Measuring Soil Health on Working Farms: A Soil Health Partnership Approach
Table of Contents

Executive Summary ...................................................................................................3

Background ..................................................................................................................4

SHP’s Approach to On-Farm Soil Health Monitoring ...........................................5

Highlights of Findings to Date ................................................................................7

Discussion and Conclusions .................................................................................14

References...................................................................................................................15

Authors

Lin Liu
GEMS Informatics Center, University of Minnesota–Twin Cities, Saint Paul, MN; Soil Health Partnership, National Corn Growers Association, Chesterfield, MO

Stephen Wood
The Nature Conservancy, Arlington, VA; Yale School of the Environment, New Haven, CT

Bradley Crookston
Matt Yost
Plants, Soils, and Climate Department, Utah State University, Logan, UT

Maria Bowman
Former Lead Scientist, Soil Health Partnership, National Corn Growers Association, Chesterfield, MO
Executive Summary

Soil health refers to the capacity of soil to function. A healthy soil is vital for farm profitability, sustainable crop production, nutrient and water cycling, and climate regulation. Soil health assessment is designed to evaluate soil quality in supporting land productivity, as well as management sustainability in the context of soil functions. Several soil properties have been identified as indicators for soil health. Scientists have been conducting extensive studies on measuring soil health in research plots under various soil health management treatments. A majority of the studies are either led by researchers or co-led with farmers, but soil health tests and practices are not yet widely adopted by farmers. Soil health needs to be addressed in the context of the risks and benefits of soil health practices for widespread adoption of the conservation management practices. Soil Health Partnership (SHP) was founded to fill this gap. SHP was established as a farmer-led research network with a mission of promoting the adoption of soil health practices for economic and environmental benefit.

In this white paper, we first describe SHP’s approach to measuring soil health on working farms. We then describe soil health of the fields in our network and the influence of cover crop practices on soil health indicator values. Lastly, we discuss opportunities for future work to examine interactions between soil health practices, indicators, and outcomes. The results we present in this white paper draw on work conducted by researchers at Soil Health Partnership, the University of Minnesota–Twin Cities, The Nature Conservancy, and Utah State University.

Several key takeaways emerged from analyzing a dataset of 1,522 strip-year observations, spanning 78 unique farms in nine states over two to five years in the SHP network:

- Soils are different in texture and in soil health indicators across the fields in our network.
- The most common soil textures in the network are silty loam, loam, and silty clay loam.
- Soil texture affects the levels of soil health indicators, particularly organic matter, active carbon, and available water capacity.
- Growing cover crops in between cash crops enhances soil health, particularly in terms of soil organic matter, active carbon, aggregate stability, and respiration, and these positive effects increase with time.
- Management practices can take time to have measurable soil-health benefits and are not always economically or agronomically relevant in the short-term.
- Changes in soil health alone may not be enough to motivate farmer adoption of soil health practices.
Soil health refers to the capacity of a soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health. While crop productivity has been much boosted with advancements in plant genetics and machinery, soil resource conservation is often overlooked. Because of the urgent need to preserve soil and to incentivize conservation practices in U.S. agriculture, scientists at the U.S. Department of Agriculture initiated a conceptual framework of soil health (Karlen et al., 1997). Decades ago, soil health was discussed in the context of soil functions, with a heavy focus on crop yield and erosion. Unsurprisingly, soil physical (e.g., bulk density and infiltration rate) and chemical (e.g., available nutrient and forms of nitrogen) properties were the focus of early soil health indicators (Karlen et al., 1997; Karlen et al., 2019). Over time, this concept has evolved, with incorporation of soil biology and the role of management practices. In the updated soil health concept, soils are viewed as a dynamic and living system, whose functions are affected by crops, soil organisms, and management. What accompanied the evolving soil health concept is a more holistic effort to simultaneously manage and improve a set of physical, chemical, and biological indicators by utilizing soil health scoring functions and assessments (Doran and Zeiss, 2000). This, in turn, spotlights soil properties that are subject to change by management practices over a relatively short period of time. Soil health indicators, such as active carbon, are now included in the soil health assessment framework (Moebius-Clune et al., 2016; Stott 2019). Nowadays, soil health is an assessment of overall soil quality, and the changes in soil health over time can be a reflection of how sustainable the land management practices are.

Because of the usefulness of soil health in monitoring soil quality and management sustainability, scientists have developed several frameworks to quantify soil health. Most soil health assessment frameworks are founded on three underlying steps: selecting soil health indicators, scoring individual soil health indicators, and integrating soil health indicators into a single soil health index (Rinot et al., 2019). Three predominant methodologies for soil health assessment are the Soil Health Assessment Framework (SMAF) and the related Comprehensive Assessment of Soil Health (CASH), along with the Haney Soil Health Test (HSHT). Soil health tests have been conducted for both research plots and commercial fields across different geographies and cropping systems in the United States (Fine et al., 2017; van Es and Karlen, 2019). Scientists from the U.S. Department of Agriculture and the land-grant universities have completed extensive work on evaluating soil health indicators and the use of soil health to evaluate management sustainability (Karlen et al., 2019; Sprunger et al., 2020; Yost et al., 2018). In spite of soil health test popularity among researchers, the tests are not widely adopted by farmers. Soil Health Partnership (SHP) was established to address this gap.

SHP was established in 2014 to improve adoption of soil health monitoring and management by “measuring and communicating economic and environmental benefits of different soil management strategies, and providing a set of regionally specific, data-driven recommendations that farmers can use to improve the productivity and sustainability of their farms.” The foundation of SHP’s approach was measuring and monitoring soil health using several different indicators and frameworks in order to evaluate how management practices such as cover crops and reduced tillage might improve soil health.

To this end, SHP performs soil testing for both soil chemical properties and soil health indicators at different spatial and temporal intensities during a farmer’s tenure in the program. The goal is to evaluate baseline soil health, and to monitor changes in soil health over time in response to the farmer’s soil health management practices. This unique dataset presents an opportunity to broaden our understanding of the distribution and variability of measured soil health indicators on working farms. This dataset also allows us to assess the sensitivity of these indicators to soil health management, and to begin contextualizing how soil health indicators might be used by farmers to make short- and long-term management decisions that enhance soil health, productivity, and resilience on their farming operations.

The purpose of this paper is to provide a brief description of SHP’s approach to evaluating soil health, and to present results from analysis of soil health data.
SHP's Approach to On-Farm Soil Health Monitoring

During the enrollment phase, a field manager works with the farmer to determine a field and the soil health practices to be trialed. Farmers select one or more management practices to trial on their farms for a contracted duration (3-5 years). Currently, a majority of farmers (about 82%) in the SHP network are trialing cover crops, and a small number of fields are testing other soil health practices, such as no- or reduced tillage, and varied N application rates.

Figure 1: Illustrations of soil health experimental plot setup and soil sampling locations in two layouts: (a) strip trial and (b) side-by-side

Trial design

SHP offers strip trial and side-by-side trial designs to systematically evaluate the effect of the soil health practices on soil health (Figure 1). SHP field managers work with an individual farmer to implement the farmer-selected soil-health practice(s) in either of the trial designs. Strip trials are commonly arranged as eight strips (n=4 for treatment and control strips, respectively) (Figure 1a). In a side-by-side layout, the selected field is divided into two parts, where the soil health practice is implemented on one portion of the field and business-as-usual practice on the other half of the field (Figure 1b). Although splitting the field in half is common, farmers may allocate as much as 80% of the field area to the treatment.

During the course of the program (3-5 years), SHP staff and partners gather data from the farmer and from the enrolled field (Table 1). When a farm enrolls, the field manager gathers basic information about their operation and trial layout; SHP staff also create a trial map and soil sample points for the field. Soil sampling points in the strip trial are laid out in a one-acre grid across the field, with the points generally in the center of the trial strips. Soils are collected from each point in the strip to be combined in a composite sample for that specific treatment or control strip. In side-by-side trials, the point locations are chosen to represent the major soil series within the field, taking into account topography and field conditions. In the spring, field managers collect a baseline soil sample, along with on-site management information, prior to trial implementation. Yield and management information are collected every year whereas soil health tests are conducted every other year (for example in years 1, 3, and 5 of the program). In contrast, soil chemical properties are measured annually. These measurement frequencies are to capture the respective relatively rapid and slow response of soil nutrient and soil health indicators to changes in management. Table 1 summarizes the types of data collected from participating farms. The focus of the remainder of this paper will be on the soil health data collected as part of the Cornell Comprehensive Assessment of Soil Health.
Currently, a majority of farmers (about 82%) in the SHP network are trialing cover crops, and a small number of fields are testing other soil health practices, such as no- or reduced tillage, and varied N application rates.

### Table 1: Description of different data types that SHP collects

<table>
<thead>
<tr>
<th>Data type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical information</td>
<td>Geographical data of field and strip boundaries, coordinates of soil sampling locations and geospatial data of cash crop yield</td>
</tr>
<tr>
<td>Remote sensing images</td>
<td>Aerial and high-resolution satellite* imagery of fields</td>
</tr>
<tr>
<td>Management</td>
<td>Management data of both whole fields and soil health trials, such as soil health trial type, tillage types, crop planting details for both cover crops and the cash crop, and fertilizer, manure, and pesticide usage</td>
</tr>
<tr>
<td>Soil health</td>
<td>Soil health indicators tested using the Cornell CASH test</td>
</tr>
<tr>
<td>Soil nutrients</td>
<td>Soil pH, and macro- and micronutrient content</td>
</tr>
<tr>
<td>Average years of conservation tillage experience</td>
<td>20 (range: 3-34)</td>
</tr>
<tr>
<td>Average years of cover crop experience</td>
<td>6 (range: 3-10)</td>
</tr>
</tbody>
</table>

*Maxar (https://www.maxar.com) and Planet (https://www.planet.com)

### Soil sampling protocol

Soil health and soil fertility are monitored on all SHP fields at predetermined sampling locations. Soils of two depths (0-2 inch and 2-6 inch) from the same sampling locations are tested for nutrient content, whereas soils (0-6 inch) are aggregated to strip level for soil health. Standardized soil sampling protocols and shipping logistics are used across the network for consistency. During the soil sampling campaigns, farmers’ agronomists, a contract soil sampler or SHP’s field staff follow the sampling protocol that has been developed in consultation with SHP’s Science Advisory Committee, and sample shipping materials are provided by SHP. Soil sampling takes place at the initial enrollment and in the spring before planting cash crops. Soil health samples are submitted to Cornell University to complete the CASH analysis. (In the past, we have also sent soil samples for the Haney test.)

SHP has collected a range of soil nutrient content and soil health indicators across its network since 2014. Tests include both macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur) and micronutrients (aluminum, copper, iron, manganese, sodium, and zinc) under soil health treatment versus control (business-as-usual, or farmer’s prior management). Soil physical (e.g., soil texture), biological (e.g., organic matter), and chemical (e.g., pH) properties are analyzed for soil health evaluation.
This novel dataset allows us to benchmark soil health on working farms, to analyze the response of soil health indicators to soil conservation management practices, and to fill the gap of current research where soil health tests have been largely conducted on research stations, or co-led by researchers and farmers.

Highlights of Findings to Date

SHP has collected soil health data from trials on mid- to large-sized working farms (about 70% of farms are >1,000 acres) across 16 midwestern states over six years. The soil health trials are led by farmers, and SHP field managers provide support to the farmer with trial layout and implementation. Though research studies have shown growing cover crops can lead to increases in soil health (e.g., organic matter and microbial biomass), it was not clear if this conclusion would hold true for on-farm trials under various weather and soil conditions across the U.S., and at what time scale these changes are detectable (Wood and Bowman, 2021).

This novel dataset allows us to benchmark soil health on working farms, to analyze the response of soil health indicators to soil conservation management practices, and to fill the gap of current research where soil health tests have been largely conducted on research stations, or co-led by researchers and farmers.

Here we show the distribution of soil texture and six soil health indicators – soil organic matter, active carbon, aggregate stability, respiration, available water capacity, and the Autoclaved Citrate Extractable (ACE) soil protein – across the fields in the network upon enrollment (Figure 2, Figures 3-6a and Figure 7). Alongside the initial soil health assessment, we show the response of four soil health indicators to growing cover crops for a short to medium time period (2-5 years) in Figures 3-6b.

We report strong evidence that soil health is increased due to growing cover crops. This finding is drawn from our recent study based on 1,522 strip-year soil-health data points from 78 farms across nine states over five years 1. This study was published in a top scientific journal, Nature Food (Wood and Bowman, 2021).

Soil Texture

Soil texture classifies soils based on the composition of clay, silt and sand. It gives a general idea of soils’ ability to hold water, nutrients and air. Soil clay is known to control a number of soil attributes, such as cation exchange capacity, soil aggregation, and organic matter retention (Karlen et al., 2017). Soil texture, an inherent soil property, is important because it is influential to soil health indicators and crop yield, though it does not change drastically by management (Moebius-Clune et al., 2016).

In our network, a majority of fields (>50%), particularly in Illinois, Indiana, Missouri, Nebraska, and Wisconsin, have silt loam soils. About 30% of fields have either loam or silty clay loam soils. Less than 15% of fields have either clay loam or sandy loam soils. The rest of the fields have silt loam or silty clay loam soils. The predominant soil types, particularly loam and silty clay loam, are fertile agricultural soils and contain high organic matter. This finding is consistent with the characteristics of the dominant soil orders, namely Alfisols and Mollisols, in the regions SHP is working in. (See Figure 2, next page.)

Soil texture classifies soils based on the composition of clay, silt and sand. It gives a general idea of soils’ ability to hold water, nutrients and air. Soil clay is known to control a number of soil attributes, such as cation exchange capacity, soil aggregation, and organic matter retention. Soil texture, an inherent soil property, is important because it is influential to soil health indicators and crop yield, though it does not change drastically by management.

Figure 2: Soil texture of SHP’s fields

(a) a diagram showing the composition of clay, silt, and sand in soil texture. The diagram includes categories such as Sa: Sand, SiLo: Silty loam, ClLo: Clay loam, etc., and shows the percentage distribution of these categories in different soils.

(b) A bar chart showing the number of experimental plots in different soil textures across various states (IA, IL, IN, KS, MO, NE, OH, WI, Other). The states are color-coded to match the soil textures.

Figure 2 (a) soil texture of fields in the SHP network, and (b) number of fields grouped by soil texture and state where it is located.
Soil Organic Matter

Soil organic matter is not only home to nutrients such as carbon, nitrogen and phosphorus, but also enhances soil water content. It plays a central role in nutrient cycling, soil water conservation, and farm profitability. Soils with low soil organic matter need additional fertilizer and/or irrigation input, particularly in drought years, to achieve yield goals (Moebius-Clune et al., 2016).

Based on initial soil test results, silty clay soils have the highest organic matter content (about 5%), followed by silty clay loam (4.5%) and clay loam (3.7%). Average organic matter content for loam and silty loam soils in our network was about 3%. Other soils contain less organic matter, namely sandy loam (2.5% organic matter), loamy sand, and sandy (both about 1% organic matter) soils (Figure 3a). The positive values in Figure 3b suggest an increase in organic matter with cover crops, and this effect grows stronger over the course of the trial from 2015 to 2019 (Figure 3b).

Figure 3: Soil organic matter

![Graph showing soil organic matter content grouped by soil texture classes and cover crop effect by year.](image)

Figure 3 (a) average and standard deviation (SD) of organic matter content (%) grouped by soil texture classes (error bar indicates standard deviation), and (b) cover crop effect on soil organic matter content grouped by year (to the right side of the dashed line means a contribution of growing cover crops to increases in soil organic matter content) (panel b is from Wood and Bowman, 2021)
Active Carbon

Active carbon represents the labile portion of soil organic carbon, which is a small fraction of total soil carbon. It is thought to be a leading indicator of changes in soil health that responds to changes in management practices over a shorter time frame than soil organic matter (Moebius-Clune et al., 2016).

The initial soil health assessment showed silty clay loam soils had the highest active carbon content (average of 615 ppm and standard deviation of 125 ppm), followed by clay loam (average of 567 ppm and standard deviation of 150 ppm), silty clay (529 ppm) and loam (average of 515 ppm and standard deviation of 124 ppm) soils. Active carbon content for sandy loam and silty loam soils was about 450 ppm. Sand and loamy sand soils had the least amount of active carbon, below 280 ppm (Figure 4a). Similar to the effect of cover crops on organic matter, our work suggests that cover crops positively impact active carbon, and that this effect increases with the amount of time cover crops are used (Figure 4b).

Figure 4: Active carbon

![Active carbon](image)

Figure 4 (a) average and standard deviation (SD) of active carbon content (ppm) grouped by soil texture classes (error bar indicates standard deviation), and (b) cover crop effect on soil active carbon content grouped by year (to the right side of the dashed line means contribution of growing cover crops to increases in soil active carbon content) (panel b is from Wood and Bowman, 2021)
**Wet Aggregate Stability**

Wet aggregate stability measures how well soil withstands simulated rainfall in the lab. Soils with high aggregate stability facilitate water infiltration and are less susceptible to erosion. It is responsive to changes in farm management (Moebius-Clune et al., 2016).

Silty clay soils had the highest aggregate stability (about 60%). Average aggregate stability for clay loam, silty clay loam and loamy sand soils was slightly less than 30%, whereas it ranged between 17% and 25% for the remaining soils, including sandy loam, loam, sand and silty loam (Figure 5a). Much like for soil organic matter and active carbon, our early research suggests that cover crops have a positive impact on aggregate stability with time (Figure 5b).

---

**Figure 5: Wet Aggregate Stability**

![Figure 5](image_url)

*Figure 5 (a) average and standard deviation (SD) of aggregate stability (%) grouped by soil texture classes (error bar indicates standard deviation), and (b) cover crop effect on aggregate stability grouped by year (to the right side of the dashed line means contribution of growing cover crops to increases in aggregate stability) (panel b is from Wood and Bowman, 2021)*

---

Wet aggregate stability measures how well soil withstands simulated rainfall in the lab. Soils with high aggregate stability facilitate water infiltration and are less susceptible to erosion. It is responsive to changes in farm management.
Respiration

Soil respiration rate measures how much carbon dioxide is released from soils. It is an indicator of soil microbial activity. A high respiration rate indicates an active microbial community and capacity for nutrient cycling (Moebius-Clune et al., 2016).

Soil respiration was the highest in clay loam soils (average of about 0.6 mg CO$_2$ g soil$^{-1}$ and standard deviation of 0.25 mg CO$_2$ g soil$^{-1}$). The respiration rate averaged around 0.5 mg CO$_2$ g soil$^{-1}$ for loam and silty clay loam. Silty loam and sandy loam soils had an average respiration rate of 0.42-0.46 mg CO$_2$ g soil$^{-1}$. For silty clay and loamy sand soils, the rate was slower, averaging around 0.3 mg CO$_2$ g soil$^{-1}$. Sand soils had the smallest respiration rate, 0.2 mg CO$_2$ g soil$^{-1}$ (Figure 6a). Respiration rate was enhanced due to cover crops. Cover crops’ positive effect on respiration rate became stronger over the course of the soil-health experiments (Figure 6b).

Figure 6: Respiration

![Figure 6](image.png)

Figure 6 (a) average and standard deviation (SD) of respiration (mg CO$_2$ g soil$^{-1}$) grouped by soil texture classes (error bar indicates standard deviation), and (b) cover crop effect on respiration grouped by year (to the right side of the dashed line means contribution of growing cover crops to increases in respiration) (panel b is from Wood and Bowman, 2021)

Soil respiration rate measures how much carbon dioxide is released from soils. It is an indicator of soil microbial activity. A high respiration rate indicates an active microbial community and capacity for nutrient cycling.
Available Water Capacity and ACE Protein

Available water capacity describes the amount of water a soil can hold. Water retention is particularly important to consider for areas and years with drought conditions (Moebius-Clune et al., 2016). Average available water capacity ranged from 0.11 to 0.29 g/g across the eight soil texture classes before the implementation of soil health practices. Soils dominated by silt, including silty clay, silty loam, and silty clay loam, tended to have high available water capacity (0.27-0.29 g/g). Clay loam, loam, and sandy loam soils had an average available water capacity of 0.25, 0.21, and 0.16 g/g, respectively. The average available water capacity was below 0.15 g/g for sand and loamy sand (Figure 7a).

Regarding the ACE protein, it quantifies the amount of organic nitrogen soil microbes can use and make available for plant uptake. This indicator is related to nitrogen mineralization. It describes potential inorganic nitrogen for plant uptake (Moebius-Clune et al., 2016). The average ACE protein content ranged from 3.9 to 5.33 mg CO₂ g⁻¹ soil⁻¹. Sandy loam, silty clay loam and loam soils had about 5 mg CO₂ g⁻¹ soil⁻¹ or more ACE protein. The protein content was 4.57-4.87 mg CO₂ g⁻¹ soil⁻¹ for silty loam, silty clay and clay loam soils. The lowest protein content (about 4 mg CO₂ g⁻¹ soil⁻¹) was found in sand and loamy sand soils (Figure 7b).

Available water capacity and ACE protein have not been impacted by 2 to 5 years of cover crops in the SHP trials (Wood and Bowman, 2021). However, available water capacity as measured in the laboratory is largely driven by soil texture class and may not represent how much water soil holds in the field, nor how well infiltration responds to management.

Figure 7: Available water capacity and ACE protein
Discussion and Conclusions

Since the establishment of SHP, we have made striving progress in achieving our missions. We were funded to measure soil health on working farms. We started with 17 fields when we were established in 2014. Since then, we have conducted on-farm soil health trials on more than 200 fields spreading across 16 states in the U.S., clustered mainly in the Midwest Corn Belt states (Figure 8). We are expanding our farmer network to the central and eastern parts of the U.S. to identify specific soil health practices that suit their interests and existing production systems. The knowledge we generate from our work contributes to the soil health research and development community, and is beneficial to the farming community, beyond states where we have soil health testing fields.

Figure 8: Spatial distribution of fields in SHP’s research network

The data collected from our farmer-led research trials have demonstrated the benefits of conservation management practices. Our unique dataset on soil health across several years (2-5 years per field) and across different regions (16 states to this date) of the U.S. allows us to rigorously test the impact of growing cover crops on soil health indicators. We found that growing cover crops increased four soil health indicators – active carbon, respiration, soil organic matter and aggregate stability – and that there’s evidence that the effect increased throughout the length of the program (Figures 3-6b). Here, we also highlighted the influence of soil texture on soil health indicators. From the initial assessment of soil health and nutrients, we saw soils with different health status and in varied levels of nutrient contents in fields within our network. These differences are most likely resulted from soil forming processes and the long-term farm management. We observed a clear trend in organic matter, active carbon and available water capacity with regard to soil texture (Figures 3-4a and Figure 7a, Wood and Bowman, 2021).

Our soil health data is one piece in the puzzle of farming for economic and environment benefits. While soil resources are the cornerstone for farms’ bottom line, soil properties – the soil health indicators included – are highly affected by crop growth, long-term climatic and short-term weather conditions, management practices, and topography. That’s why, in addition to collecting soil health and nutrient data, we are collecting crop yield, information about historical and current management practices, and financial records. We are also leveraging remote-sensing images and publicly accessible topographic and weather datasets to examine the potential effect of localized weather and landscape on soil health. Analyzing soil health indicators and the yields of soybean and corn in 96 SHP fields in 2014-2018, we found soil health indicators or assessment scores often do not directly relate to crop yield, indicating that other outcomes also need to be considered (Crookston et al., 2021). That’s why, at SHP,
we are measuring other outcomes of the soil health practices; to name a few, this includes soil water quality, soil temperature and soil water content. Our goal of collecting a variety of data is to link together conservation practices, soil health indicators, and outcomes.

Our role goes beyond measuring and monitoring soil health. With the growing number of farmers in our network, we spread recognition of the importance of soil health in our farming communities. We provide year-round support to farm operations. Through our partnership approach, we have brought together farmers, researchers at universities, the U.S. Department of Agriculture, and associates in private companies and nonprofits. With our partners, we have generated insights on the monetary value of soil-health practices\textsuperscript{2,3,4}. We are untangling the linkage between the soil health indicator values and farm management decisions. Ultimately, our work contributes to the adoption of soil health practices on commercial farms.

References


\textsuperscript{3} https://www.soilhealthpartnership.org/business-case/incorporating-cover-crops-profitably-on-highly-erodible-land-in-west-central-indiana
