SOM by soil texture (left) compared to 2022 ACE protein relationship to SOM to by soil texture.*

7.3 Site Specificity of SHI

Every site is different, and SHIs respond accordingly. While the discussion above attempts to make some overall generalizations based on common characteristics of sites, ultimately SHI levels and responses to management will be site-specific taking into consideration all factors including soil texture and inherent capability, topography, degree of degradation, management history (tillage, livestock or manure application, residue management, etc.). For example, the data from Site 6 highlighted in the left graph below (Figure 19) indicates an above average level of AC for that level of

SOM; this may be due to a history of manure application at this site, but other factors could be involved. At this stage in the ONFARM program, there isn't sufficient long-term data to elucidate the dominant factor(s). The Figure 19 graph on the right (Site 3, a sandy loam site with a higher organic zone) shows the impact of organic levels on AC. This is consistent for other SHIs at this site as well.

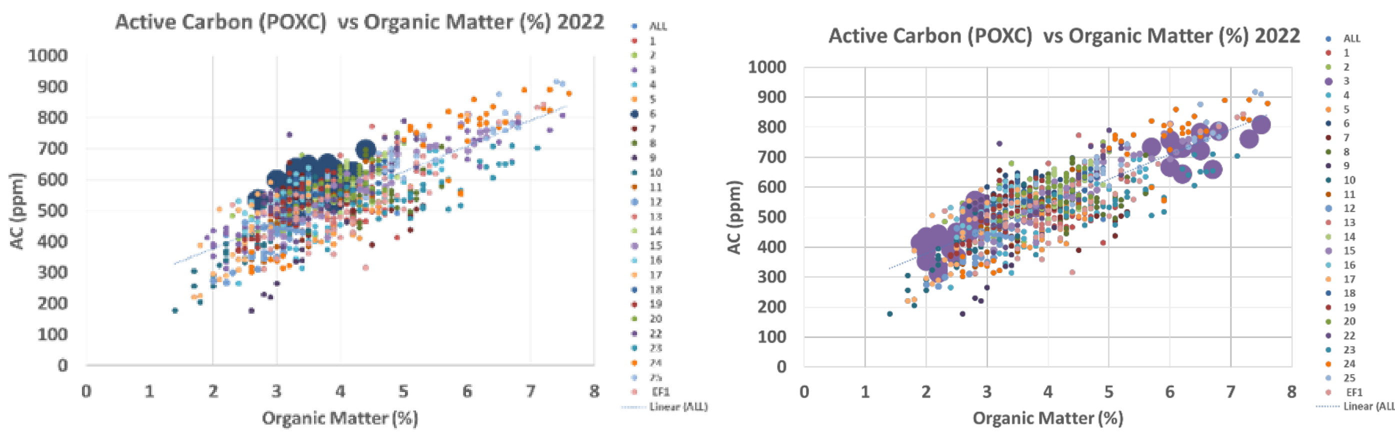


Figure 19. *Site 6 (left) and Site 3 (right) AC levels relative to SOM (2022)*

The rate and extent of change of a SHI in response to BMP implementation may also be impacted by the starting level of the SHI at a particular site. The capacity for any given site to improve from the current status will be dependent on its starting point with respect to its natural capability, i.e., room for improvement, crop rotation and management in addition to its physical characteristics like soil texture. For example, in comparing Site 15 (moderately sloping, fine loamy with areas of tillage erosion) and Site 17 (undulating, coarse loamy), Site 15 has a more recent history of pasture/hay management, and the SOM levels in the pre-treatment strips are only marginally lower than the adjacent native (fence row) location (Figure 20). At this site there is room to improve some of the degraded areas (upper slope position), but site-wide improvements that approach the natural baseline are improbable when considering goal setting for BMP use. In fact, at this site, the BMP goals may be to maintain the good SOM levels in most of the field as well as improving the degraded zones. In contrast, the average SOM levels at Site 17 are roughly half of the adjacent native (fence row) position. At this site, there may be considerable room for improvement in SOM and other SHIs across the whole field. The rate at which the SHIs can be improved needs longer term investigation.

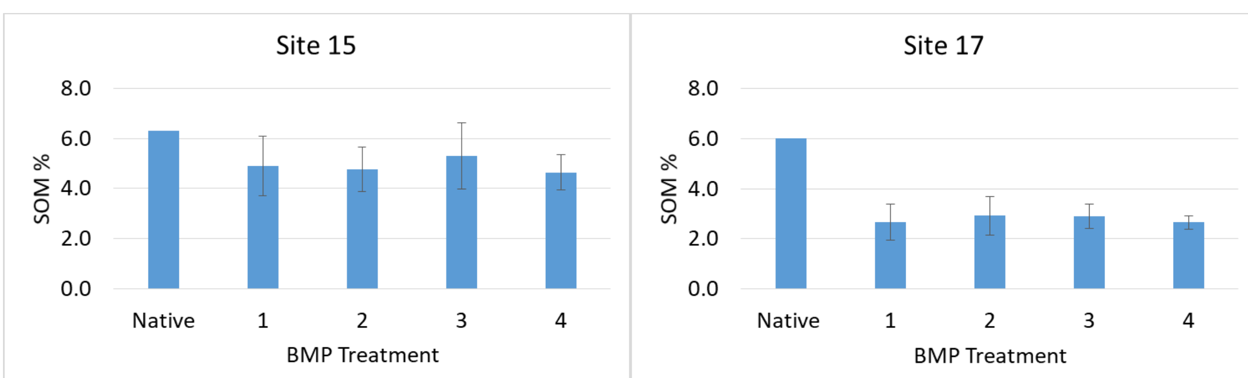
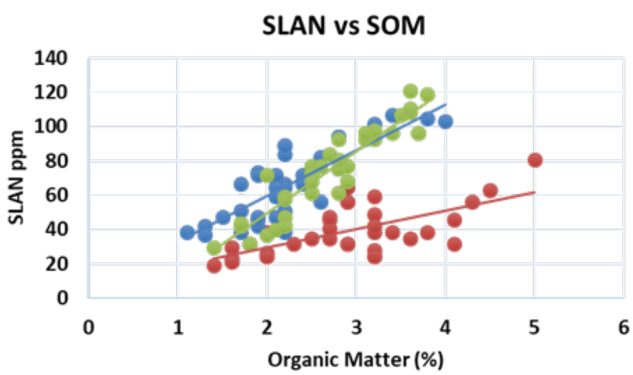


Figure 20. *Site 15 (left) and Site 17 (right) 2020 SOM levels (mean, standard deviation), comparing native (fence row) soils to designated treatment strips within study fields.*

It was also noted that ACE protein measurements corresponded to SOM more strongly on a site-by-site basis compared to the combined sites (mean correlation coefficient of 0.77 (strong) for individual sites compared with 0.65 for all site data combined). This is in contrast to most other SHIs (mean correlation coefficient for individual sites of 0.68 compared to 0.73 for all sites combined). Strong site level correlations may make it particularly useful for producers as a means of tracking soil health changes.

7.4 Annual Variations of SHI

Differences in SHI ranges were observed from year to year, which could be due to different stages in the crop rotation, annual temperature and rainfall differences, etc. When compared to SOM, SHIs responded differently, as shown in Figure 21 below for SLAN and Solvita CO_2 burst for Site 10 sampled close to the same dates in 2020, 2021, and 2022. Solvita CO_2 respiration appears to be much less affected by the specific annual weather/crop conditions than SLAN. These differences have not been fully explored, given that for most sites, the ONFARM program encompassed only one rotation.



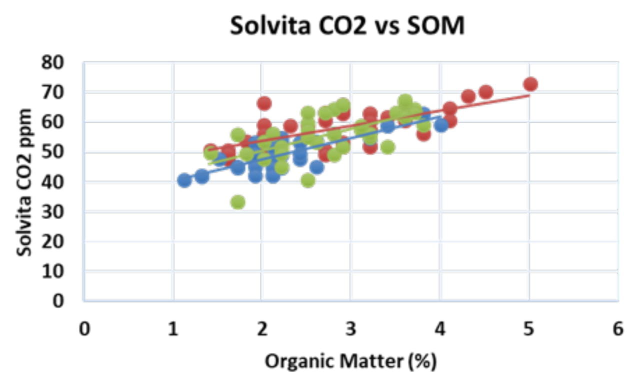
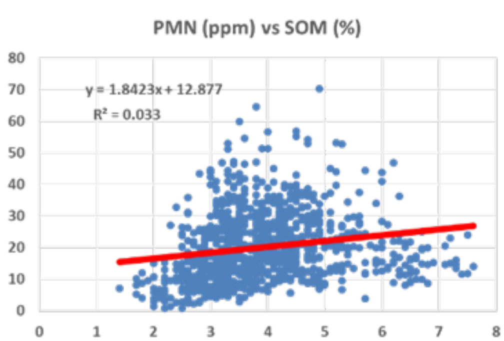


Figure 21. *Comparison of SLAN (left) Solvita CO2 (right) levels at Site 10 compared to SOM for 2020, 2021, and 2022.*

7.5 SHI Variability and Responsiveness

The data showed a wide range of variability among the selected SHIs, both in the overall data and within individual benchmark locations. As an example, the graphs shown below in Figure 22 for all samples taken in 2022 for PMN and SLAN plotted against SOM indicate much wider scatter for PMN (r^2=0.03) than for SLAN (r^2=0.51).



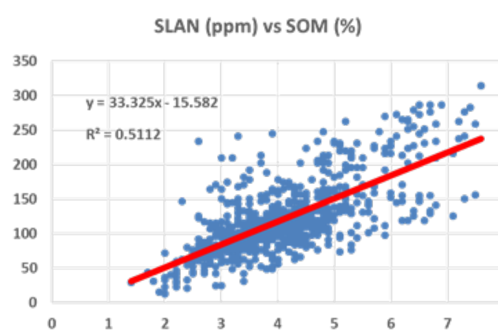


Figure 22. *PMN (left) and SLAN (right) compared to SOM, 2022.*

In order to quantify and rank the variability of the SHI tests, the coefficients of variation (CV; a calculation of standard deviation/mean) for triplicate samples at all benchmark sampling locations were calculated for the combined 2020, 2021, and 2022 data.

The overall mean CV levels for all 3 years indicate a significant range across the different SHI tests (Table 31). While every test showed high variability at some benchmarks in some years, on average, Solvita CO_2 burst, ACE protein, BD and SOM were relatively consistent. Active Carbon, soil moisture content, and SLAN were moderately consistent, and PMN and Nematode counts had very high variability.

Table 31. *Variability of SHI test results across all sites as CV levels*

Solvita CO_2 Burst	ACE Protein (2022)	Bulk Density	Aggregate Stability	Soil Organic Matter	Active Carbon	Soil Moisture	Solvita Labile Amino Nitrogen (SLAN)	Potentially Mineralizable Nitrogen (PMN)	Nematode counts (parasitic; total) (2020)
5%	6%	6%	7%	7%	9%	11%	14%	28%	62%; 42%

Given the short length of time the sites were under different management scenarios, a measurement was needed to assess overall responsiveness. Since SOM can be considered the core soil property from a soil health perspective, each of the other SHIs were plotted against SOM to derive a linear regression, on a site by site and combined basis. Note that in the overall dataset, benchmarks with SOM greater than 10% were not included in the regression analysis because they are not representative of most (98%) of the benchmarks and skew the regression lines. As an initial investigation, the slope of the regression line can be considered reflective of how well a SHI will respond to management that is aimed at maintaining or increasing SOM. In this assessment, the greater the slope, the more 'responsive' the SHI. For example, data for 2022 AC and Solvita CO_2 respiration are shown in the Figure 23 below; AC has a greater slope than Solvita CO_2, which would indicate that AC would likely increase more rapidly than Solvita CO_2 in response to increases in SOM.

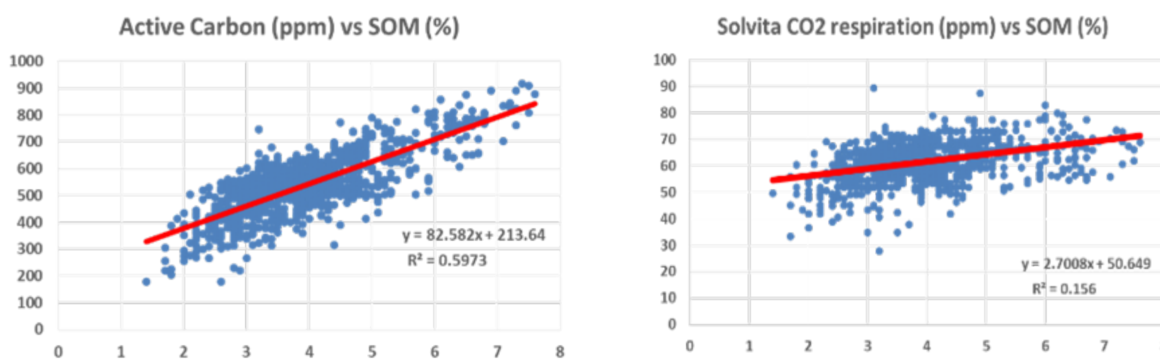


Figure 23. *AC compared to SOM (left) and Solvita CO2 respiration compared to SOM (right), 2022.*

To normalize the data, responsiveness to changing levels of SOM was evaluated as the slope of the linear regression equation expressed as a percentage of the range of data for each SHI; the greater the percentage, the more responsive the test. The 2022 responsiveness values shown below in Table 32; the order was similar for the other 2 years. The results indicate that PMN was least responsive; BD, AggStab, Soil Moisture and Solvita CO_2 were only moderately responsive; and SLAN, ACE protein and AC were most responsive.

Table 32. Responsiveness values of SHI test results across all sites

Potentially Mineralizable Nitrogen (PMN)	Bulk Density	Aggregate Stability	Soil Moisture	Solvita CO_2 burst	Solvita Labile Amino Nitrogen (SLAN)	ACE protein (2022)	Active Carbon
3%	5%	6%	6%	7%	10%	11%	13%

Overall, if a SHI has a high variability but low responsiveness, it would not be considered a very useful indicator, whereas one with a low variability and moderate to high responsiveness would be considered useful in the shorter term. Indicators that have low variability and low responsiveness may be good indicators over a longer time scale.

Based on the ONFARM data thus far, AC and ACE protein would be the preferred indicators in the shorter term (2 rotations, 5-10yrs) and possibly SLAN though it is more variable. Solvita CO_2 burst, BD and AggStab would likely be good in the longer term. PMN and nematode counts were extremely variable, and based on this study, would not be recommended for general use in Ontario.

7.6 Overall SHI Consistency

From the above discussion, an overriding take away message is that identifying consistent responses of an SHI to BMP implementation will take some time, likely over multiple rotation cycles and BMP treatment applications.

The frequency of soil sampling at ONFARM sites (yearly for some parameters and biennially for the whole set) has captured a wide range in changes in most soil health indicators on a year-to-year basis. Even the SOM measurement showed inter-year variability at most sites, even though it is generally accepted that it is an indicator that requires several years of management improvement to see a consistent measurable change. With ONFARM soil sampling happening consistently across sites in June every year and the use of triplicate sampling around each benchmark to enable rigorous statistical analysis, annual differences in the crops being grown or crop-specific management and weather (particularly heat and soil moisture) may have had an impact on some of the indicators.

A conceptual model of indicator changes over time is shown in Figure 24, where the stable blue line represents an expected path for soil health improvement over time, but the measured values may oscillate around that line, with exaggerated increases, decreases or no change. The ONFARM program (blue box) is at the beginning of this process.

The conceptual model demonstrates the need to monitor soil health consistently, and over a long period of time to better capture soil health improvement or degradation.

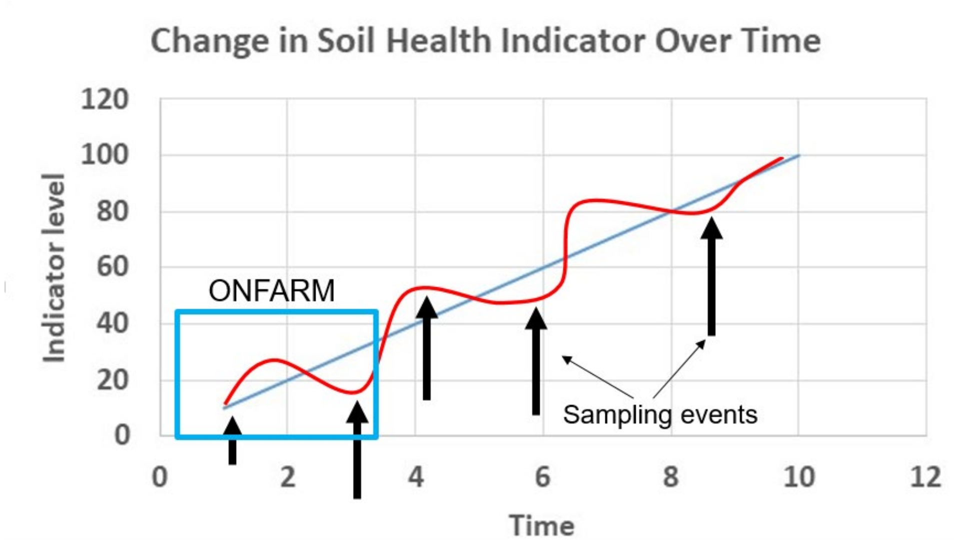


***Figure 24**. Conceptual model of changes in a SHI over time with Implementation of BMPs.*
The blue line represents a theoretical linear improvement over time, and the red line represents a more realistic result based on periodic sampling over time. The blue box represents the ONFARM timeframe.

7.7 Practicality of SHI Tests

To be adopted by the broader farming community as routine measurements that can be usefully incorporated into management decisions, SHIs also need to be practical at a time scale, field scale, and lab scale, and be affordable.

Table 33 summarizes some practical information on the indicators and what they measure, responsiveness and timeframe when they would be expected to show consistent changes, variability, how often they should be sampled, and lab availability and cost. Some potential alternative procedures are also noted.

It should be noted that soil moisture content, while it is not a true soil health indicator that can be used to compare across seasons or distant locations and not been included in the table, was conducted in this study since it is a simple measure that could be used to assess the effect of BMP management on the ability of the soil to hold water for crop requirements, at any one point in time at a given site, and thus an important consideration for risk management. A more robust SHI would be available water holding capacity, but that is a much more expensive and less available test, not suited for routine laboratory analysis.

The table provides guidelines based on the information gathered so far during the ONFARM program. With longer term data, it is expected these numbers can be refined and clarified.

__Table 33.__ Guideline information of Soil Health Indicator use in Ontario

Indicator	What does it measure?	Responsive to BMPs?[1]	Time-scale (years)[2]	Benchmark Variability	Sampling Frequency	Lab Practicality[3]	Approx. Cost	Alternative/ In-field Procedures and Notes
Physical								
Bulk Density	Structure/porosity	Inconsistent	5-15?	6%	2 rotations	Poor	$65	Can be done on-farm
Infiltration Rate	Movement of water into soil	Yes	5-15?	60%	2 rotations	n/a	n/a	Demonstration tool
Aggregate Stability	Physical structure	Yes	5-15?	7%	2 rotations	Good	$20	Wet agg. stability by image analysis (Apps)
Penetrometer	Compaction	Yes	10-20?	n/a	1 rotation	n/a	n/a	Shovel or tile probe
VESS (Visual Assessment of Soil Structure)[4]	Soil structure	Yes	10-20?	Not available	Unsure	n/a	n/a	In-field assessment only
Carbon								
Soil Organic Matter (SOM)	Organic carbon	Yes	10-20?	7%	1-2 rotation	Good	$10	No good substitute
Active Carbon (POXC)	Readily available carbon	Yes	5-10?	9%	1 rotation	Good	$35	In-field test kits
Solvita CO_2 Burst	Microbial respiration/biomass	Yes	5-15?	5%	1 rotation	Good	$25	In-field test kits
Nitrogen								
Potentially Mineralizable N (PMN)	Potentially available nitrogen	Yes	???	28%	Unsure	Poor	$40	PSNT a partial measurement
Solvita Labile Amino N (SLAN)	Readily available nitrogen	Yes	5-10?	12%	1 rotation	Good	$25	In-field test kits
ACE Protein	Stored organic N	Yes	5-10?	TBD	1 rotation	Good	$30	Should follow SOM
Biological Diversity								
Nematodes (totals or ratios)	Nematode types and populations	Unsure	???	42%-57%	Unsure	Poor	$60+	Earthworm counts in-field

7.8 Key Recommendations for a Producer SHI Sampling Program:

A producer SHI sampling program should incorporate practices aimed at minimizing the impacts of the sources of variability discussed above, including:

- Identify benchmark locations in the field, and go back to these same locations at each sampling event. This reduces the impact of field variability.
- Take composite samples from around that benchmark, to reduce variability even more. A soil probe is recommended to get a consistent depth and volume of sample
- Take separate samples from different landscape positions, or degraded areas etc. to track differential BMP impacts
- Consider including a reference location that is not likely to change (e.g. fence row, pasture etc.) as a location that can be used to look for year to year changes.
- When comparing treatment effects, include a check strip.
- Sample either in late spring (June) or early fall (late September). Decide which suits your work schedule best – but then always take your samples during that same period.
- Know your lab: what SHI tests do they do? Price? Convenience (location etc.). Aim to use the same lab for each sampling event.
- Be consistent – same sampling location, same time, same lab.
- Be patient and persistent – change will come, but expect variability along the way and don't be discouraged by it.

8.0 BMP Cost Benefit Analysis

8.1 Cover Crop BMP Net Returns

A CC only BMP treatment was included at all but one of the 25 sites, and varied from single species to mixtures of 2 to 14 species. Mixtures were most often seeded after a wheat crop, and cereal rye was used most often after the harvest of soybean or corn crops. Beyond the costs of the seed and planting, about 1 in 5 of the cooperators applied a herbicide to terminate the CC, an expense not required if the CC was winterkilled. Only a small number of cooperators applied a herbicide before CC planting to control weeds. If a cooperator's normal practice was to apply a burndown prior to planting the field crop, the cost was not included. If the herbicide use was increased to help terminate the CC, the cost of the increased amount of herbicide was used.

Cover crop revenue came from the harvest of CCs for feed as silage (rye and oats), baled or grazed. The seed cost of CCs depended on 3 things: cost of seed, seeding rate and single species versus mixtures with a median value of $24.41 and a range from $8.00 to $76.00 per acre. At the low end, some cooperators were able to access relatively inexpensive seed grown locally or on-farm, whereas high seeding rates contributed to higher costs in some cases. CC mixtures, especially complex mixtures, were generally more expensive than the single species options. About one third of the trials incurred a herbicide cost either as a preplant treatment or to terminate the crop. Total costs for CCs had a median value of $60.50 and a range from $17.35 to $145.00 per acre.

There was a tremendous range of CC related expenses but when net revenue comparisons were lumped together considering the difference in yield returns from the check treatment, the net returns across all CC BMP treatment strips compared to the check treatment had a median loss value of $29.03 per acre (Table 34). The range in net returns was from -$344.50 to $248.10 per acre. The lower and upper end of the range in net returns and crop value is due to large yield gains or losses in higher value crops and a significant feed dollar value for the harvested CC. Net returns for just the sites which harvested CCs had a median of -$7.08 and a range of -$77.18 to $194.69 per acre. If the CC harvest sites are removed, the range stays the same and the loss is about $6.00 more.

Table 34. *Cost and Returns of Cover Crop BMP*

Sources of Changes in Net Income	Average $ (per acre)	Median $ (per acre)	Range $ (per acre)	
			Low	High
Change in Revenue				
Change in yield value of following crop	- 0.99	6.11	- 280.25	292.80
Revenue from cover crop harvest	125.71	120.00	50.00	300.00
Change in Costs				
Cover crop seed cost	27.70	24.41	8.00	76.00
Cover crop planting cost	20.20	24.00	6.00	30.00
Cover crop harvest cost	64.28	70.04	23.04	94.00
Cover crop preplant herbicide cost*	20.22	17.80	15.00	31.00
Cover crop tillage termination cost	17.60	18.00	16.00	18.00
Cover crop herbicide termination cost*	20.60	16.00	14.50	38.95
Total cover crop cost	63.06	60.50	17.35	145.00
Net Change in Profit	- 35.39	- 29.03	- 344.50	248.10

* Herbicide cost includes cost of application

8.1.1 Cover Crop Case Study

For Site 1, there were three CC treatments for comparison (1 biostrip treatment and 2 different CC mixes), but no OA. A no-till drill at 7.5in row spacing was used to plant a bio-strip CC after winter wheat in which a mixture of a cereal, legumes and a brassica CC were seeded in 2 rows, and the other 2 rows were left bare. This unplanted area was worked and planted into using a no-till corn planter which the corn crop yield revenue was used for the treatment comparison (Table 35). A herbicide was applied prior to planting the CC to control weeds and reduce competition from the volunteer winter wheat. This is a typical situation from a CC cost perspective, but first use of CCs is not expected to provide a significant yield increase. The significant CC growth did a good job of suppressing weeds between the corn rows and would have supported the soil life and contributed some organic matter to the soil. The legume CCs would also have contributed some nitrogen to the corn crop though these benefits are hard to put a dollar value on.

Table 35. *Cover Crop case study economic summary*

Cover Crop Pre-Plant Herbicide Cost ($/ac)	Cover Crop Pre-Plant Herbicide Application Cost ($/ac)	Cover Crop Seed cost ($/ac)	Cover Crop Planting cost ($/ac)	Total Cover Crop cost ($/ac)	Difference in yield revenue ($/ac)	Net Income: revenue - costs ($/ac)
7.80	10.00	19.30	24.00	61.10	4.13	- 56.97

8.2 Organic Amendment BMP Net Returns

Organic amendment treatments were conducted on 17 of the 25 sites. The treatments included: manure - liquid dairy, liquid hog, solid chicken, solid beef, solid chicken/beef compost, solid horse manure; and biosolids - liquid anaerobic digestate, liquid sewage biosolid, solid municipal compost, green bin compost, mushroom compost, and sewage biopellets. The 9 livestock farms utilized their manure and one farm utilized its on-farm generated anaerobic digestate of which no cost for the manure or digestate was applied as the cooperators generally attributed it to the livestock operation. The cost for application, however, was included in the net return calculation. The other cooperators sourced the non-agricultural source material off-site. In most cases, samples of the organic amendment were collected at application time for analysis, or the cooperator provided a copy of the analysis to determine a nutrient value. If required, database values were used from OMAFRA's AgriSuite program to calculate nutrients available from the manure organic amendment.

Costs of the organic amendments varied significantly (Table 36), and it was challenging in many cases to clarify the different costs. Often delivery and/or application costs were combined making it difficult to separate out. There was a wide range of product costs. Some of the factors affecting cost were: source and type of product, delivery, and application. One advantage with off-farm sources (e.g., biosolids) was the ability of cooperators to negotiate prices that reflected delivery and/or application costs only. Cooperators had to consider and source biosolids with constituents that met their needs: if soil nutrient levels are adequate or high -- then organic amendments that are low in nutrients and high in dry matter are most suited to build organic matter levels. Such circumstances require the use of organic amendments low in nutrients an d high in dry matter. This was accomplished at one sandy loam soil site that used chicken and beef compost. The net per acre cost of the product plus application minus the nutrient value resulted in an estimated cost of $51.00 per acre. The cooperator feels this was a good investment in future higher yields and improved crop resiliency.

Net revenue comparisons were summarized with due consideration for the difference in yield returns from the check treatment. When comparing the organic amendment treatment BMPs with the respective check treatments, results showed a median value of $2.03 and a range of a loss of $486.57 to a net revenue of $455.89 per acre. The nitrogen, phosphorus and potassium fertilizer value of each organic amendment application was calculated and subtracted from the costs of the organic amendment. The median nutrient value was calculated to be $152.93. The range varied significantly from a low value of $29.80 for cattle manure up to $418.53 for an application of poultry manure.

Table 36. *Cost and Returns of Organic Amendment BMP*

Sources of Changes in Net Income	Average $ (per acre)	Median $ (per acre)	Range $ (per acre)	
			Low	High
Change in Revenue				
Change in yield value of following crop	12.54	32.40	- 374.40	218.70
Reduction in Costs				
Organic amendment (OA) nutrient value	152.93	127.00	29.80	418.53
Change in Costs				
OA product cost	147.99	120.00	32.00	560.00
OA delivery cost	197.67	63.00	30.00	500.00
OA application cost	52.12	42.00	10.00	215.04
Total OA cost	165.36	141.50	27.00	592.00
Net Change in Profit	2.82	2.03	- 486.57	455.89

8.2.1 Organic Amendment Case Study

The cash crop cooperator at Site 5 was able to source biosolid pellets to apply as an organic amendment BMP treatment to the site plot for the next crop year. The material was delivered and applied by the provider at a rate of 2 tons per acre. In the second year, they sourced anaerobic digestate which again was delivered and spread by the provider at about 5,700 gallons per acre. In both years, the cooperator applied an equivalent amount of N, P, and K fertilizer that were applied from the organic amendment in those treatments that did not receive the organic amendment. That equivalent fertilizer value is reflected in the fertilizer applied column of Table 37. In this case, the biosolid pellets were relatively inexpensive and provided a significant amount of nutrients that turned into a significant financial gain for that crop year. The biosolid pellets have a higher dry matter content, but the low rate did not result in a significant amount of organic matter added to the soil. For the following crop year, the anaerobic digestate was more expensive per acre and lower in nutrients so that the bottom line was not as favourable. This material also had a lower dry matter content so would not provide much organic matter to improve soil levels.

Table 37. *Organic Amendment Case Study economic summary*

Year	OA Product Cost ($/ac)	OA Applicat'n Cost ($/ac)	Fertilizer Applied ($/ac)	Fertilizer Applicat'n Cost ($/ac)	Fertilizer Total ($/ac)	Yield (bu/ac)	Difference in yield from check (bu/ac)	Difference in yield revenue ($/ac)	Net Income: revenue - costs ($/ac)
2021	105.00		234.00	10.00	244.00	67.5	2.5	37.92	176.92
2022	80.00	120.00	117.00	10.00	127.00	262	3.7	30.24	- 42.76

8.3 Cover Crop and Organic Amendment BMP Net Returns

At the 17 sites where organic amendment BMPs were included in the plot plan, there was also a combination or BMP suite of treatments that included a CC and organic amendment in one treatment. A practical advantage of this combined CC-OA treatment was the fact that the OA provided nitrogen and other nutrients for uptake by the CC, thereby increasing its growth. When combined with a good crop rotation with reduced or no tillage, CCs and organic amendments are recommended for farms across Ontario to improve soil health.

The partial cost analysis from across the combination BMP treatments (Table 38) determined the median net change in profit was a loss of $49.71 although there was a very wide range of returns from -$508.23 to $467.37 per acre. The upper end of the range of net revenue was represented by sites where livestock manure was available on the farm (only application cost) and the CC was harvested for feed. The lower end of net loss reflects the high costs to source the organic amendment from off-farm and the relatively low value of nutrients in the organic amendment. Overall, the influence of the difference in treatment yield from the check treatment was a slight yield advantage to the BMPs but some higher value crop yield losses brought down the average yield value return.

Table 38. *Cost and Returns of combined Organic Amendment and Cover Crop Treatment*

Sources of Changes in Net Income	**Average $ (per acre)**	**Median $ (per acre)**	**Range $ (per acre)**	
			Low	High
Change in Revenue				
Change in yield value of following crop	- 12.05	16.27	- 379.20	172.45
Revenue from cover crop harvest	135.00	120.00	60.00	300.00
Reduction in Costs				
Organic amendment (OA) nutrient value	161.72	131.16	29.80	418.53
Change in Costs				
Cover crop seed cost	26.72	26.00	12.00	60.00
Cover crop planting cost	22.17	24.00	6.00	30.00
Cover crop harvest cost	54.37	46.08	23.04	94.00
Cover crop preplant herbicide cost*	20.64	19.60	16.00	31.00
Cover crop tillage termination cost	16.00	16.00	16.00	16.00
Cover crop herbicide termination cost*	22.64	19.50	14.50	38.95
OA product cost	148.69	108.00	32.00	560.00
OA delivery cost	197.67	63.00	30.00	500.00
OA application cost	45.96	28.00	10.00	215.04
Total OA + Cover crop cost	230.58	211.79	64.00	580.00
Net Change in Profit	- 57.92	- 49.71	- 508.23	467.37

* Herbicide cost includes cost of application

8.3.1 Cover Crop and Organic Amendment Case Study

The case study demonstrating the use of CC and organic amendment treatment was a dairy farm site, Site 6, which had within its operation an anaerobic digester. The sequence of crop and BMP management began following a winter wheat crop in 2020, when an oat CC was seeded in the combination treatment strip that was followed a month later with an anaerobic digestate application at a rate of 3500 gallons per acre onto the emerged oats. Growth of the oats CC was greater in this treatment strip compared to the CC alone treatment strip when harvested as silage later in the fall. A second application of anaerobic digestate at the same rate was applied prior to a silage corn crop planted the following spring. After harvest of the silage corn September 30th, a cereal rye CC was planted which grew through the fall, overwintered, and received an early spring anaerobic digestate application at a rate of 4750 gallons per acre. The cereal rye CC was harvested in late May as silage prior to planting grain corn. The BMP treatment costs incurred by the cooperator over the study period are summarized and listed in the crop year when the crop benefit would be realized (Table 39). For example, the digestate applied in 2020 would benefit the corn silage crop in 2021. In 2020, the value of the oats as feed offset the cost of the CC seed and CC harvest costs that year. The following year in 2021, the value of the nutrients and the yield benefit more than offset the cost of the digestate application. In the final crop year of 2022, the nutrient value of the digestate and the feed value provided a significant return to the combination BMP. As a result, the net return over the three crop year period of the anaerobic digestate application and the CC treatment was $679.67 per acre. The significant gain realized in this case study shows the economic advantage livestock operations can have over cash crop operations when utilizing a BMP suite of both organic amendment and CC.

Table 39. *Cover Crop and Organic Amendment Case Study economic summary*

Year	Cover Crop Seed cost ($/ac)	Cover Crop Planting cost ($/ac)	Cover Crop Harvest cost ($/ac)	OA Applicat'n cost ($/ac)	Total Fertilizer cost ($/ac)	Difference in yield revenue ($/ac)	Cover Crop Feed Value ($/ac)	Net Income: revenue - costs ($/ac)
2020	24.00	25.00	94.00				150.00	7.00
2021				112.00	228.20	89.10		205.30
2022	26.00	25.00	94.00	56.00	288.99	79.38	300.00	467.37
					Total 3-year net revenue			679.67

9.0 Conclusions and Recommendations

The ONFARM soil health monitoring program has established a network of 33 cooperator sites that represent predominant soil landscape conditions and agricultural crop management across Ontario. The baseline soil health assessment approach has identified different forms and extent of degraded soil conditions found at most sites. Degradation by historic tillage erosion was considered the most severe form followed by near surface compaction as the most abundant. The reduction in soil condition and rooting zone in upper landscape positions most affected by past tillage erosion were often reflected by the various soil health indicators tested. Sampling a field for SHIs should consider representative zones of contrasting topography to allow for a range of results.

After the baseline assessment and initial soil health indicator measurement at the BMP trial sites, the soil health BMPs were implemented using cooperator selected combinations of CC, organic amendment and a suite of both. Cover crop BMPs demonstrated mixed results in improving soil health indicator levels in this timeframe compared to organic amendments. Organic amendments were a more effective BMP for driving change in SHIs, particularly carbon based indicators, in the short term and were shown to be adaptable for a number of cropping systems. Pairing CCs with an organic amendment frequently improved SHI responses compared to CCs alone. A consistent benefit of combining BMPs was the improved CC stand that will help to hold organic amendment nutrients in the system for the next field crop and may enhance carbon return.

The testing of a package of established and novel soil health indicators (SHI) over a wide spectrum of site conditions to test BMP efficacy is an unprecedented initiative for Ontario. The goal to identify key soil health indicators to best reflect a range of Ontario conditions will need to be continued but some positive findings were observed in the short term. Continuing to measure soil organic matter should be considered essential. The more responsive indicators to a change in management appear to be Active Carbon (AC), with Solvita Labile-Amino Nitrogen (SLAN) as an indicator of soil nitrogen availability appearing more promising than Potentially Mineralizable Nitrogen (PMN). Solvita CO_2 respiration appears to be the slowest indicator to respond of the novel indicators but in contrast shows low variability, and pairs well with active carbon to better understand how available carbon might be cycling in the soil. The study baseline measurements included total nematode and parasitic nematode counts as an indicator of soil health but because of the high variability of the results and the relatively high cost of analysis, it was not continued and is not recommend for use at this time in Ontario. Similarly, the soil water infiltration test was also found to be highly variable with replication even within a small area, challenging the need for a suitable field test. The Autoclaved Citrate Extractable (ACE) soil protein test used in the 2022 monitoring campaign also shows promise as a relatively sensitive indicator of soil nitrogen dynamics, but with only one year of data, its responsiveness to BMP implementation has yet to be determined.

The ONFARM results are encouraging for the use of recommended indicators to show impacts from the BMPs tested. However, BMP treatment effects cannot be expected to result in consistent measured change in many of the SHIs in the timespan of the study. With two field seasons of BMP implementation completed, conclusions drawn from the SHI results should be considered preliminary – at least another three years are recommended to compare results over two crop rotations to determine the longer-term stability of these changes. What is also clear is that there is no one best indicator – identifying a group of indicators that best reflect soil health conditions in Ontario should continue to be a research goal.

Furthermore, the range of results across the various sites should be interpreted based on site details since response of SHI to specific BMPs can be influenced by pre-existing conditions and/or external factors including the type and degree of soil degradation, inherent soil capabilities, region/climate, soil texture, and management history. The practical use of SHIs for sampling of a field should consider representative zones of contrasting topography to allow for a range of results. Overall, the results demonstrate the need for continued monitoring of the ONFARM cooperator sites to further improve the understanding of indicator variability in developing a long-term dataset.

10.0 References

Black, C.A., 1986. Methods of Soil Analysis Part 1, America Society of Agronomy, SSSA, Madison Wisconsin

Carter, M.R., 1993. Soil Sampling and Methods of Analysis, Canadian Society of Soil Science, Lewis Publishers.

Goh, T.B. and A.R Mermut, 2007. Approximate Gravimetric Method. P. 217-218. In Soil Sampling and Methods of Analysis. Carter, M.R and E.G. Gregorich (eds) CSSS. Lewis Publishers, London;

NAPT. 1997. Soil Carbonates. P 92-93. Soil and Plant Analytical Methods.

Cornell University Comprehensive Assessment of Soil Health Laboratory Standard Operating Procedures, February 2016. Schindelbeck, R.R., B.N. Moebius-Clune, D.J. Moebius-Clune, K.S. Kurtz and H.M. van Es. http://www.css.cornell.edu/extension/soil-health/manual.pdf

Drinkwater, L., C.A. Cambardella, J.D. Reeder, C.W. Rice. 1996. Potentially Mineralizable Nitrogen as an Indicator of Biologically Active Soil Nitrogen. Methods for Assessing Soil Quality, 217-229. SSSA. Madison, WI.

Land Resource Science, University of Guelph, Soil Physics Laboratory Notes, Particle Size Analysis, 1984

Royal Eijkelkamp, 2022. Wet sieving apparatus, Manual. https://www.royaleijkelkamp.com/media/0v3hahtq/m-0813e-wet-sieving-apparatus.pdf

Ontario Ministry of Agriculture, Food and Rural Affairs, 2017. Agronomy Guide for Field Crops, Pub 811, p 202. https://www.ontario.ca/page/agronomy-guide-field-crops

Ontario Ministry of Agriculture, Food and Rural Affairs, Soil Fertility Handbook, 3rd Edition, Chapter 5; https://files.ontario.ca/omafra-soil-fertility-handbook-en-2022-10-13.pdf

McKeague, J.A. Ed., 1978, Manual of Soil Sampling and Methods of Analysis, 2nd Edition, 1978, Canadian Society of Soil Science

Solvita, SLAN Manual - Version 2019/N https://solvita.com/product/slan-manual/; hard copy available.

Solvita, Soil CO_2 – Burst Manual – SOP2019Rev.1 (DCR Models 701.2+) https://solvita.com/product/solvita-soil-co2-burst-manual/ ; hard copy available.

United States Department of Agriculture (USDA) 1999 . Soil Quality Test Guide. https://efotg.sc.egov.usda.gov/references/public/WI/Soil_Quality_Test_Kit_Guide.pdf

United States Golf Association, USGA, Green Section Record March/April 1993

Weil, R., K.R. Islam, M.A. Stine, J.B. Gruver, S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simple method for laboratory and field use. Amer. J. Alternative Agric. 18(1):3-17

Appendix 1: ONFARM Soil Health Report Guide to the Indicator Results

Soil Health Indicator Ratings and Interpretations

The Soil Health and Fertility Report for your site provides a table of the baseline soil health results from the benchmark sampling locations. The tables below will help with the interpretation of those results. The last column in the table provides the surface soil texture. Use this texture in the tables below where the ratings are broken out by soil texture. All samples except the bulk density measurement were taken from a 0 to 6 inches (0 to 15 cm) sample. Some of the ratings are taken from U.S. sources as there currently is not enough data to develop Ontario ratings.

Organic Matter (biological indicator)

The following table was taken from the Agronomy Guide for Field Crops, Ontario Ministry of Agriculture, Food and Rural Affairs Publication 811 Table 8-6, page 202. http://www.omafra.gov.on.ca/english/crops/pub811/p811toc.html It states "Soils with adequate organic matter levels will be more productive, have better aggregate stability and nutrient cycling. Producers should try to improve the organic matter levels of soil rated "poor" or "fair" to the good category."

	Organic Matter Rating (%)			
Soil Texture	**Poor**	**Fair**	**Good**	**Very Good**
Sand (S)	< 1.2	1.2 – 2.0	2.1 – 3.0	> 3.0
Sandy loam (SL)	< 1.6	1.6 – 2.5	2.6 – 3.5	> 3.5
Loam (L)	< 2.1	2.1 – 3.0	3.1 – 4.0	> 4.0
Clay loam, clay (CL,C)	< 2.6	2.6 – 3.5	3.6 – 4.5	> 4.5

Active Carbon (biological indicator)

The active carbon rankings below were adapted from the Comprehensive Assessment of Soil Health, third edition, Cornell University. https://soilhealth.cals.cornell.edu/training-manual/ It states "Active carbon is an indicator of the small portion of soil organic matter that can serve as a readily available food and energy source for the soil microbial community, thus helping to maintain a healthy soil food web. Active carbon is positively correlated with percent organic matter, aggregate stability and with measures of biological activity." It is thought to be a more responsive indicator to management changes than organic matter.

	Active Carbon Rating (ppm)				
Soil Texture	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Coarse (S, LS, SL)	< 280	280 - 400	401 - 505	506 – 625	> 625
Medium (SCL, L, SiL, Si)	< 350	350 – 455	456 – 550	551 – 665	> 665
Fine (SC, CL, SiCL, SiC, C)	< 405	405 – 525	526 – 620	621 – 745	> 745

Solvita Measurements (biological indicators)
Solvita is a U.S. company that has developed ways to measure some biological indicators in the field and in the lab. The ratings below are taken from their website https://solvita.com (https://solvita.com/wp-content/uploads/2017/06/Solvita-TechMemo3.pdf)

Solvita CO_2-Burst measures the CO_2 release from a dried and rewetted sample for a given period of time. The indicator is a measure of soil respiration which is a measure of microbial activity. The more CO_2 released the more likely there is a larger, more active soil microbial community.

Solvita Labile Amino-Nitrogen Test (SLAN) measures organic nitrogen reserves present as amino-sugars in soil, those associated with organic matter. It should have some correlation to potentially mineralizable nitrogen.

	Solvita Rating (ppm)		
	Low	**Medium**	**High**
CO2-Burst	0 - 40	40 - 140	140 - 300
Labile Amino-Nitrogen Test (SLAN)	0 - 40	40 - 150	150 - 350

Potentially Mineralizable Nitrogen (PMN) (biological indicator)
The PMN rankings below were adapted from the Comprehensive Assessment of Soil Health, third edition, Cornell University. https://soilhealth.cals.cornell.edu/training-manual/ It states “Potentially Mineralizable Nitrogen (PMN) is an indicator of the capacity of the soil microbial community to convert (mineralize) nitrogen tied up in complex organic residues into the plant available form of ammonium. The PMN test provides us with one indication of the capacity of the soil biota to recycle organic nitrogen that is present into plant available forms.”

	Potentially Mineralizable Nitrogen (ppm)				
	Very Low	**Low**	**Medium**	**High**	**Very High**
PMN	< 10	10 - 14	15 - 18	19 - 21	> 21

Wet Aggregate Stability (physical indicator)
The wet aggregate stability rankings below were adapted from the Comprehensive Assessment of Soil Health, third edition, Cornell University. https://soilhealth.cals.cornell.edu/training-manual/ It states “Wet Aggregate Stability is a measure of the extent to which soil aggregates resist falling apart when wetted and hit by rain drops. Soils with low aggregate stability tend to form surface crusts and compacted surface soils, which can reduce air exchange and seed germination, increase plant stress and susceptibility to pathogen attack, and reduce water infiltration and thus storage of water received as rainfall.”

	Aggregate Stability Rating (%)				
Soil Texture	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Coarse (S, LS, SL)	< 23	23 - 35	36 – 46	47 - 60	> 60
Medium (SCL, L, SiL, Si)	< 17	17 - 27	28 – 36	37 - 46	> 46
Fine (SC, CL, SiCL, SiC, C)	< 21	21 – 30	31 – 40	32 – 51	> 51

Soil Bulk Density (physical indicator)
The bulk density ratings below are taken from the United States Department of Agriculture (USDA) Soil Quality Test Kit Guide https://efotg.sc.egov.usda.gov/references/public/WI/Soil_Quality_Test_Kit_Guide.pdf

It states “Bulk density is defined as the ratio of oven-dried soil (mass) to its bulk volume, which includes the volume of particles and the pore space between the particles. Compacted soil layers have high bulk densities, restrict root growth, and inhibit the movement of air and water through the soil. Soil bulk density can serve as an indicator of compaction and relative restrictions to root growth. Typical soil bulk densities range from 1.0 to 1.7 g/cm3, and generally increase with depth in the soil profile.” The measurements were taken in the top 2 inches (5 cm) of the soil.

	Bulk Density Rating (g/cm^3)		
Texture	**Ideal**	**May affect root growth**	**Restrict root growth**
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.30	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, some clay loams (35-45% clay)	< 1.10	1.49	> 1.58
Clays (>45% clay)	< 1.10	1.39	> 1.47

Nematodes

The nematode samples were taken from a 2 to 8 inches (5 to 20 cm) depth. The soil was analyzed for the total number of nematodes and for each individual group of parasitic nematodes. In a soil there are many different species of nematodes, both parasitic and beneficial. Researchers in Ontario are still trying to understand what constitutes a healthy nematode population and what might be a good ratio of the beneficial or parasitic nematodes. In the report, the total number of nematodes is reported and the number of root lesion nematodes if they were over the economic threshold in one or more of the samples (see OMAFRA’s Factsheet 628: Sampling Soil and Roots for Plant Parasitic Nematodes http://www.omafra.gov.on.ca/english/crops/facts/06-099.htm#economic). In most cases they were just over the threshold or were limited to a few benchmarks. At most sites the average number of root lesion nematodes was below the threshold. We will provide further information on the nematode counts in future updates.

Autoclaved Citrate Extractable (ACE) Protein (biological indicator)

The ACE protein rankings below were adopted from the Comprehensive Assessment of Soil Health, third edition, Cornell University https://soilhealth.cals.cornell.edu/manual/. It states “Autoclaved Citrate Extractable (ACE) Protein Index is an indicator of the amount of protein-like substances that are present in the soil organic matter. ACE represents the large pool of organically bound nitrogen (N) in the soil organic matter, which microbial activity can mineralize, and make available for plant uptake. Protein content is well associated with overall soil health status because of its indication of biological and chemical soil health, in particular, the quality of the soil organic matter (SOM).”

	ACE Protein Rating (ppb)				
Soil Texture	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Coarse (S, LS, SL)	<4200	4201-6400	6401-8200	8201-10300	>10301
Medium (SCL, L, SiL, Si)	<3500	3501-5700	5701-7200	7201-9200	>9201
Fine (SC, CL, SiCL, SiC, C)	<3200	3201-5200	5201-6600	6601-8500	>8500

Appendix 2: ONFARM Single Factor Anova Summaries for 2020, 2021, 2022

Blue boxes indicate a significant effect at *p<0.1*

ONFARM 2020 Summary of SH Test by Landscape Position

SH Test*	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
Site										
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										no data
Total Sign	17	16	18	17	13	16	6	11	2	12

* OM= Organic Matter, AC= Active Carbon, SLAN= Solvita Labile Amino-Nitrogen, PMN=Potentially Mineralizable Nitrogen, AggStab= Aggregate Stability, BD= Bulk Density

ONFARM 2020 Summary of SH Test by Treatment Strip

SH Test*	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
Site										
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										no data
Total Sign	10	9	4	7	5	8	3	6	10	6

ONFARM 2021 Summary of SH Test by Landscape Position

SH Test*	OM	AC	Solvita	SLAN	BD	Yield
Site						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
Total Sign	18	14	14	19	11	10

ONFARM 2021 Summary of SH Test by Treatment Strip

SH Test*	OM	AC	Solvita	SLAN	BD	Yield
Site						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
Total Sign	2	9	7	3	2	7

ONFARM 2022 Summary of SH Test by Landscape Position

SH Test*	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
Site									
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16								No data	
17									
18									
19									
20									
21									
22									
23									
24									
25									
Total Sign	23	19	15	22	13	19	14	13	22

ONFARM 2022 Summary of SH Test by Treatment Strip

SH Test*	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
Site									
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16								No data	
17									
18									
19									
20									
21									
22									
23									
24									
25									
Total Sign	12	12	15	13	15	10	11	19	7

2020 ONFARM SHI Correlations for regions and soil texture categories

2020 Correlation Coefficients for SH Indicators in Lake Erie East (n=180)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.4624									
Solvita	0.3402	0.3800								
SLAN	0.6511	0.4285	0.4982							
PMN	0.5131	0.0250	0.2841	0.4596						
AggStab	0.6648	0.2211	0.5477	0.5825	0.6070					
Infiltration	0.1854	-0.0852	0.1209	0.1779	0.3286	0.3144				
BD	-0.4642	-0.1009	0.0976	-0.2234	-0.3108	-0.2939	-0.2017			
Nematodes	-0.0797	-0.0983	-0.1856	-0.0950	-0.1071	-0.2299	0.0285	-0.1568		
Yield	0.4336	-0.0717	-0.0865	0.1401	0.1713	0.1337	-0.1931	-0.3375	-0.0560	

2020 Correlation Coefficients for SH Indicators in Lake Erie East (n=180)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.0194									
Solvita	0.5288	0.1998								
SLAN	0.1700	0.1045	0.5479							
PMN	0.6205	-0.0233	0.5088	0.1654						
AggStab	0.4510	0.4837	0.4193	0.3856	0.4477					
Infiltration	-0.2540	0.0383	-0.1896	-0.2074	-0.2446	-0.1575				
BD	0.3942	-0.3544	0.3026	0.2161	0.5309	0.0735	-0.3892			
Nematodes	-0.2466	-0.1451	-0.1608	-0.1980	-0.2004	-0.3625	0.2416	-0.1103		
Yield	**-0.7442**	-0.1932	-0.3880	-0.1918	-0.6064	-0.6603	0.3923	-0.5485	0.4405	

2020 Correlation Coefficients for SH Indicators in Western (n=171)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.2870									
Solvita	0.2415	0.1856								
SLAN	**0.7648**	0.3836	0.4020							
PMN	0.3947	0.0901	0.1108	0.2789						
AggStab	0.5579	0.1900	0.2137	0.5545	0.1415					
Infiltration	0.0338	-0.1234	-0.1845	-0.1401	0.3967	-0.1516				
BD	-0.3911	-0.2090	-0.1691	-0.5295	-0.5284	-0.2870	-0.1371			
Nematodes	-0.0713	0.0118	-0.4458	-0.0495	-0.1787	-0.0176	-0.1384	0.0182		
Yield	0.1603	0.1175	0.0691	0.2886	0.5543	0.0794	0.2838	**-0.7410**	-0.0314	

2020 Correlation Coefficients for SH Indicators in Central (n=189)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.6191									
Solvita	0.1754	0.2694								
SLAN	0.4022	0.5552	0.4243							
PMN	0.1038	0.3122	0.2873	0.4481						
AggStab	0.0866	-0.0688	-0.2918	-0.0438	0.0369					
Infiltration	0.2070	0.2116	0.1033	0.1285	0.0407	0.0222				
BD	-0.3040	-0.3379	-0.2422	-0.2827	-0.2168	0.0382	-0.1173			
Nematodes	-0.2230	-0.1764	0.0281	-0.0503	-0.0272	-0.1665	-0.0926	0.0937		
Yield	0.4935	0.2886	-0.1185	0.1118	-0.0461	0.3215	0.1442	0.0317	-0.0755	

2020 Correlation Coefficients for SH Indicators in Eastern (n=171)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	**0.7608**									
Solvita	0.3314	0.4105								
SLAN	**0.9294**	**0.8236**	0.4496							
PMN	0.6885	0.4875	0.6075	**0.7216**						
AggStab	0.4203	0.4666	0.3982	0.5452	0.4503					
Infiltration	0.1205	0.0622	0.2858	0.1097	0.3142	0.1885				
BD	-0.6733	-0.5988	-0.4162	-0.7023	-0.6597	-0.4365	-0.1821			
Nematodes	-0.0474	-0.1161	-0.2559	-0.1281	-0.1363	-0.1273	0.0087	0.1497		
Yield	0.3042	0.3072	0.0263	0.3163	0.3736	0.2836	0.2149	-0.2551	-0.0741	

2020 Correlation Coefficients for SH Indicators at Fine (n=207)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.5974									
Solvita	0.3481	0.229								
SLAN	0.5460	0.6306	0.29292							
PMN	0.0159	0.11022	0.59758	0.15202						
AggStab	0.4157	0.1676	0.49027	0.22202	0.31216					
Infiltration	-0.00487	0.12602	0.01029	0.10076	0.04294	-0.0527				
BD	-0.17944	-0.46169	-0.03357	-0.33226	-0.11389	0.23019	-0.52421			
Nematodes	-0.0133	0.09572	-0.10234	0.09605	-0.04971	0.01492	-0.00043	0.07081		
Yield	-0.3951	0.00427	0.08503	0.07385	0.48783	-0.06984	0.2162	-0.24541	0.05965	

2020 Correlation Coefficients for SH Indicators at Fine Loamy (n=144)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.62542									
Solvita	0.56539	0.62765								
SLAN	**0.85388**	**0.72376**	0.56633							
PMN	0.65074	0.17787	0.32364	0.6108						
AggStab	0.34335	-0.07331	0.23794	0.16916	0.34693					
Infiltration	0.4474	-0.17036	0.1318	0.36683	0.63383	0.36735				
BD	-0.54569	-0.45971	-0.34168	-0.69785	-0.47116	0.03166	-0.35962			
Nematodes	0.19226	0.03871	0.03021	0.14974	0.14685	0.03866	0.20577	-0.21121		
Yield	-0.09052	0.25136	-0.00333	-0.09163	-0.33706	-0.08709	-0.60412	0.2342	-0.10359	

2020 Correlation Coefficients for SH Indicators at Coarse Loamy (n=468)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.30731									
Solvita	0.19916	0.24109								
SLAN	0.57406	0.41873	0.52088							
PMN	0.36388	0.16231	0.52308	0.56126						
AggStab	0.31308	0.30455	0.15877	0.3402	0.30968					
Infiltration	0.10572	0.00005	-0.17036	-0.02121	-0.07977	-0.01135				
BD	-0.26205	-0.32374	0.00374	-0.23729	-0.16565	-0.21554	-0.31489			
Nematodes	-0.06224	-0.10779	-0.04661	-0.04487	0.00035	-0.13092	-0.06236	0.02024		
Yield	0.39591	0.16726	0.04939	0.35439	0.29876	0.45033	-0.03216	-0.11725	0.03434	

2020 Correlation Coefficients for SH Indicators at Coarse (n=72)

	OM	AC	Solvita	SLAN	PMN	AggStab	Infiltration	BD	Nematode	Yield
OM										
AC	0.53067									
Solvita	0.65268	0.6002								
SLAN	0.46373	0.46088	0.48379							
PMN	0.35798	0.48903	0.60086	0.15955						
AggStab	0.56155	0.39847	0.58511	0.31151	0.38107					
Infiltration	-0.11082	-0.0437	-0.14429	-0.09395	-0.2578	0.06615				
BD	0.03755	-0.28448	-0.06183	-0.02824	0.24231	0.14294	-0.23852			
Nematodes	-0.17157	-0.15483	-0.14925	-0.02333	-0.16582	-0.14773	0.14779	-0.50247		
Yield	-0.17715	0.172	-0.07122	-0.04027	-0.32193	-0.30318	0.22137	**-0.76131**	0.36975	

2021 ONFARM SHI Correlations for regions and soil texture categories

2021 Correlation Coefficients for SH Indicators in Lake Erie West (n=180)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.63018					
Solvita	0.26003	0.33941				
SLAN	**0.77872**	0.63806	0.31114			
BD	-0.20057	-0.34722	0.2691	-0.27185		
Yield	0.11215	-0.01552	0.06202	0.29528	0.13647	

2021 Correlation Coefficients for SH Indicators in Lake Erie East (n=180)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.63825					
Solvita	**0.74317**	**0.7885**				
SLAN	0.58018	0.59261	0.65381			
BD	0.20152	0.03978	0.13253	-0.1172		
Yield	-0.42	-0.35893	-0.37977	-0.5623	0.02641	

2021 Correlation Coefficients for SH Indicators in Western (n=171)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.58224					
Solvita	0.49891	0.36927				
SLAN	**0.74987**	0.58662	0.56556			
BD	-0.33787	-0.49496	-0.22762	-0.29827		
Yield	0.38968	0.15572	-0.17506	0.30916	-0.00982	

2021 Correlation Coefficients for SH Indicators in Central (n=189)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.38405					
Solvita	0.35998	0.27853				
SLAN	0.34108	0.5158	0.35166			
BD	-0.14488	-0.19159	-0.20984	0.12342		
Yield	-0.38424	0.08088	0.12107	0.6053	0.11097	

2021 Correlation Coefficients for SH Indicators in Eastern (n=171)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	**0.74338**					
Solvita	0.54103	0.56281				
SLAN	0.6448	0.67818	**0.76835**			
BD	-0.50436	-0.54206	-0.27952	-0.20668		
Yield	-0.087	0.00759	0.37718	0.48168	0.29179	

2021 Correlation Coefficients for SH Indicators at Fine (n=207)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.48271					
Solvita	0.28424	0.42844				
SLAN	0.46884	0.69932	0.62925			
BD	-0.52222	-0.36175	0.01061	-0.20708		
Yield	-0.31641	-0.13364	0.47149	0.1495	**0.76131**	

2021 Correlation Coefficients for SH Indicators at Fine Loamy (n=144)						
	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.57502					
Solvita	0.41704	0.68425				
SLAN	**0.76448**	0.65236	0.51991			
BD	-0.20692	-0.53359	-0.36462	-0.38642		
Yield	-0.24538	0.16111	0.13265	0.00624	-0.21575	

2021 Correlation Coefficients for SH Indicators at Coarse Loamy (n=468)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.60424					
Solvita	0.44645	0.36792				
SLAN	**0.72028**	0.59576	0.47927			
BD	-0.29707	-0.27975	-0.09195	-0.31309		
Yield	-0.21943	-0.1104	-0.08471	0.1146	-0.00495	

2021 Correlation Coefficients for SH Indicators at Coarse (n=72)

	OM	AC	Solvita	SLAN	BD	Yield
OM						
AC	0.59317					
Solvita	**0.73823**	0.64669				
SLAN	0.57086	0.39451	0.3956			
BD	0.02884	0.13194	0.19362	-0.34036		
Yield	-0.37874	-0.29355	-0.55008	0.37052	-0.44883	

2022 ONFARM SHI Correlations for regions and soil texture categories

Correlation Coefficients for SH Indicators in Lake Erie West (n=180)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.74677**								
Solvita	0.61776	0.48839							
SLAN	**0.85437**	0.62564	0.61125						
PMN	0.25647	-0.11217	0.39335	0.35729					
AggStab	0.60297	0.31617	0.48564	0.64023	0.3867				
BD	-0.19402	-0.14694	0.12576	-0.3055	0.11035	-0.31576			
Yield	-0.06117	0.09247	-0.24334	0.00409	-0.08546	0.04548	-0.38053		
Ace	**0.80377**	**0.7366**	0.31345	0.66357	-0.04918	0.38142	-0.44309	0.16524	

Correlation Coefficients for SH Indicators in Lake Erie East (n=180)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	0.5106								
Solvita	0.57969	0.46158							
SLAN	0.69253	0.52674	0.60103						
PMN	0.34801	0.52918	0.5147	0.38415					
AggStab	0.39839	0.30603	0.27273	0.32807	0.20052				
BD	0.22831	0.27967	0.31567	0.14916	0.21927	0.19687			
Yield	-0.55562	-0.09224	-0.18593	-0.23329	-0.11775	-0.14602	-0.28819		
Ace	0.22436	0.24227	0.20492	0.37835	-0.01432	0.18306	-0.35553	0.469	

Correlation Coefficients for SH Indicators in Western (n=171)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.89898**								
Solvita	0.56991	0.49278							
SLAN	0.65264	0.57414	0.55958						
PMN	0.63933	0.57336	0.34693	0.06319					
AggStab	0.26017	0.13738	0.20096	0.38211	0.0571				
BD	-0.67332	-0.62585	-0.37153	-0.3701	-0.6123	0.00397			
Yield	-0.22488	-0.1365	-0.15758	-0.16018	-0.20565	-0.43952	0.00449		
Ace	**0.79594**	**0.76664**	0.57808	0.67558	0.39156	0.2093	-0.49089	-0.22459	

Correlation Coefficients for SH Indicators in Central (n=189)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.77719**								
Solvita	0.22321	0.24461							
SLAN	0.28217	0.3361	0.38551						
PMN	0.17836	0.25436	-0.05446	-0.13654					
AggStab	0.1451	0.01447	0.20989	0.31363	-0.44111				
BD	-0.06087	-0.07257	-0.14399	-0.11306	-0.37904	0.04224			
Yield	0.61515	0.44957	-0.32541	-0.00015	0.41276	-0.11862	0.0084		
Ace	0.56758	0.57628	0.45965	0.3322	0.26829	-0.11122	-0.17058	-0.01895	

Correlation Coefficients for SH Indicators in Eastern (n=171)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.83787**								
Solvita	0.42076	0.65849							
SLAN	0.63868	**0.74726**	0.60723						
PMN	0.09013	0.12377	0.19036	-0.09734					
AggStab	0.51094	0.64065	0.55319	**0.72116**	0.09398				
BD	-0.48683	-0.54638	-0.37731	-0.31906	-0.37681	-0.44652			
Yield	0.26914	0.38611	0.30194	0.49194	-0.07114	0.2121	-0.06234		
Ace	**0.7161**	**0.75921**	0.60941	**0.76567**	0.20863	0.67362	-0.388	0.35666	

Correlation Coefficients for SH Indicators at Fine (n=207)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.69234**								
Solvita	0.22767	0.38485							
SLAN	0.61871	0.53394	0.40301						
PMN	-0.03135	0.20801	0.30609	0.04237					
AggStab	0.46664	0.30195	0.29621	0.5167	-0.06855				
BD	-0.44077	-0.41341	-0.05704	-0.24154	-0.07126	-0.37773			
Yield	0.13786	0.29226	0.06385	0.13589	0.25591	0.17968	-0.65841		
Ace	**0.73717**	0.66895	0.33256	0.68498	0.15208	0.38495	-0.50749	0.49507	

Correlation Coefficients for SH Indicators at Fine Loamy (n=144)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.87254**								
Solvita	0.56498	0.5871							
SLAN	**0.76959**	0.66669	0.5319						
PMN	0.10647	-0.01177	0.09973	-0.08004					
AggStab	0.52454	0.44532	0.51913	0.67004	-0.05102				
BD	-0.52026	-0.3768	-0.12537	-0.50041	-0.34046	-0.3026			
Yield	0.12695	0.12997	-0.34326	0.13416	-0.17288	-0.19766	-0.27022		
Ace	**0.84401**	**0.72758**	0.598	**0.82625**	0.02055	0.69328	-0.46938	0.038	

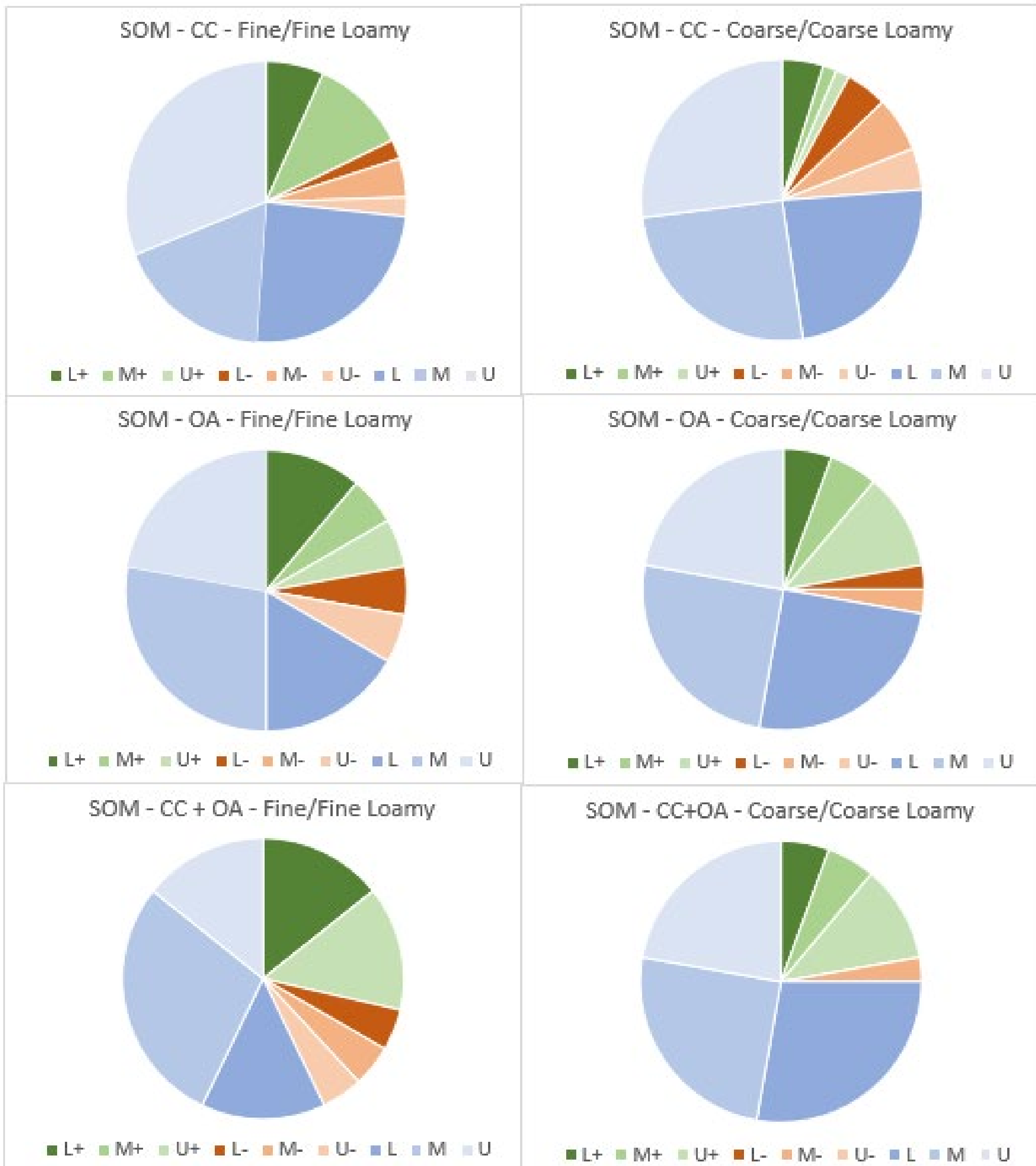
Correlation Coefficients for SH Indicators at Coarse Loamy (n=468)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.72801**								
Solvita	0.30841	0.42709							
SLAN	0.6496	0.57868	0.4839						
PMN	0.17415	0.08484	0.08804	0.04137					
AggStab	0.20414	0.1225	0.43381	0.25418	-0.14448				
BD	-0.28231	-0.25106	0.01306	-0.25122	-0.18726	0.17313			
Yield	0.38373	0.23649	-0.12023	0.17687	0.39435	-0.18571	-0.20996		
Ace	**0.7182**	0.64288	0.3132	0.56594	0.25712	-0.00624	-0.35227	0.18085	

Correlation Coefficients for SH Indicators at Coarse (n=72)

	OM	AC	Solvita	SLAN	PMN	AggStab	BD	Yield	Ace
OM									
AC	**0.8269**								
Solvita	0.61009	0.44939							
SLAN	0.61769	0.51178	0.48236						
PMN	0.39196	0.41612	0.21852	0.21898					
AggStab	0.69352	0.45738	0.48561	0.52906	0.05368				
BD	-0.02199	-0.19213	0.30341	0.07424	-0.52052	0.42332			
Yield	0.07099	0.23976	-0.18527	0.02637	0.45131	-0.29011	**-0.73111**		
Ace	0.62641	**0.71336**	0.23837	0.33944	**0.73355**	0.25132	-0.5814	0.57391	

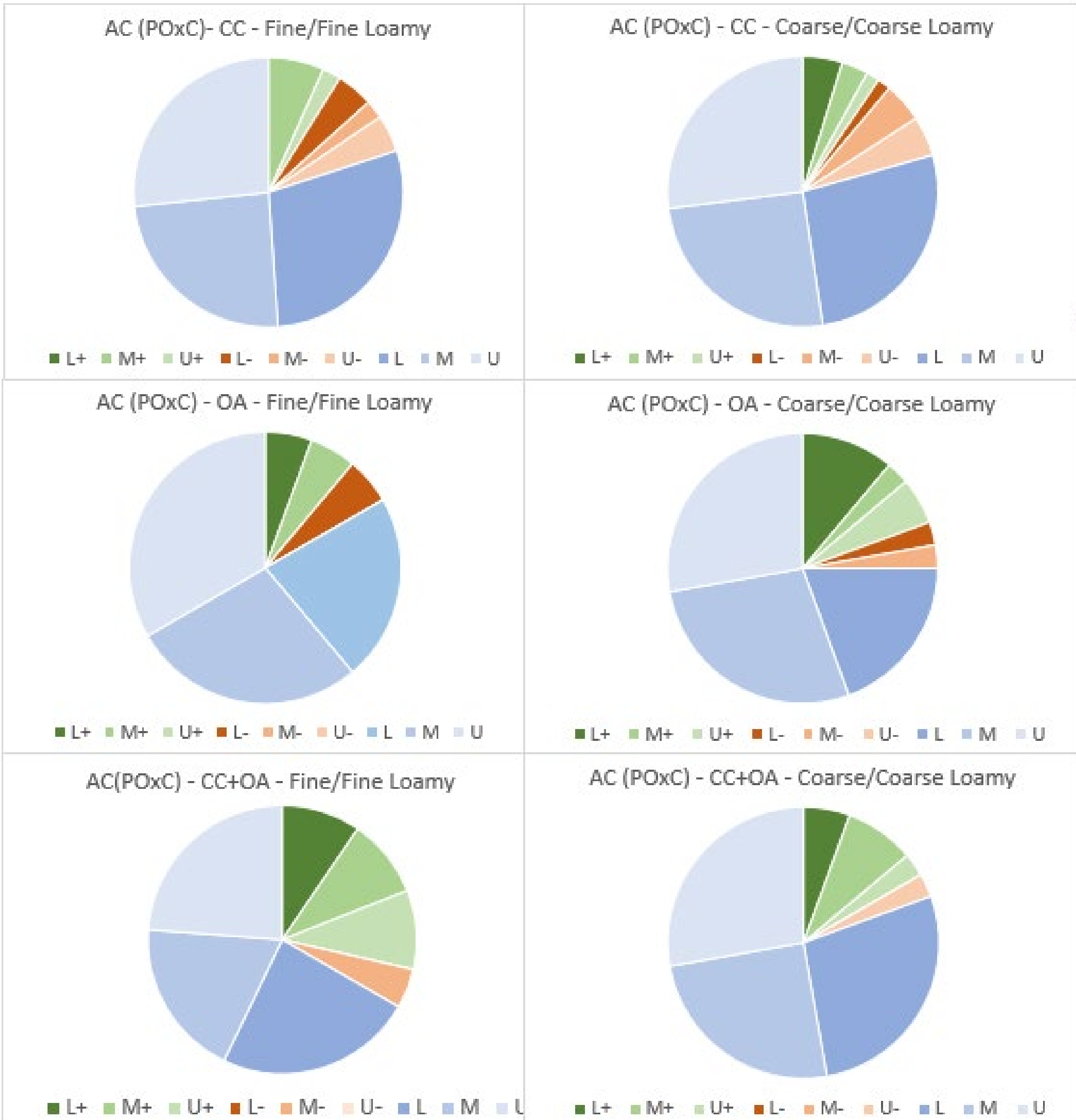
Appendix 3: ONFARM Multivariate Analysis Summaries for Soil Health Indicators 2022



Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and ‘+’, significant negative change in red shades and ‘-’, no significant change in blue shades.

Multivariate covariate analysis of change in organic matter (SOM) as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks.

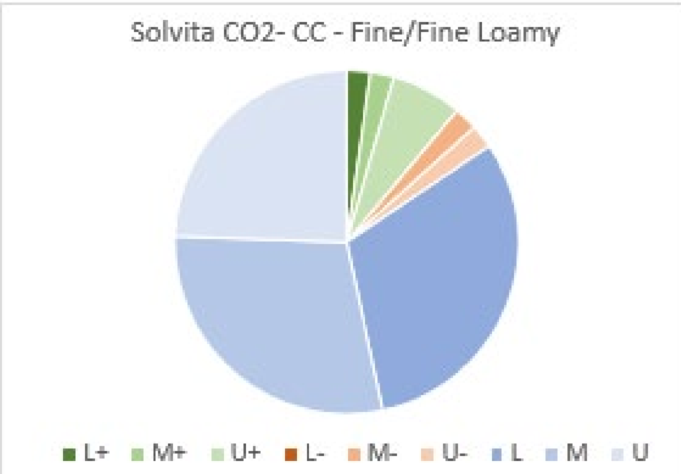
In both soil groups, SOM showed more significant positive than negative interactions when OAs were applied.   CC alone resulted in some negative interactions, particularly in the coarser textures.

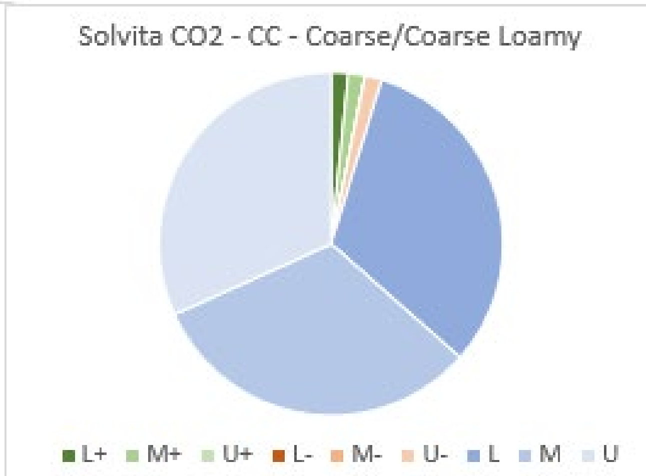


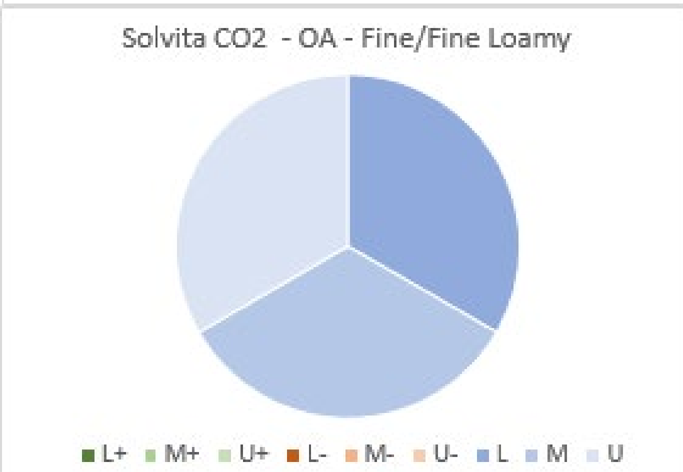
Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

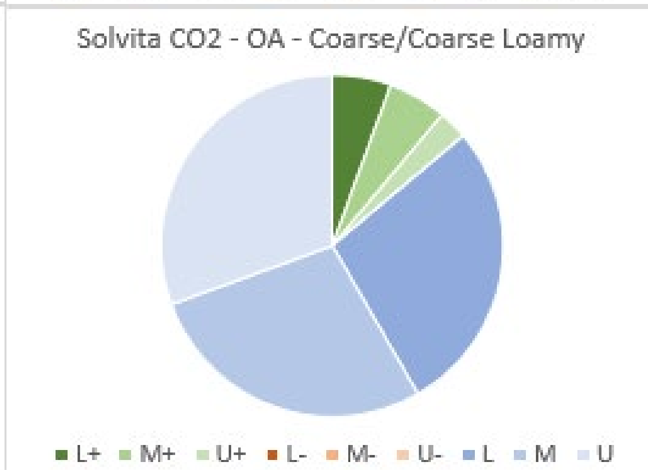
Multivariate covariate analysis of change in active carbon (AC) as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks.

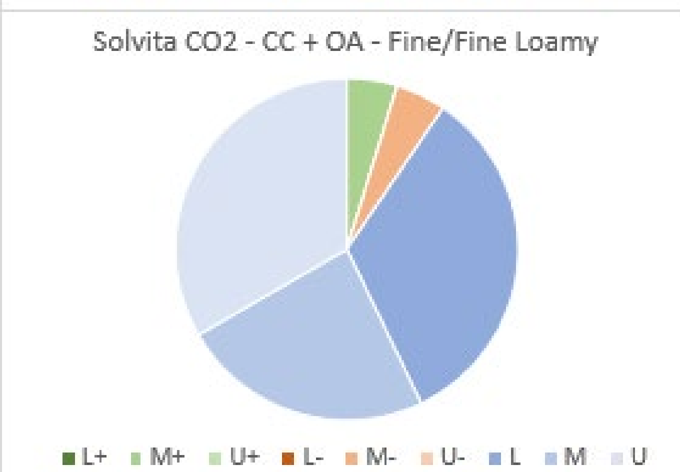
Besides SOM, AC was the SHI that showed the highest number of significant positive responses to BMP implementation. CC resulted in slightly more significant negative than positive interactions in both texture groups. OA resulted in more positive than negative interactions

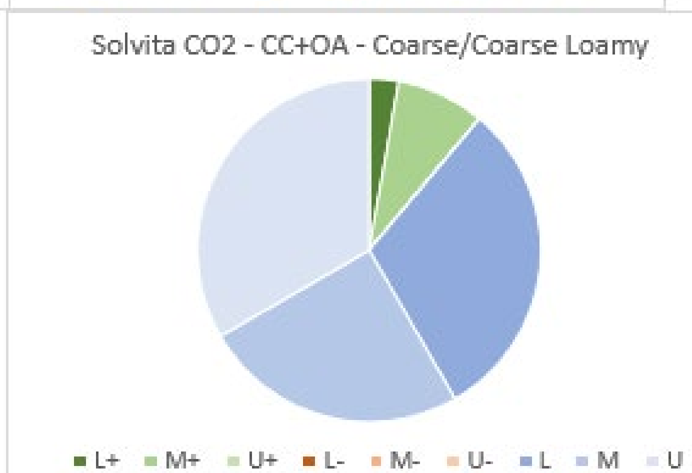












Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

Multivariate covariate analysis of change in Solvita CO_2 as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks.

There were fewer significant impacts on the Solvita CO_2 than on the other indicators. OA with/without CC had positive impacts in the coarser soils. CC had more positive than negative impacts in the finer soils.

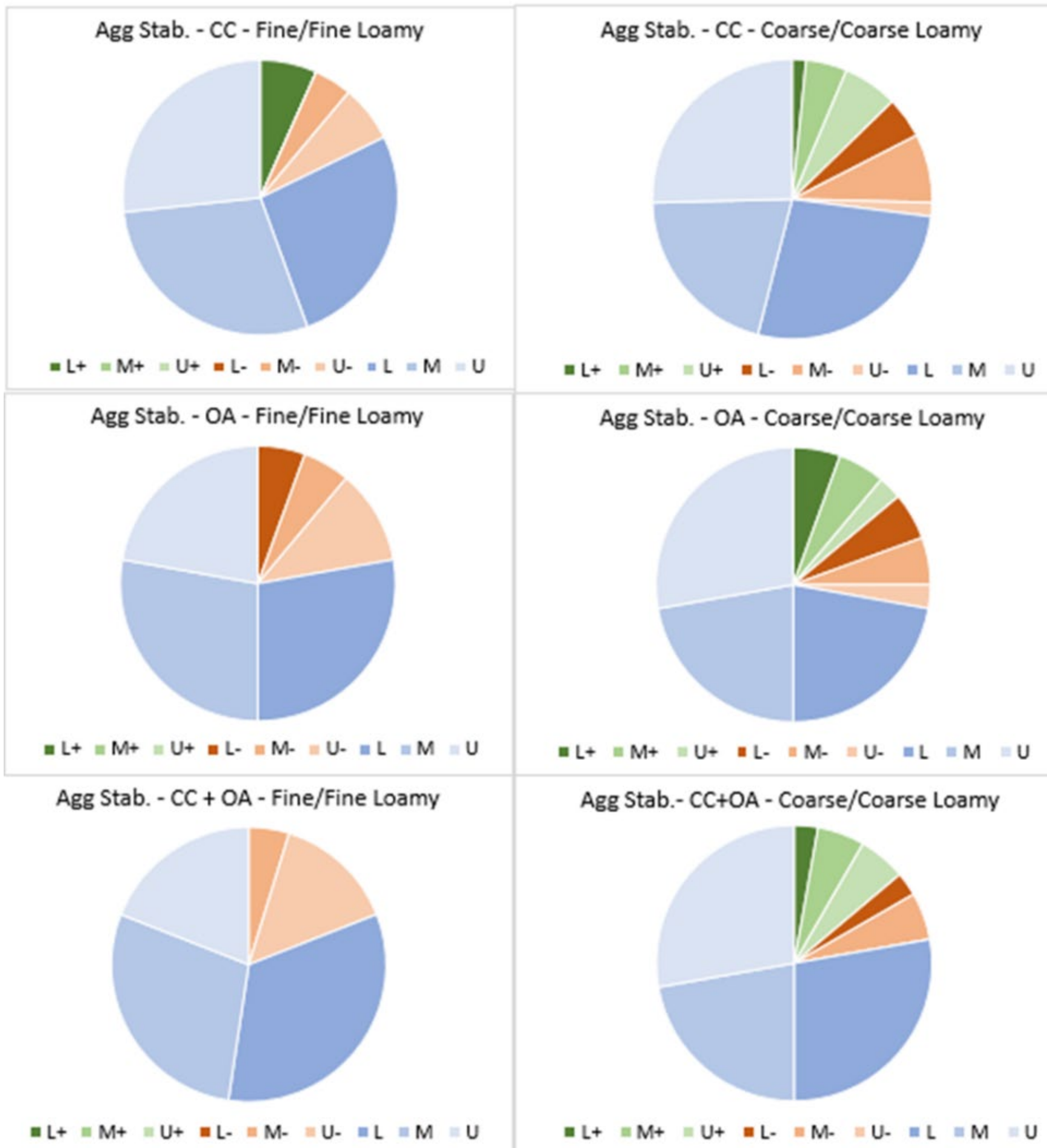
Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

Multivariate covariate analysis of change in Solvita Labile Amino Nitrogen (SLAN) as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks.

Significant positive and negative impacts resulted from CC alone in both soil groupings. OA with and without CC resulted in fewer negative and more positive impacts in the coarser textured soils.

Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

OA with or without CC resulted in more positive than negative impacts in the coarser soils. The finer textured soils had relatively more significant negative impacts on PMN with all treatments compared to the coarser textured soils.



Legend: landscape position as Lower (L), Middle (M), and Upper (U); significant positive change in green shades and '+', significant negative change in red shades and '-', no significant change in blue shades.

Multivariate covariate analysis of change in aggregate stability (AggStab) as proportion of landscape position*BMP treatment interaction effect and soil texture combinations for all benchmarks.

CC had both significant positive and negative impacts on AggStab in both soil groupings. OA with or without CC had only negative impacts on AggStab in the finer textures, but both positive and negative impacts in the coarser soils.