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# Soil Health Benchmarks

## 2021 Report

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*Cover photo: Cheryl Burns, Capital RC&D*

This report is available on Pasa's website at pasafarming.org/soil-benchmarks-2021.

Pasa Sustainable Agriculture cultivates environmentally sound, financially viable, community-focused farms and food systems.

For more information about this report, contact research@pasafarming.org.

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# EXECUTIVE SUMMARY

Building and preserving soil health is a fundamental component of a secure food system that effectively protects ecosystems and communities. Pasa Sustainable Agriculture's **Soil Health Benchmark Study** is a collaborative research project designed to help farmers monitor and evaluate the nuanced soil health strengths and challenges that can exist simultaneously within their fields. Our project is one of the largest and most diverse community soil health research projects in the nation, amassing data from a wide range of farm scales and management systems, soil types, and farmer experiences.

Since we initiated the study in 2016, we've worked alongside more than 100 farmers to collect soil samples and field management records from their pastured livestock, row crop, and vegetable farms in Pennsylvania and Maryland. We compile the collective results of soil tests—analyzed by Cornell University's Soil Health Testing Laboratory—and field records to develop annual, custom soil health benchmark reports for each of the farms participating in the study. These benchmarks offer insights into common soil health issues in our region, as well as challenges that are unique to individual farms. Equipped with their custom benchmark reports, farmers can improve their soil health management strategies and connect with a supportive learning community of their peers.

This report shares both the latest soil health benchmarks we've compiled from the 2019 season, as well as observations in soil health trends over time from farms who have participated in the study over multiple years. It includes benchmarks for 10 soil health indicators, and three farm management benchmarks. It additionally includes our analysis of significant trends in the data we've collected. Our findings include:

- **Perennial pastured livestock farms are the "gold standard" for soil health, achieving optimal scores for every soil health indicator we measured on nearly all fields we measured.** Most annual row crop and vegetable farms have excellent or optimal soil health in many respects, but often show challenges with low aggregate stability—a key measure of a soil's structure and resistance to erosion—and high phosphorus, a critical plant nutrient that can become an environmental pollutant when applied excessively.

- **Climate change in Pennsylvania, Maryland, and throughout the Northeast region will bring new challenges for soil stewardship.** In 2018, following historic rainfall totals—most of it arriving in extreme doses—we observed a 60% and 54% drop in aggregate stability on row crop and vegetable farms, respectively, in the region. While most of these farms were able to partially or substantially rebuild their aggregate stability in 2019, which brought more amenable weather and field working conditions, it's likely that extreme rainfall events and consistently wet seasons will become more common in the future, creating ongoing challenges for maintaining healthy soil structure.

- **Many farms that rely on tillage for controlling weeds and preparing fields are still able to achieve optimal soil health by balancing tillage with a holistic soil health management strategy.** Many farmers and agricultural professionals believe that no-till farming techniques are essential for building and preserving soil health in annual crop rotations. While we found that most no-till row crop farms do in fact have optimal soil health, we also found many examples of optimal soil health on organic row crop and vegetable farms that till intensively, including some farms with low annual inputs of mulches, composts, and manures. Planting cover crops, allowing full-season fallows, and carefully timing tillage are likely key to balancing tillage and soil health, but we need more data to evaluate these techniques in the context of our study.

Farmer collaborators report drawing substantial value from our study: 92% return to submit soil samples and fields records for multiple years. Additionally, a variety of farmers and technical service providers located in areas outside of Pennsylvania and Maryland have expressed interest in helping to grow and further diversify the study. We expect this report to be the first of a series of soil health benchmark reports that we will publish regularly to help farmers, technical service providers, scientists, policymakers, and communities better understand soil health and how best to protect it.

Nitrogen nodules on roots.

# INTRODUCTION

Soil is the foundation of sustainability on any farm. It is also at the center of many of our most pressing social and environmental problems. With healthy soils, farmers can grow an abundant and nutritious food supply, strengthen local economies, protect clean water, nurture diverse ecosystems, and help control climate change. But without actively working to build and preserve soil health, farmers can become locked in a costly downward spiral of increasing chemical inputs, losing their most fertile topsoil to erosion, and degrading vital natural resources.

The state of our nation's soils has increasingly become a top priority for farmer associations, multinational corporations, and government agencies alike. Grassroots farmers' organizations like the Pennsylvania No-Till Alliance, Practical Farmers of Iowa, and the National Corn Growers' Association are providing soil health education and technical assistance to farmers across the country. Major food manufacturers like General Mills and Dannon are seeking to bolster the sustainability of their brands and supply chains by investing in their vendor farms' soil health. And with the establishment of its Soil Health Division in 2012, soil health research and technical assistance has also become a top directive for the USDA Natural Resource Conservation Service.

Preserving and improving soil health has catalyzed into a global movement in response to a pattern of troubling trends. Scientists estimate that U.S. soils have lost 30–60% of the organic matter they contained before farmers cleared vast swaths of native forests and grasslands for food production[1,2]—and the rate of soil depletion continues to far outpace recovery. Connections between land stewardship and water quality have also drawn wider attention: Agricultural runoff is one of the top sources of water pollution and contamination across the U.S.[3] And as climate change continues to accelerate, soils are increasingly damaged by floods, droughts, and severe storms. Ultimately, it has become eminently clear that public health, ecosystem health, and the security of our local, regional, and national food systems are inextricably linked to the state of our soils.

> **"The state of our nation's soils has increasingly become a top priority for farmers associations, multinational corporations, and government agencies alike."**

As an organization that directly engages with thousands of farmers in Pennsylvania and surrounding states each year, Pasa Sustainable Agriculture initiated the Soil Health Benchmark Study in 2016. The ongoing study aims to offer farmers, scientists, communities, policymakers, and other stakeholders valuable soil health insights from a growing network of more than 100 working farms. Our study participants include pastured livestock farms, diversified vegetable farms, and grain and row crop farms that operate at various scales and employ a variety of management systems. As the most diverse soil health community science project in the nation, our Soil Health Benchmark Study lets us synthesize data and share insights among a wide range of production systems. The study contributes to the soil health movement by providing new ways to measure, compare, and promote soil health on farms everywhere.

## What is soil health?

Understanding soil health extends beyond any technical definition—it's a mindset. We must learn to see soil not only as a medium for delivering nutrients to crops, but as a living, breathing, highly complex ecosystem. As a living system, soil can thrive or deteriorate depending on how it's cared for. While many aspects of soil health remain a frontier of research and discovery, scientists and farmers broadly agree about how we can assess whether soil ecosystems are functioning well or poorly, or somewhere in between.

Measuring soil health requires evaluating three types of overarching characteristics:[4]

- **Physical:** Healthy soils have a stable physical structure that resists erosion and supports root growth.
- **Biological:** Healthy soils have an ample stock of organic matter that feeds a diversity of invertebrates and microorganisms, working to cycle nutrients for plant growth and regulate pathogens and harmful microbes.
- **Chemical:** Finally, healthy soils provide a balanced supply of essential plant nutrients and maintain pH levels optimal for plant growth and microbial life.

> **"We must learn to see soil not only as a medium for delivering nutrients to crops, but as a living, breathing, highly complex ecosystem."**

For decades, soil health testing labs primarily focused on measuring a soil's chemical attributes—levels of acidity; nitrogen, phosphorus, and potassium; and micronutrients. While this provided farmers with some basic information about soil fertility, such a narrow scope of analysis offered farmers a highly limited, and often misleading, understanding of a soil's true health. Critically, this approach does not take into account a wealth of other attributes, such as whether a soil is resistant to erosion, or to what extent beneficial microorganisms are present. In contrast, our study employs a holistic approach to soil testing: We measure not only a soil's chemical health, but also its physical and biological health.

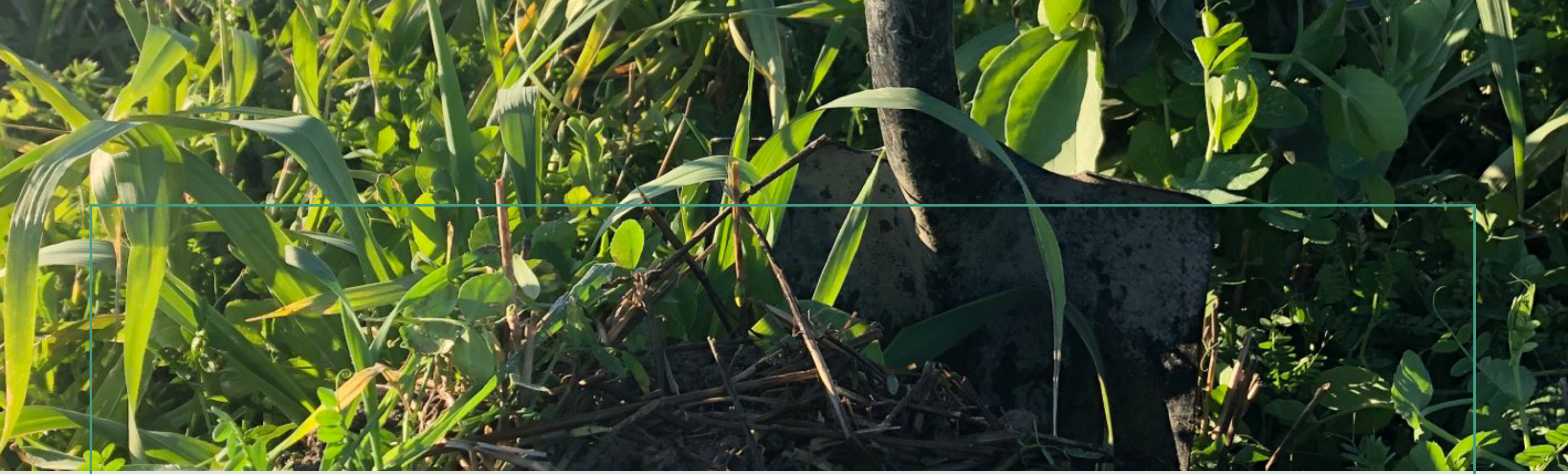
Just as there is growing consensus about the importance of soil health and how we can measure it, there is also emerging agreement among farmers and scientists about the practical steps that we can take to improve soil according to this holistic framework. Farmer experience and scientific research has shown that we can grow healthy soils by 1) minimizing soil disturbance; 2) maximizing soil cover and living roots; 3) increasing biological diversity, 4) integrating crops and livestock; and 5) reducing external nutrient and fertility inputs.[4,5]

## Empowering farmers with data & community

Farmers are shouldering an enormous responsibility to grow a more sustainable future. As the primary stewards of roughly 20% of the land area in Pennsylvania and more than 55% nationally,[14] farmers well understand the importance of soil health to a sustainable future. Most farmers have a deep appreciation for the value of the soil resources they steward, and many are actively working to implement the core principles of soil health management. But while the principles of reducing disturbance, maximizing cover, increasing biodiversity, integrating livestock, and cutting inputs are easy to understand in concept, it can be difficult to bring them into practice within the constraints and challenges of a working farm. To develop a soil health management strategy that's both effective and practical, farmers need at least two elements: an accurate assessment of their farms' soil health over time, and a supportive network of peers that they can work with to vet ideas, compare results, and generate new innovations.

**Farmers steward roughly 20% of the land in Pennsylvania, and 55% nationally.**

Our Soil Health Benchmark Study supports farmers in this process of data-collection and peer-to-peer learning for continuous improvement. In this report, we'll share our community science methods, present soil health benchmark data collected between 2016 and 2019, and demonstrate how farmers can work together for meaningful change on their farms and in their communities.



## BENEFITS OF HEALTHY SOILS

- **Better bottom lines.** Farmers who focus on sustaining and improving soil health can often substantially increase their net incomes. By providing natural fertility, healthy soils can help farmers substantially cut expenses on fertilizers and pesticides.[6,7] Increased water infiltration and water holding capacity can also help farmers reduce variation in yield through droughts and heavy rainfall years, helping to secure more consistent revenues.[8,9] The Nature Conservancy estimated that soil health improvements could directly save U.S. farmers $3 billion annually in reduced expenses and more consistent yields on corn acres alone.[10]

- **Cleaner water.** Healthy soil can turn fields and pastures into clean-water powerhouses.[11] Today, agricultural runoff is one of the top sources of water pollution in the U.S.[3] Improving soil health to reduce erosion and cut fertilizer applications could be one of the most cost-effective solutions for improving water quality for hundreds of millions of people nationwide.

- **Mitigating climate change.** Farmland soils are a critical component of any comprehensive plan to address human-caused climate change. Soil health practices like cover cropping, reduced tillage, or managed grazing can draw carbon dioxide out of the atmosphere and sequester it underground as soil organic matter. And with diverse crop rotations that include legumes, farmers can feed their crops with home-grown nitrogen and cut their dependence on nitrogen fertilizers, which require fossil fuels to manufacture and release the powerful greenhouse gas nitrous oxide as they are processed by microbes in the soil. Collectively, soil health strategies could provide as much as 16% of the greenhouse gas reductions needed to avert the most serious climate change scenarios.[12]

- **Resilience to severe weather.** Because healthy soils act like sponges that can rapidly absorb water during downpours and slowly meter it out over dry periods, soil stewardship can help farmers prepare for the extreme weather associated with climate change. The Union of Concerned Scientists has estimated that soil health improvements on just the most highly erodible acres in Iowa alone could reduce storm runoff by 9–20% and flood frequency by 13–20% across the state, saving billions of dollars in crop losses and property damage from the most severe floods.[13]

# PARTICIPATING FARMS

## Recruitment

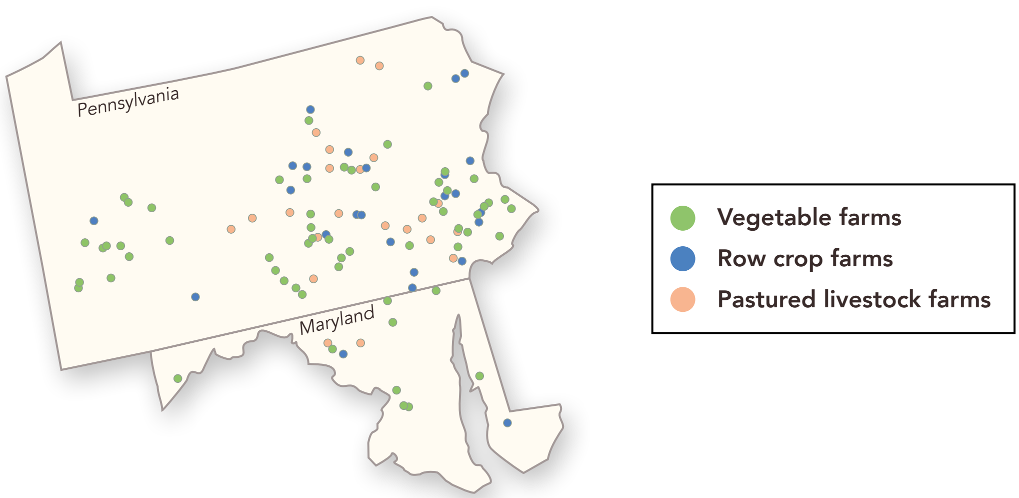
We recruit farmers through an open-enrollment process. We promote the opportunity to participate in the study through our website, in-person and virtual events, email list, social media, and word of mouth. As a result of these open recruitment methods, our project does not reflect a representative sample of agriculture in the Mid-Atlantic region, and likely includes a bias toward farmers who are interested in soil health and are already honing their soil-building practices. Our cohorts also include more small vegetable farms (<15 acres) and fewer larger row crop farms ( >250 acres) than would be proportional to Pennsylvania agriculture as a whole.

Although we do not have a truly representative statistical sample, our project is well-designed to accelerate a more comprehensive understanding of soil health among farmers—including study participants and farmers at large—and inspire innovative soil health management systems that are both effective and practical.

## Location

Most farms that have or are currently participating in this study are located across Pennsylvania. A smaller group of Maryland farms were added to the study in 2019. Participating farms manage land that spans a variety of soil types and topographies (Figure 1).

### Figure 1. Map of collaborating farms by cohort, 2016–2019



# Cohorts

The Soil Health Benchmark Study includes three primary farm cohorts: pastured livestock, row crop and grain, and diversified vegetable farms. Beginning with a small pilot cohort of 12 vegetable farms in 2016, we've progressively increased the number and variety of farms each year. At the time of publishing this report, 106 farms have contributed data to this study (Table 1).

### Table 1. Collaborating farms in each cohort by year, 2016–2019

| Year | Number of farms | | | |
|---|---|---|---|---|
| | Pastured livestock | Row crop | Vegetable | Total |
| 2016 | - | - | 12 | 12 |
| 2017 | - | 4 | 26 | 30 |
| 2018 | 8 | 15 | 36 | 59 |
| 2019 | 21 | 26 | 48 | 95 |

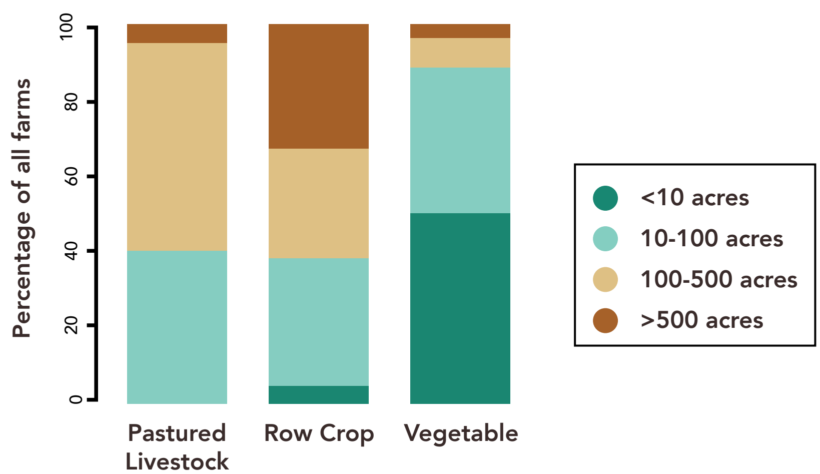
### Table 2. Study cohort farming systems, 2016–2019

| Cohort | Farming system | Number of farms |
|---|---|---|
| Pastured livestock | Beef cows | 9 |
| | Dairy cows | 10 |
| | Pigs | 4 |
| | Goats, sheep | 5 |
| | Poultry | 3 |
| Row crop | Conventional or reduced-tillage | 4 |
| | No tillage | 16 |
| | Certified organic | 7 |
| Vegetable | Intensive crop rotations | 58 |
| | Seasonal cover crops | 42 |
| | Full-season cover crops | 8 |
| | Integrated livestock | 5 |

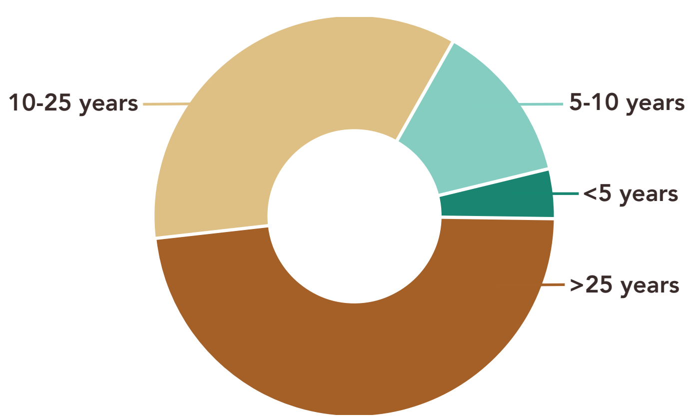
Within each cohort, farmers practice a diversity of techniques and management systems (Table 2). The pastured livestock cohort includes grazing dairies, grass-finished beef farms, goats and sheep, and pastured pig and poultry operations, as well as several farms that practice multi-species grazing. The row crop cohort includes continuous no-till farms, farms practicing reduced or conventional tillage, and certified organic farms using conventional tillage. Our vegetable cohort includes mostly certified organic farms, or farms using organic practices but not certified, as well as four conventional farms that use synthetic pesticides and fertilizers.

Additionally, within each cohort, there is a wide diversity of farm sizes and farmer experience levels (Figures 2 and 3). This diversity enables a unique cross-pollination of soil health management ideas and practices.

## Figure 2. Study cohorts & farm scales, 2016–2019




## Figure 3. Farming experience among collaborating farmers, 2016–2019



*Farmer study participants take soil samples.*

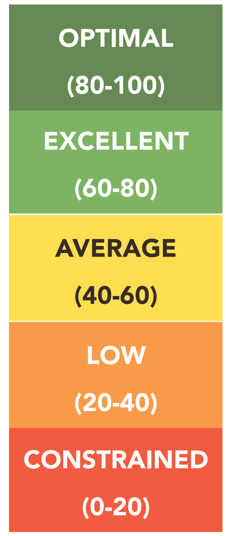
# METHODS

Our Soil Health Benchmark Study collects and analyzes two primary data sources: 1) field soil samples and 2) farm management records. We consult with collaborating farmers to choose three study fields that span typical crop rotation practices on that farm. For instance, if a farmer practices a six-year crop rotation involving two years of corn silage, to one year of soybeans, to three years of alfalfa, we would choose one study field in first year corn, the second study field in soybean, and the third study field in second-year alfalfa. If a vegetable farmer practices a three-year vegetable rotation involving fall brassicas in one year, to tomatoes and peppers in the next year, to a full year of cover crops, we would choose one field in each of these phases for sampling. We also choose fields that represent typical soil types and topographic positions on each farm.

In October and November of each study year, we work with collaborating farmers to collect soil samples from each study field. For farms participating in the project for the first time, Pasa staff members visit the farm to collect soil samples and train the farmer on appropriate sampling techniques. After the first year of study participation, farmers collect their own samples. Sampling is generally timed to occur after fall harvest and cover crop seeding operations have concluded.

We subsample to a depth of six inches (15 centimeters) from five locations in each study field, homogenize the samples, and submit them to the Cornell Soil Health Testing Laboratory. Cornell runs a battery of tests, evaluating 13 different physical, biological, and chemical indicators of soil health. For each indicator, Cornell returns both the original measured values and a rating, normalized on a bell curve to a 0–100 scale (Figure 4). Samples from different soil texture classes are rated on distinct normal curves, which allows us to make comparisons across soils that may have different inherent soil properties.

Figure 4.
Cornell Comprehensive Assessment of Soil Health rating scale & rating classes




Throughout the project year, collaborating farmers maintain logs of farm operations in the selected fields, using either template spreadsheets provided by Pasa, farmOS software, or paper notebooks. Records include: 1) tillage, cultivation, and any farm operations involving soil disturbance or compaction; 2) planting and termination dates for crops and cover crops, 3) application dates and quantities for all fertilizers and soil amendments, and 4) animal movements and stocking densities for pastured livestock. We organize these data and generate three additional indicators that provide a snapshot into some of the management practices that most influence soil health: 1) days of living cover, 2) tillage intensity, and 3) organic inputs.

We collate the Cornell soil health test data and our management indicators into detailed, custom benchmark reports for each collaborating farmer. These reports serve as a reference point for conversations and events where farmers can share and refine their soil health strategies.

We developed our methods with input from participating farmers and scientists at Penn State University, Cornell University, Rodale Institute, and Stroud Water Research Center.

**For more details about our methods, please see our Methods Guide for Research Collaborators.**[15]

*Credit: Cheryl Burns, Capital RC&D*

# SOIL HEALTH BENCHMARKS

This section outlines the soil health benchmarks achieved by the 21 pastured livestock, 26 row crop, and 48 vegetable farms in Pennsylvania and Maryland that participated in our Soil Health Benchmark Study in 2019. Our benchmarks are divided into five categories: physical benchmarks, biological benchmarks, chemical benchmarks, overall soil health score benchmarks, and management benchmarks.

The 0–100 ratings throughout this section are color coded according to Cornell University's Comprehensive Assessment of Soil Health's rating scale and rating classes (see Figure 4 in Methods). A rating between 0–20 is *constrained*; 20–40 is *low*; 40–60 is *average*; 60–80 is *excellent*; and 80–100 is *optimal*.

Soil samples are grouped according to texture classes (coarse, medium, and fine), and rated against a bell curve for all samples in Cornell's database for that texture class. The reference manual for the Comprehensive Assessment of Soil Health provides a detailed review of the relationships between measurements and ratings for each indicator.[4]

## Physical benchmarks

We measured two indicators of a soil's physical health using Cornell University's Comprehensive Assessment of Soil Health: *available water capacity* and *aggregate stability*.

### Table 3. Available water capacity measurements & ratings by cohort, 2019

| | Measurements (g/g) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 0.2 | 0.3 | 0.3 | 78 | 91 | 99 |
| Row crop | 0.2 | 0.2 | 0.3 | 68 | 89 | 98 |
| Vegetable | 0.2 | 0.3 | 0.3 | 74 | 92 | 99 |

*Available water capacity* is a measure of the amount of water accessible to plant roots relative to the total amount of water the soil can hold under saturated conditions. It is measured in units of grams of water per grams of dry soil. Soils with greater available water capacity allow plants to perform better under drought conditions.

Across pastured livestock, row crop, and vegetable cohorts, nearly all farms had "optimal" available water capacity ratings in 2019, with 11 farms rated "excellent."

### Table 4. Aggregate stability measurements & ratings by cohort, 2019

| | Measurements (% by mass) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 22 | 53 | 66 | 35 | 86 | 97 |
| Row crop | 16 | 35 | 70 | 21 | 56 | 98 |
| Vegetable | 7 | 27 | 65 | 9 | 42 | 97 |

*Aggregate stability* is a measure of the extent to which soil structure can withstand wind, rain, and other stressors. Aggregate stability is measured as the percentage of soil aggregates that hold together through a standardized rainfall simulation. Good aggregate stability helps promote germination and root growth.

Unlike ratings for available water capacity, we saw a great degree of variation among study cohorts' aggregate stability ratings. Nineteen pastured livestock farms had "optimal" aggregate stability ratings, with only one of 21 farms rated in the "low" rating group. Many farms in the row crop (14 of 28) and vegetable (36 of 48) cohorts had "average" or "low" ratings, with vegetable farms generally rating lower than row crop farms.

# Biological benchmarks

We measured four indicators of a soil's biological health: *organic matter, soil protein, soil respiration,* and *active carbon.*

### Table 5. Organic matter measurements & ratings by cohort, 2019

| | Measurements (% by mass) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 3.0 | 4.4 | 7.2 | 50 | 92 | 100 |
| Row crop | 0.9 | 4.0 | 6.3 | 9 | 83 | 100 |
| Vegetable | 1.8 | 3.9 | 8.2 | 15 | 87 | 100 |

*Organic matter* is measured as the percent of total soil mass that contains carbon compounds derived from living or once-living biomass. Organic matter is a core measurement of soil health—it's the foundation of soil life, contributes to the formation of stable soil aggregates, helps to improve available water capacity, and provides a slow-release supply of nutrients.

Across all cohorts, most farms showed "optimal" organic matter ratings, but three of 26 row crop and five of 48 vegetable farms had "low" or "constrained" ratings for their soil types. Only two pastured livestock farms had ratings below "excellent."

### Table 6. Soil protein measurements & ratings by cohort, 2019

| | Measurements (mg/g) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 5.4 | 7.4 | 12.1 | 37 | 62 | 94 |
| Row crop | 3.8 | 6.5 | 16.5 | 21 | 50 | 100 |
| Vegetable | 4.0 | 6.9 | 23.2 | 18 | 53 | 100 |

The *Soil Protein* measures the amount of protein contained in soil organic matter. Proteins contain a substantial amount of nitrogen. Microbes in the soil can break down these proteins and make the nitrogen available to plants. Soil protein is measured as milligrams protein extracted per gram of soil.

Across all cohorts, soil protein was one of the lowest rated soil health indicators. Seven row crop and 13 vegetable farms showed "low" or "constrained" soil protein ratings. While 12 of 21 pastured livestock farms rated "excellent" or above, soil protein was still the lowest-rated indicator on most pastured livestock farms.

### Table 7. Soil respiration measurements & ratings by cohort, 2019

| | Measurements (mg/g) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 0.4 | 0.7 | 1.2 | 23 | 66 | 96 |
| Row crop | 0.3 | 0.7 | 1.4 | 16 | 64 | 98 |
| Vegetable | 0.3 | 0.6 | 1.3 | 17 | 52 | 100 |

*Soil respiration* measures the abundance and activity of microbial life in the soil. Soil microbes work to break down plant residues in the soil and cycle nitrogen and other nutrients from organic matter into plant-available forms. As they break down organic matter, microbes release carbon dioxide, so microbial activity can be measured by capturing the carbon dioxide produced by soil microbes over a four-day incubation period in the lab. Respiration is expressed in units of milligrams of carbon dioxide per gram of soil.

The soil respiration measurements showed similar patterns as soil protein. Five row crop and 13 vegetable farms had "low" or "constrained" soil protein ratings. While 19 pastured livestock farms rated "excellent" or better, four farms showed "low" respiration ratings.

### Table 8. Active carbon measurements & ratings by cohort, 2019

| | Measurements (ppm) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 556 | 743 | 1,041 | 62 | 89 | 100 |
| Row crop | 377 | 757 | 1,034 | 25 | 88 | 99 |
| Vegetable | 413 | 715 | 1,352 | 32 | 87 | 100 |

*Active carbon* is a measurement of the small portion of soil organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. It is measured in parts per million (ppm). Active carbon is a good leading indicator of biological soil health, and tends to respond to changes in management earlier than total organic matter content.

Across all cohorts, most farms showed "optimal" active carbon measurements. Five row crop and nine vegetable farms had "average" or "low" ratings, while pastured livestock farms consistently showed "excellent" or "optimal" ratings.

## Chemical benchmarks

We measured four indicators of a soil's chemical health: *pH level, phosphorus, potassium,* and *minor elements.*

### Table 9. pH measurements & ratings by cohort, 2019

| | Measurements (ph units) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 5.9 | 6.4 | 7.0 | 68 | 98 | 100 |
| Row crop | 5.7 | 6.7 | 7.2 | 38 | 99 | 100 |
| Vegetable | 5.6 | 6.7 | 7.3 | 26 | 100 | 100 |

*pH* is a measurement of how acidic the soil is, which controls how available nutrients are to crops. If pH is too high, nutrients such as phosphorus, iron, manganese, copper, and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium, and molybdenum become unavailable. The value is presented in standard pH units, and rated using a hump-shaped curve, with a pH between 6.2–6.8 optimal for most crops.

Across all cohorts, almost all farms showed "optimal" pH ratings. Only two pastured livestock farms rated "excellent", while a two row crop and five vegetable farms had "average" or "low" ratings.

## Table 10. Phosphorus measurements & ratings by cohort, 2019

| | Measurements (ppm) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| **Pastured livestock** | 3 | 10 | 41 | 15 | 100 | 100 |
| **Row crop** | 3 | 14 | 247 | 0 | 88 | 100 |
| **Vegetable** | 2 | 20 | 251 | 0 | 69 | 100 |

*Phosphorus (P)* is an essential plant nutrient and is used by plant cells to build DNA and regulate metabolic reactions. At high levels, phosphorus can become a risk to water quality. At very high levels it can interfere with plant uptake of micronutrients, including iron and zinc. Note that Cornell scores phosphorus measurements using a hump-shaped curve, such that both low and high parts per million (ppm) values get ratings towards zero. Optimal values for phosphorus vary based on the texture and geology of individual soil types, but ratings above 30 ppm are typically considered excessive.

Phosphorus ratings were highly divergent. While most farms showed "excellent" or "optimal" ratings, one pastured livestock farm, five row crop farms, and eight vegetable farms received "constrained" ratings due to problems with excessive phosphorus. The vegetable cohort showed the most number of farms with excessive phosphorus challenges.

## Table 11. Potassium measurements & ratings by cohort, 2019

| | Measurements (ppm) | | | Ratings (0–100) | | |
|---|---|---|---|---|---|---|
| | Min. | Median | Max. | Min. | Median | Max. |
| Pastured livestock | 57 | 130 | 296 | 82 | 100 | 100 |
| Row crop | 51 | 120 | 319 | 75 | 100 | 100 |
| Vegetable | 49 | 137 | 368 | 71 | 100 | 100 |

*Potassium (K)* is an essential plant macronutrient that contributes to heat and cold tolerance and promotes fruit development in horticultural crops. It is measured in parts per million by mass.

Almost all farms had "optimal" potassium ratings, with just two row crop and one vegetable farm showing "excellent" levels.

## Table 12. Minor element (magnesium, iron, manganese, zinc) ratings by cohort, 2019

| | Ratings (0–100) | | |
|---|---|---|---|
| | Min. | Median | Max. |
| Pastured livestock | 71 | 100 | 100 |
| Row crop | 56 | 100 | 100 |
| Vegetable | 85 | 100 | 100 |

*Minor elements* including magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn) are essential for various plant biochemical reactions but are only required in small quantities. If any minor elements are deficient, yield and crop quality will decrease, but toxicities can also occur when concentrations are too high. Cornell provides individual measurements in parts per million for each of these four minor elements, but aggregates all four into a composite minor element rating.

Almost all farms showed "optimal" minor element ratings, with one pastured livestock farm rated "excellent" and one row crop farm rated "average". Among the three cohorts, vegetable farms consistently had the highest minor element ratings.

## Overall soil health score benchmarks

### Table 13. Overall soil health ratings by cohort, 2019

| | Ratings (0–100) | | |
|---|---|---|---|
| | Min. | Median | Max. |
| Pastured livestock | 71 | 86 | 95 |
| Row crop | 55 | 80 | 96 |
| Vegetable | 57 | 78 | 86 |

Cornell's *overall soil health score* is a simple average of the ratings for the full set of 13 chemical, biological, and physical indicators in the Cornell Comprehensive Assessment of Soil Health. The overall score can be a useful general summary, but individual indicators will be more valuable for identifying specific strengths or management challenges in a given field.

In terms of the Cornell soil health indicators, the pastured livestock farms clearly set the gold standard: 16 of the 21 pastured livestock farms rated "optimal" for overall soil health, with the remaining five still achieving an "excellent" rating. Row crop and vegetable farms had similar profiles, with most farms rated "optimal" or nearly so, and two row crop and one vegetable farm scoring in the "average" category.

## Management benchmarks

In addition to the Cornell soil health indicator benchmarks, we created three new management benchmarks that are designed to measure how well a farm is adhering to key soil health management best practices, like maximizing living vegetation, reducing soil disturbance, and limiting off-farm inputs. Instead of lumping our farms into discrete management systems (e.g. no tillage versus conventional tillage), these benchmarks allow us to assess each farm along a continuous gradient of soil management possibilities.

### Table 14. Days of living cover (days per year) by cohort, 2019

| | Min. | Median | Max. |
|---|---|---|---|
| Pastured livestock | 298 | 365 | 365 |
| Row crop | 93 | 326 | 360 |
| Vegetable | 76 | 218 | 350 |

Living vegetation protects soil from wind and water erosion while also supplying the soil with fresh organic matter. Linking together annual crops, cover crops, and perennial pastures and forages to maximize days of living cover is a fundamental soil-building practice. Our *days of living cover* benchmark is the number of days between crop or cover crop seeding (or transplant) and termination (or winter kill), or between pasture establishment and renovation. For each field, we weighted the days of living cover for different crops and cover crops by the area planted, then summed over all the crops and cover crops.

True to their perennial nature, most of our pastured livestock farms had living cover all 365 days of the year, or with only a short gap where one of the study fields may have been used to grow an annual feed crop. Impressively, many of the no-till row crop farms also achieved year-round living cover, typically by planting spring cash crops into living winter cover crops, then terminating the cover crops with herbicides before the cash crop emerged from the soil—a practice commonly known as "planting green." Generally, vegetable farmers had the fewest days of living cover, either because they left the pathways between vegetable beds bare during the summer growing season, or because they did not consistently plant a fall cover crop in fields with late-season cash crops.

### Table 15. Tillage intensity index by farm cohort, 2019

| | Min. | Median | Max.. |
|---|---|---|---|
| Pastured livestock | 0 | 1.6 | 23.3 |
| Row crop | 1.7 | 8 | 170.3 |
| Vegetable | 1.1 | 98.7 | 297.3 |

Tillage can degrade soil structure and organic matter, but it can also be a valuable tool for weed management and incorporating cover crops. The *tillage intensity index* uses data from a Natural Resources Conservation Service (NRCS) soil erosion model to assign a soil-disturbance score to all management operations that can compact or disturb soil. We weighted the scores for each machinery operation based on the area covered, then summed over the season—the higher the score, the more soil disturbance. For context, NRCS assigns a single pass with a moldboard plow a score of 65; a disc harrow a score of 19.5; and a grain drill a score of 2.4.[16]

Pastured livestock farms showed little to no soil disturbance. Row crop farms demonstrated a wide range of tillage systems, including continuous no-till operations; organic and conventional farms with primary tillage multiple times a year; and organic and conventional farms that alternate primary tillage some years with perennial forages other years. Vegetable farms had the highest tillage intensities, although our data set does include some innovative reduced-tillage systems. Examples included rotating vegetable fields with perennial grazing pastures, and transplanting vegetable seedlings into cover crop beds terminated with herbicides and a single pass with a disc harrow.

## Table 16. Organic matter inputs (tons of dry matter per acre) by farm cohort, 2019

| | Min. | Median | Max. |
|---|---|---|---|
| Pastured livestock | 0 | 0 | 1.8 |
| Row crop | 0 | 0.5 | 13.3 |
| Vegetable | 0 | 1 | 75.7 |

*Organic matter inputs* including composts, manures, and straw mulches can stimulate the formation of soil organic matter, add microbiology to the soil, and supply macro- and micro-nutrients. However, continuous inputs can also contribute to soil health challenges, such as excessive phosphorus levels.

Our organic matter input benchmark shows the total organic inputs—composts, manures, and mulches—farmers apply in each field, measured in units of tons per acre. We use farmer-supplied analysis or published data to estimate the percentage of dry matter of each organic matter input, then standardize all inputs on a dry-matter basis. We only take into account inputs brought in from outside the study field; we don't include manure deposited by animals grazing in that field, or biomass generated by crops and cover crops.

We found that most pastured livestock farms had few off-farm organic matter inputs, with the exception of some larger dairy farms with winter manure storage from barns. Most row crop farms also had low amounts of organic matter inputs, with the exception of a few farms connected to confined animal operations that provide a cheap and accessible manure source. Vegetable farms varied tremendously in their use of manures and composts—some applied these off-farm inputs heavily in each field each year, and others worked to provide fertility through cover crops or concentrated fertilizer sources.

# SOIL HEALTH INSIGHTS

## Tough weather is tough on soil

Climate change is already happening in Pennsylvania and neighboring states, and maintaining soil aggregate stability in the face of new weather patterns has emerged as a key challenge on many of our collaborating farms. Total annual precipitation in the northeast United States has increased over the past half century by about 10%, or five inches per year. But this gradual change is overshadowed by a much sharper increase: Incidents of extreme precipitation—defined as more than one inch of rain during a 24-hour period—have increased 71% since 1950.[17]

In 2018, farmers in Pennsylvania and much of the Northeast and mid-Atlantic regions experienced total precipitation 50% above normal, and many locations experienced dozens of extreme precipitation events.[18] Possibly as a result of this historic rainfall, we saw a crash in aggregate stability on many farms between 2017 and 2018 (Table 17). Aggregate stability improves water infiltration, helps prevent erosion, and provides a better substrate in which roots and soil microbes can grow.

Fortunately, aggregate stability is a dynamic soil property. Previous research suggests that soil aggregates can be repaired through cover cropping and rotations that put living roots back in the soil.[19] After a year of more typical growing and field conditions in 2019, we observed a median 64% and 53% rebound of aggregate stability on row crop and vegetable farms, respectively.

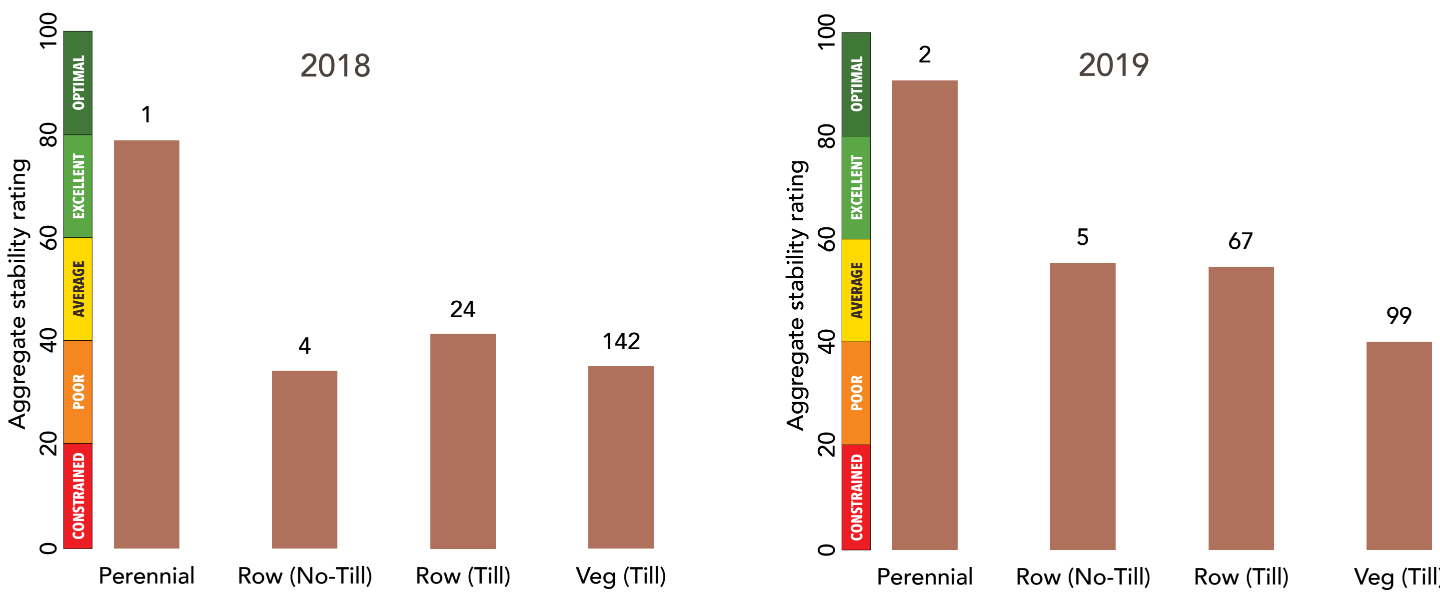
### Table 17. Annual precipitation in Pennsylvania & median aggregate stability ratings by cohort, 2017–2019

| Year | Avg. precipitation (in.) | Ratings (0–100) | | |
|---|---|---|---|---|
| | | Pastured livestock | Row crop | Vegetable |
| 2017 | 46.6 | - | 89 | 77 |
| 2018 | 64 | 81 | 36 | 27 |
| 2019 | 50.8 | 87 | 57 | 40 |

As shown in the table above, crashes in aggregate stability occurred mainly in annual cropping systems; aggregate stability on pastured livestock farms remained high even after the fall deluges of 2018. Interestingly, despite achieving nearly year-round crop cover and drastically minimizing soil disturbance compared to vegetable farms, no-till row crop farms were not spared the 2017–2018 drop in aggregate stability (Table 17). During this time, many farmers reported that the difficult weather conditions often forced them to bring planting, spraying, and harvesting equipment into wet soils that weren't ready to be worked, suggesting that even without tillage or cultivation, farmers can still put substantial stress on soil structure with heavy machinery. In 2019, we found that row crop farms, including no-till and conventionally tilled farms, both rebounded their aggregate stability more than vegetable farms (Figure 5).

## Figure 5. Relationships between tillage systems, tillage intensity & aggregate stability ratings, 2018 & 2019

*Bars indicate the mean aggregate stability for each tillage system, while the numbers above each bar indicate the mean tillage index. For context, NRCS assigns a single pass with a moldboard plow a score of 65; a disc harrow a score of 19.5; and a grain drill a score of 2.4.[16]*




Planting fibrous-rooted cover crops and successfully timing field operations may be a key strategy for rebuilding soil aggregates after years with severe weather. In general, the row crop farmers in our study planted cover crops more consistently than the vegetable farmers (Table 17).

*Wheat cover crop planted and growing in soybean stubble at Woodside Vu Farm (Credit: Woodside Vu Farm)*

## PARTICIPANT CASE STUDY: WOODSIDE VU FARM

For row crop farmers, the window between harvesting corn silage, soybeans, or corn grain and successfully planting a winter cover crop can be very narrow. At Woodside Vu Farm in York County, Pennsylvania, father and son team Joe and Ben Hushon have been planting cover crops, including winter rye and barley, for a decade, but they've had a mixed record of success. The deciding variables often seem to be the timing of days where the soil is fit to handle machinery and the number of mild fall days after cover crops get in the ground.

Motivated to fine-tune their cover crop strategy after the big drop in aggregate stability they observed on their farm in 2018, Ben has been exploring earlier-maturing soybeans and is considering switching from a later-maturing soybean. Although they will probably experience some yield loss with a shorter-season variety harvested in late September, the Hushons feel that having three to four extra weeks of good October weather to plant and grow cover crops will more than compensate the farm with soil health benefits. As they continue to participate in our Soil Health Benchmark Study, the Hushons can monitor whether their updated cover crop strategy is effectively defending their soil from drops in aggregate stability, and ultimately helping their farm better withstand severe weather.

# Tillage can be part of a holistic soil health system

Discussions around soil health can often become entrenched around prescriptive extremes, with advocates passionately promoting strictly defined systems and formulaic sets of practices. Contrary to these polarized perspectives, our data point to a wide spectrum of management systems that can build healthy soils.

In many ways, organic matter is the central soil health indicator. Organic matter influences the formation of stable aggregates; provides long-term, slow-release soil fertility; and provides food and habitat for beneficial microorganisms. Viewed through the lens of soil organic matter, our data show that healthy soils can be achieved with a range of management systems and tillage practices.

Farmers have traditionally worked soils to control weeds and prepare seed beds for planting. Tilling and cultivating can severely deplete soil organic matter by disturbing soil structure and exposing soil to air (oxygen stimulates microbes to metabolize organic materials). It would therefore be reasonable to predict that soil disturbance could have a drastic and unavoidable negative impact on soil health. If this were true, we would expect a steep and consistent negative relationship between tillage intensity and organic matter (Figure 6, left panel). Where cases of heavy tillage co-occurred with healthy organic matter levels on individual farms, we would expect to see consistent and heavy inputs of organic matter from outside the farm (e.g. manure, compost, or mulch) to counterbalance the negative effects of soil disturbance.

Our data do not support these predictions. Instead, we found a shallow and weak correlation between tillage intensity and organic matter (Figure 6, right panel). We also observed nine row crop and vegetable farms that utilize primary tillage implements, which score greater than 50 on the Tillage Intensity Index (tillage index >50), yet these farms still achieved an "optimal" rating for level of organic matter according to Cornell's Comprehensive Assessment of Soil Health. Interestingly, many of these farms apply relatively small quantities of organic matter inputs to their fields annually, although some farms may have had significant inputs in years before our study began.

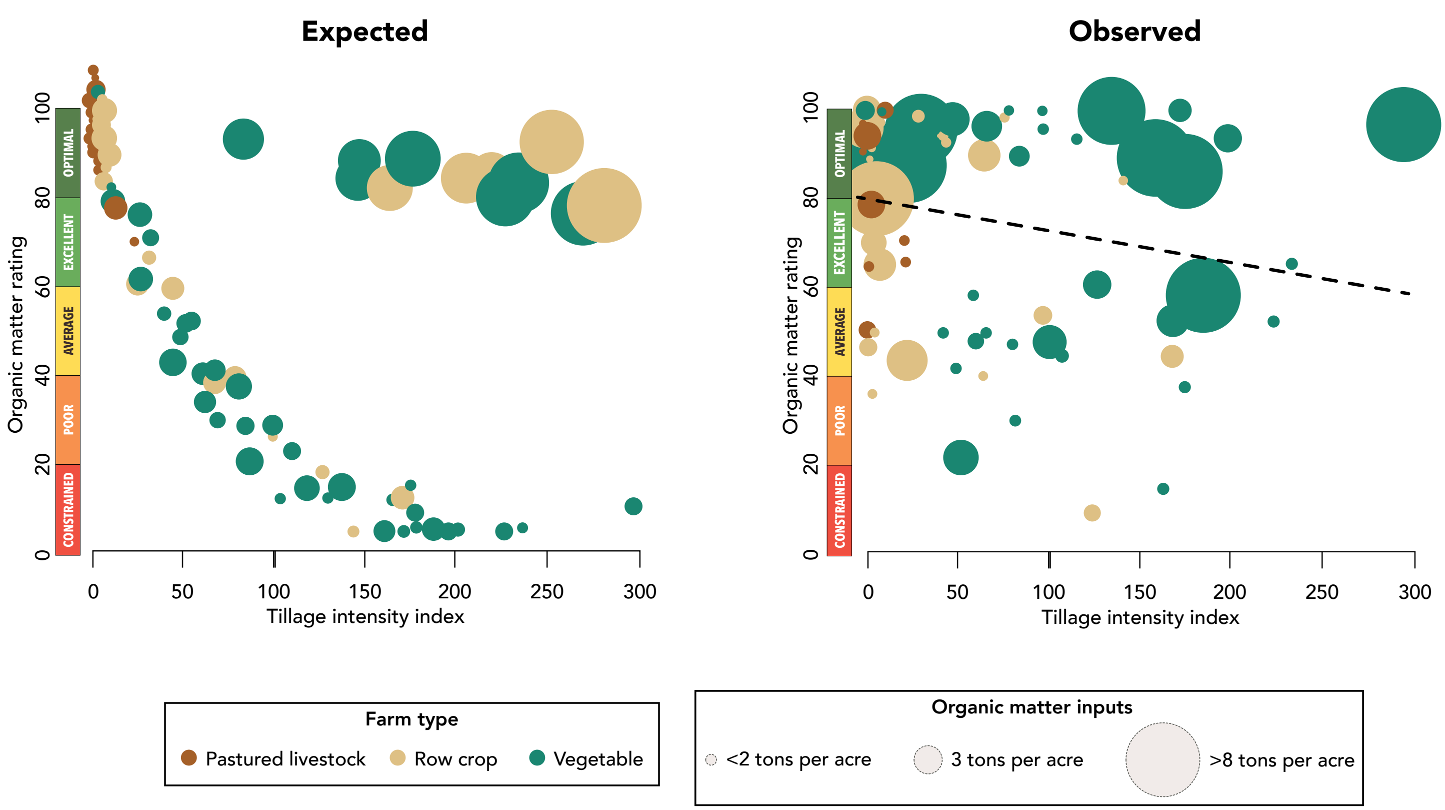
The no-till approach to building soil health is based on the idea that eliminating nearly all soil disturbance on annual crop farms will result in a high degree of soil health that could not be achieved with even judicious tillage. Most no-till farmers are able to avoid tillage by relying, to some degree, on herbicides to control weeds and terminate cover crops. While some small farms and farming organizations are experimenting with organic no-till methods, this approach remains largely elusive to organic farmers who typically need at least some "steel in the field" to effectively control weeds. At the same time, because of the escalating prevalence of herbicide-resistant weeds and the growing public health and environmental problems associated with herbicide use, continuous no-till may not be a sustainable soil health management method.[20]

Our data indicate it's possible to achieve optimal soil health while still conservatively tilling and cultivating to control weeds and terminate cover crops. These findings point to exciting possibilities for blending the best practices from both no-till and organic systems to help farmers and other stakeholders make more informed decisions about how to best preserve soil health while also protecting human and ecosystem health.

## Figure 6. Expected & observed relationships between tillage intensity, organic matter inputs & organic matter rating by cohort, 2019

*The graph on the left shows the expected relationship between tillage intensity, organic matter inputs, and organic matter rating, while the graph on the right shows the observed results. Each data point reflects the average of a collaborating farm's three study fields.*

*In the graph on the right, the dashed line shows a linear regression model between tillage intensity and organic matter rating ($p=0.01$, $r^2=0.15$). For context, the USDA Natural Resources Conservation Service assigns a single pass with a moldboard plow a Tillage Intensity Index of 65; a disc harrow a score of 19.5; and a grain drill a score of 2.4.*



*Covers protect Spiral Path's windrows of homemade compost until it is spread in the field (Credit: Spiral Path Farm)*

## PARTICIPANT CASE STUDY: SPIRAL PATH FARM

At Spiral Path Farm—an organic vegetable farm in Perry County, Pennsylvania—the Brownback family have grown their soil organic matter levels to 5% on soil types that typically show only 2% organic matter, despite many years of annual passes with a disc harrow and occasional use of a moldboard plow (their average Tillage Intensity Index score is 165, while the median value for vegetable farms in our study was 98.7). They feel they have achieved this feat through an advanced on-farm composting system that stimulates soil microbial life and helps provide crops with optimal nutrition. The Brownbacks apply compost at moderate rates (0.9–2.3 tons dry matter per acre; the median value on vegetable farms in our study was 1.0) that provide some fertility and stimulate microbes without major inputs of organic matter. Vigorously growing crops and cover crops then return carbon and organic matter to the soil, helping build soil health in return.

The Brownbacks also implement a detailed crop rotation that includes alternating uses of winter-kill and overwinter cover crops—in 2019, they were near the top-of-the curve with 301 days of living cover, while the median value on vegetable farms in our study was only 218 days. Among other benefits, the diverse cover crop schedules help them avoid field work bottlenecks that might bind them into bringing heavy equipment into fields that aren't ready to be worked. They recently began phasing out the disc and moldboard plow, and instead terminating cover crops with one or two passes of a spader machine. Perhaps especially for organic farmers, observations from Spiral Path Farm and similar farms in our study indicate that farmers can integrate a range of techniques to sustain soil health to counteract the impact of tillage.

## Better-calibrated fertilizer inputs will improve soil health & water quality

Many vegetable farms and some row crop farms in our study struggle with excessive phosphorus levels (Table 18). Through runoff and erosion, excessive phosphorus can leak from fields and pollute streams and estuaries by causing blooms of algae that exhaust oxygen from the water and kill other life forms. At the global scale, phosphorus is a nonrenewable resource, mined from a limited number of deposits across the globe, then shipped to crop farms.[21] Once phosphorus is lost to rivers and diluted in the vast ocean, it won't be available again to future generations.

For vegetable farmers, excessive phosphorus can also significantly weaken crop vigor. At parts per million levels in the hundreds, depending on soil type and crop, phosphorus can inhibit a plant's uptake of iron and zinc.[22] Deficiencies in these micronutrients can impede crop growth and increase susceptibility to pests. In most cases in our study, high phosphorus levels could be attributed to heavy manure or compost applications. For farms relying on manure or compost as a nitrogen source, phosphorus is typically supplied in excess of crop needs.

> **"Phosphorus is a nonrenewable resource … Once [it] is lost to rivers and and diluted in the vast ocean, it won't be available again to future generations."**

For vegetable and row crop farms in our study, the distribution of phosphorus ratings according to Cornell's Comprehensive Assessment of Soil Health tended to be polarized (Table 18). Most farms had either developed a fertility program that successfully balanced phosphorus inputs with other crop nutrient needs, or they were dealing with a major, long-term excessive phosphorus challenge; relatively few farms fell between these poles. To prevent or correct excessive phosphorus in soil, farmers can develop a balanced fertility plan by reviewing the specific nutrient needs of their crops, the chemical composition of the amendments and fertilizers they use, and the existing levels of phosphorus and other nutrients in their soil.

## Table 18. Distribution of phosphorous rating classes & measurements by farm cohort, 2019

*Each cell in the table indicates the percentage of sampled fields falling in the corresponding phosphorous rating class according to the Cornell Comprehensive Assessment of Soil Health rating system. Note that for phosphorus, higher parts per million concentrations are assigned lower ratings.*

| | Pastured livestock | Row crop | Vegetable |
|---|---|---|---|
| Optimal (3–23 ppm) | 79% | 67% | 57% |
| Excellent (21–23 ppm) | 5% | 4% | 2% |
| Average (23–25 ppm) | 5% | 1% | 5% |
| Low (25–35 ppm) | 3% | 5% | 5% |
| Constrained (35–400 ppm) | 8% | 23% | 31% |

*Fall vegetables interseeded with an overwintering clover cover crop at New Morning Farm (Credit: New Morning Farm)*

## PARTICIPANT CASE STUDY: NEW MORNING FARM

For years, New Morning Farm—an organic vegetable farm in Huntingdon County, Pennsylvania—had relied on poultry manure to provide nitrogen to crops. In 2016, farm owner and manager Jennifer Glenister began noticing yield declines and new pest and disease problems that leaf tissue tests suggested may have been linked to low iron and zinc levels. Our benchmark soil tests that year also confirmed sky-high soil phosphorus levels at approximately 150 parts per million (the optimal range is 3–23). To try to lower the level of phosphorus in the farm's soil, Jennifer cut poultry manure out of the fertility plan and began relying more on feather meal, which contains very little phosphorus, to supply supplemental nitrogen. She has also adapted her cover crop plan to include more legumes for a home-grown nitrogen supply, including some full-season windows with biennial red clovers.

Since 2017, phosphorus levels have been holding steady. Excessive phosphorus is a long-term problem—it can take years to draw soil levels down. Although a common recommendation is to harvest crop and cover crop residues to try to remove phosphorus from the field, Jennifer has opted to keep biomass in the field and replace some of the organic matter and biological-stimulation provided by the manure. Jennifer feels she is starting to see better results with pest pressure and crop health over the past three years, although she feels she is far from finished developing her soil fertility practices.

## Headed in the right direction?

Growing soil health is a long-term commitment. In most cases, our data set is probably much too young to meaningfully assess change in soil health over time. Still, for a sub-group of three row crop farms and 15 diversified vegetable farms, we have collected consistent data from the same fields in 2017, 2018, and 2019. This lets us offer observations about how soil health has improved, decreased, or remained constant over the course of three years (Table 19):

- As discussed earlier, after the historic wet weather of 2018 we observed a sharp decline in aggregate stability. Despite a partial recovery in aggregate stability in 2019, most farms experienced an overall decline in this indicator from 2017.

- Organic matter is a notoriously slow-changing indicator, so it's not surprising that most of these farms showed no substantial change in organic matter levels. Good rates of organic matter accumulation may be around 0.1–0.4% per year, but actually achievable rates depend on climate, soil type, and the background soil health conditions when a farmer begins implementing best management practices.[23] Still, these slow rates of change can have major implications for improving water holding capacity[13] and carbon sequestration.[23]

- As a promising sign, 16 of the 18 farms showed a 10% or greater increase in active carbon, which can be a leading indicator of organic matter development and support healthy soil life.[4]

- For management indicators, we saw a range of trends between 2017 and 2019. Some vegetable farms increased their days of living cover, while others showed small to substantial declines. Seven of the farms increased tillage intensity, nine decreased tillage intensity, while two stayed about the same. Because all of the fifteen vegetable farms are highly diversified with complex rotations, our sample of three fields might not cover the range of tillage and cover cropping schedules applied on the farm in a given year. Thus, it's unclear whether these changes in living cover and tillage reflect a directional change, or regular variation over the span of a complex rotation.

- As the Soil Health Benchmark Study continues to mature, we'll be able to supply unique insights about how soil health changes over time on working farms with diverse, complex rotations.

## Table 19. Trends in soil health & soil management indicators on vegetable farms, 2017–2019

*Each cell shows the number of farms with a 10% decline, a 10% increase, or little change (less than 10% total change) in a given indicator.*

| | >10% decrease | Little change (<10% total change) | >10% increase |
|---|---|---|---|
| Available water capacity | 4 | 14 | 0 |
| Aggregate stability | 17 | 1 | 0 |
| Organic matter | 5 | 11 | 2 |
| Soil protein | 2 | 7 | 9 |
| Soil respiration | 15 | 3 | 0 |
| Active carbon | 1 | 1 | 16 |
| pH | 0 | 18 | 0 |
| Phosphorous | 14 | 2 | 2 |
| Potassium | 12 | 4 | 2 |
| Days in living cover | 4 | 8 | 6 |
| Tillage Intensity Index | 9 | 2 | 7 |
| Organic matter inputs | 7 | 2 | 9 |

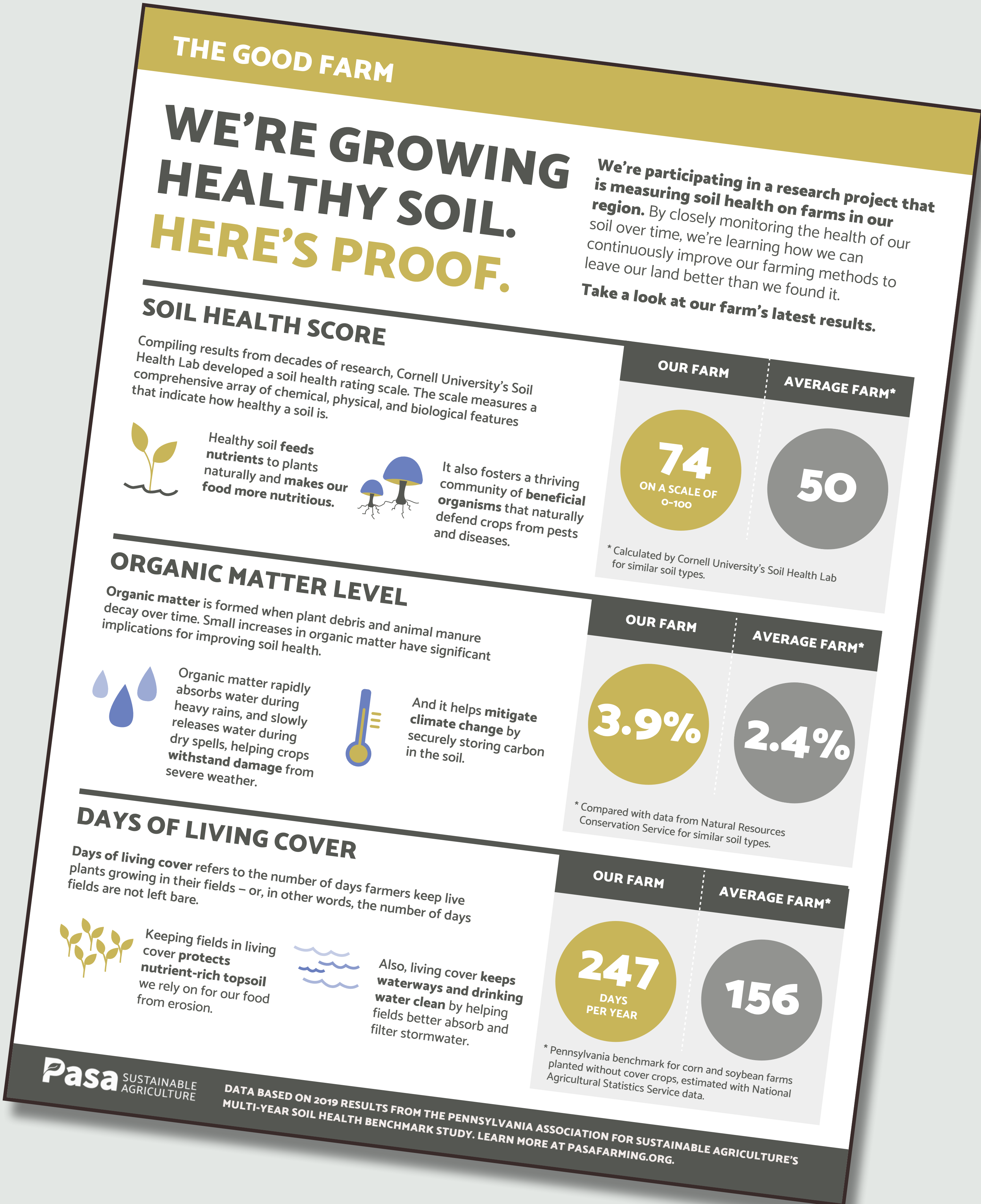
*Vetch and oat cover crop*

# MARKETING HEALTHY SOILS

Healthy soils grow more nutritious products, fight climate change, and protect water. Farmers who practice excellent soil stewardship therefore deserve a better price and bigger markets for their products. We developed custom infographics for each collaborating farm to help them show customers, neighbors, and other stakeholders the measurable impact of their soil health management efforts. Each infographic conveys individual farm averages for three key statistics:

- Overall soil health score (see page 24) compared to the average soil health score for all soils in the Cornell database, which is set to 50 in their rating system.
- Percent organic matter (see page 19) compared to the percent organic matter estimated by the Natural Resources Conservation Service's Soil Survey for the soil types sampled on the farm.
- Days of living cover (see page 25) compared to a Pennsylvania benchmark for a corn and soybean rotation planted without cover crops. Estimates for corn and soybean days of living cover were taken from planting and harvest dates reported by the National Agricultural Statistics Service.[14] Recent estimates from the Census of Agriculture report that only 13% of Pennsylvania cropland acres are cover cropped, so the benchmark of no cover crops is a fair assessment of the status quo.

Farmers have displayed these infographics on their farm's website, or shared print copies with their wholesale buyers, farmers market customers, and Community Supported Agriculture (CSA) subscribers. As the Soil Health Benchmark Study continues, we will be working to collect customer feedback on this information. Anecdotally, several farms have found the custom infographics to be a valuable tool for helping tell their farm's soil stewardship story.



THE GOOD FARM

# WE'RE GROWING HEALTHY SOIL. HERE'S PROOF.

**We're participating in a research project that is measuring soil health on farms in our region.** By closely monitoring the health of our soil over time, we're learning how we can continuously improve our farming methods to leave our land better than we found it.

**Take a look at our farm's latest results.**

## SOIL HEALTH SCORE

Compiling results from decades of research, Cornell University's Soil Health Lab developed a soil health rating scale. The scale measures a comprehensive array of chemical, physical, and biological features that indicate how healthy a soil is.

Healthy soil **feeds nutrients** to plants naturally and **makes our food more nutritious.**

It also fosters a thriving community of **beneficial organisms** that naturally defend crops from pests and diseases.

| OUR FARM | AVERAGE FARM* |
|---|---|
| 74 ON A SCALE OF 0–100 | 50 |

* Calculated by Cornell University's Soil Health Lab for similar soil types.

## ORGANIC MATTER LEVEL

**Organic matter** is formed when plant debris and animal manure decay over time. Small increases in organic matter have significant implications for improving soil health.

Organic matter rapidly absorbs water during heavy rains, and slowly releases water during dry spells, helping crops **withstand damage** from severe weather.

And it helps **mitigate climate change** by securely storing carbon in the soil.

| OUR FARM | AVERAGE FARM* |
|---|---|
| 3.9% | 2.4% |

* Compared with data from Natural Resources Conservation Service for similar soil types.

## DAYS OF LIVING COVER

**Days of living cover** refers to the number of days farmers keep live plants growing in their fields – or, in other words, the number of days fields are not left bare.

Keeping fields in living cover **protects nutrient-rich topsoil** we rely on for our food from erosion.

Also, living cover **keeps waterways and drinking water clean** by helping fields better absorb and filter stormwater.

| OUR FARM | AVERAGE FARM* |
|---|---|
| 247 DAYS PER YEAR | 156 |

* Pennsylvania benchmark for corn and soybean farms planted without cover crops, estimated with National Agricultural Statistics Service data.

Pasa SUSTAINABLE AGRICULTURE

DATA BASED ON 2019 RESULTS FROM THE PENNSYLVANIA ASSOCIATION FOR SUSTAINABLE AGRICULTURE'S MULTI-YEAR SOIL HEALTH BENCHMARK STUDY. LEARN MORE AT PASAFARMING.ORG.

*All study participants receive a custom infographic for their farm that lets them easily share their soil health data with customers.*

*Farmers discuss soil health practices with each other at a winter workshop for Soil Health Benchmark Study participants*

# PEER-TO-PEER LEARNING NETWORKS

Farmers participating in our Soil Health Benchmark Study interact regularly to discuss findings, troubleshoot challenges, and brainstorm ideas for innovative yet practical solutions. Collaborating farmers can participate in quarterly conference calls with peers in their cohort, as well as an annual full-day winter workshop where pastured livestock, row crop, and vegetable farmers convene to discuss the state of their soils.

In addition to fostering a learning community among our research collaborators, we share insights from the study to broader audiences during webinars, field days, and conferences. We've delivered dozens of presentations and workshops, reaching hundreds farmers and agricultural professionals regionally and nationally.

We've also published a series of detailed case studies exploring common soil health challenges and solutions we've identified through our study, which can be found at **pasafarming.org/resources**.

Farmers participating in the study draw considerable value from the benchmarking project and learning communities: 92% of farm collaborators return to participate in the study for more than one year. In the spring of 2020, we distributed a survey to all current research collaborators. All farmers who responded (more than 25% of all study participants) rated their experience with the study as “good” or “excellent.” What they value as a participant in this study is just as varied as the diversity of farms they represent:

- “It’s made me think more seriously about preserving soil porosity and minimizing intensive tillage.”
- “[We valued] the information from the soil test and being able to convey [our soil health outcomes] to our customers.”
- “The project is guiding me to a better understanding of soil health and giving me the opportunity to better manage my small fields with information and coaching and comparisons.”

# CONCLUSION

The future of our farms, food, water, and climate depend on developing and scaling new solutions for soil stewardship. Our Soil Health Benchmark Study empowers farmers with site-specific data and peer learning networks that support finding and implementing practical solutions for addressing soil health challenges.

So far, our data point to healthy benchmarks for many aspects of soil health on our collaborating farms, including impressive results for organic matter and days of living cover. Our data also point to challenges in managing aggregate stability and excess phosphorus on many row crop and vegetable farms. Farmer collaborators are actively drawing on the data and collective knowledge revealed by this community science project to raise the bar for soil stewardship.

Our open-recruitment methods mean that participants in our study probably over-represent farmers who are passionate about soil stewardship and who have been working to improve soil health on their farms for some time. Therefore, we caution readers not to interpret our benchmarks as indicative of soil health in Pennsylvania and Maryland as a whole.

Moving forward, we are working to continue monitoring soil health on our current network of farms while expanding the study to better represent the diversity of our region's farming systems. We are also expanding the study to measure additional soil health indicators, including water infiltration and crop nutrient density.

**Farmers interested in participating in our Soil Health Benchmark Study can apply at pasafarming.org/research.** We welcome your comments and suggestions for this evolving, farmer-driven research project.

# ACKNOWLEDGMENTS

Thank you to the 106 farmers who have invested their time and expertise into this project. Dan Dalton, Aaron de Long, and Helen Kollar McCarthur at Pasa assisted with farmer recruitment and field operations. Lisa Garfield at Future Harvest coordinated 12 contributing farms in Maryland. Melissa Cipollone and Marie Hathaway at Pasa provided a careful editorial review of this report. Halston Maierle of H6 Design produced the layout for this report. We also thank Bob Schindelbeck and Joseph Amsili (Cornell University's Soil Health Testing Laboratory); Charlie White, Kristy Borreli, and John Spargo (Penn State University); Drew Smith and Yichao Rui (Rodale Institute); and Lamonte Garber and Lisa Blazure (Stroud Water Research Center) for assistance developing this project, analyzing data, and drafting this report.

The Soil Health Benchmark Study was initially made possible thanks to generous financial investments from Lady Moon Farms, the Jerry Brunetti family, the Shon Seeley family, and more than 120 individual donors committed to supporting farmers' efforts to build and preserve soil health. Additional support has been provided through the William Penn Foundation, the Hillman Foundation, the Pennsylvania Department of Agriculture, and the USDA Conservation Innovation Grants program.

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