CHARACTERIZATION OF SOIL HEALTH IN NEW YORK STATE

Technical Report

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NEW YORK SOIL HEALTH

Acknowledgements

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Key Points

- 1,456 samples were analyzed to assess the state of soil health across New York State.
- Soil health in New York is affected by both inherent properties, like soil type, and management factors related to carbon and nutrient cycling and soil disturbance.
- New metrics were established to evaluate soil health in New York State.
- Aspirational soil health goals were established for different soil types and cropping systems.
- Soil carbon storage potential was assessed for different soil types and cropping systems: Annual Grain and Processing Vegetable systems have greater potential for carbon farming than Pasture, Dairy Crop, and Mixed Vegetable systems.

Executive Summary

The soil is a foundational resource for life on earth, and its health is critical to the sustainability of agriculture, food systems, and green infrastructures in New York State. The soil also plays an important role in water and air quality, the integrity of the biosphere, and the climate. Soil health concepts, practices, and testing have generated a growing awareness of the soil's central role. They also highlight that sustainable soil management requires an understanding of biological, physical, and chemical processes and their interrelationships. Furthermore, it is recognized that while inherent soil properties often define the soil's basic functions and production potential, human management can significantly degrade or improve the quality of the soil.

This research characterized 1,456 composite soil samples from across New York State that were analyzed by the Cornell Soil Health Laboratory between 2014 and 2018 and highlights the important effects of soil type and cropping system on biological, physical and chemical soil characteristics. Additionally, the report explores relationships among indicators and estimates soil organic carbon saturation across different cropping systems and thereby their potential for storing carbon through improved management ("carbon farming"). This report also establishes new scoring functions and sets aspirational goals for different cropping systems and soil types in New York State. These new metrics can be used by policy makers, agricultural professionals, and farmers to interpret soil health data and set goals for improved soil health and carbon farming.

The report reaffirms the strong influence of soil texture (relative sand, silt, and clay contents) on biological and physical soil health parameters, including soil organic matter, active carbon, soil respiration, and available water capacity. But it also found strong differences in soil health among five different cropping systems: Annual Grain, Processing Vegetable, Dairy Crop, Mixed Vegetable, and Pastures. These differences can be linked to management practices that affect carbon and nutrient flows and soil disturbance through tillage. Pastures and Mixed Vegetable systems had the highest soil health scores, followed by Dairy Crop. Annual Grain and Processing Vegetable cropping systems had the lowest soil health. Annual Grain and Processing Vegetable cropping systems also generally contain much less soil organic carbon than their potential storage capacity, indicating that improved management and carbon inputs in these systems are more beneficial for soil health and carbon storage compared to Mixed Vegetable, Dairy Crop, and Pasture systems that are already closer to their carbon saturation point.

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Introduction

Across the nation, farmers, agriculture professionals, and researchers are embracing the term soil health (SH), which has been defined as "the capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA-NRCS, 2020). This national interest surrounding soil health is rooted in the growing recognition that soil biology, soil physics, and soil chemistry need to be considered holistically to manage our soil resources sustainably. In the last 30 years, scientists have exponentially deepened their understanding of the major role that soil biology plays in many ecosystem functions that are critical to the success of agriculture and the health of the environment. These essential functions include supplying and retaining nutrients, improving soil structure, promoting root growth, degrading harmful compounds, and suppressing disease. The soil health movement has also been influenced by humans' tremendous capacity to degrade or improve the health of the soil. While natural soil formation is the product of the complex interplay among climate, parent material, biology, and relief over thousands of years, human land use has dramatically sped up the rate of change to the world's soils.

New York State (NYS), through Cornell University, has been a global leader in the development of soil health programs, including the development of testing methodologies. NYS land managers are becoming increasingly excited about improving the health of their soils. While it is well understood that inadequate nutrient availability constrains crop productivity, biological and physical constraints are harder to recognize. Soil health testing has emerged as a way to assess biological and physical processes in the soil in conjunction with traditional nutrient testing. Indicators were selected that were agronomically meaningful, low-cost, and sensitive to management. As a result, soil health testing can be a useful part of land managers' strategies to assess the health of their soils and address constraints.

The Cornell Soil Health Testing Laboratory measures a suite of biological, physical, and chemical indicators of soil health. Since 2014, the standard Comprehensive Assessment of Soil Health (CASH) package has included texture, soil organic matter (SOM), active carbon (ActC), soil protein (Protein), soil respiration (Resp), wet aggregate stability (AgStab), available water capacity (AWC), and seven chemical indicators. These indicators are scored on a 0-100 scale to help users interpret their measurements. Separate scoring functions for coarse, medium, and fine-textured groups were developed for certain indicators to account for the strong influence of texture on the measured value.

As progress is made in characterizing the biological and physical health of soils nationwide, researchers will be able to develop regionally specific scoring functions (interpretive metrics) that are shaped by the interplay of soil management with soil types and climate. The Cornell Soil Health team has recognized this need and is working to develop scoring functions by region, texture, and different types of cropping systems. As part of that effort, we have summarized soil health data from New York State to understand soil health differences across soil texture and types of agricultural management, as well as soil organic carbon saturation. These efforts allow for NYS-specific SH scoring functions and aspirational soil health goals based on soil texture and cropping system.

Methods

New York State Soil Health Database

The NYS Soil Health dataset was compiled from 1,456 NYS soil samples collected from 2014 to 2018 (Figure 1). All samples were run through the standard Comprehensive Assessment of Soil Health (CASH) package at the Cornell Soil Health Laboratory. (https://soilhealth.cals.cornell.edu/). Composite soil samples were assumed to have been collected to a depth of 0-6 inches. Samples were derived from all over NYS, although most were from agricultural regions. Urban and manufactured soils were removed from the database to make interpretations more useful for agricultural soils. Furthermore, samples with OM percentages above 7.4 %, 7.6 %, 7.6 %, and 8.1 % for coarse, loam, silt loam, and fine texture groups were excluded to further ensure that all heavily amended soils were removed. These criteria represent the 98th percentile of organic matter from these four texture groups in NYS.

Soil health results were summarized by four textural groups, which included coarse, loam, silt loam, and fine textural groups (Figure 2, Table A1). More than half of these soil samples (n=868) included surface and subsurface penetrometer data. Additionally, approximately half of the dataset (n=664) had reliable GPS coordinates, which allowed for extraction of soil survey data, namely soil order and soil suborder (Table A2).

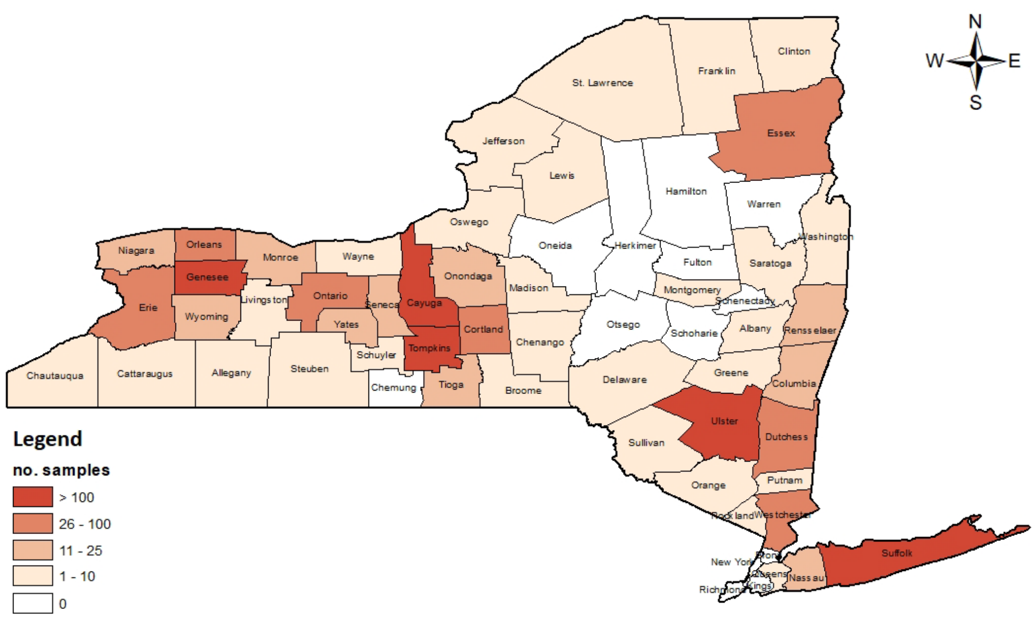

Figure 1. Distribution of soil health samples by county across New York State (n=1,456).

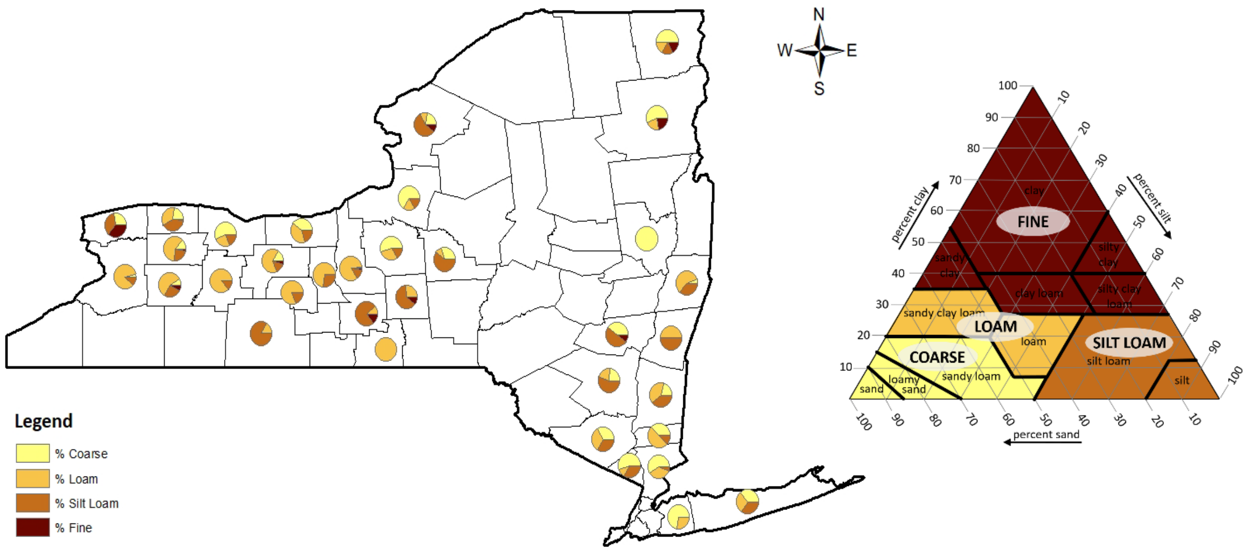

Figure 2. The NYS map shows the percentage of samples belonging to each soil texture group by county (n=1,456). Counties with less than five soil samples were excluded from the map. The report characterizes soil health indicators by coarse (sand, loamy sand, sandy loam), loam (sandy clay loam, loam), silt loam (silt loam, silt), and fine (sandy clay, clay loam, silty clay loam, silty clay, clay) texture groups.

Furthermore, approximately one-third of the soil samples (n=549) included crop code information ([Agro-One Crop Codes]). Soil samples with crop code information were split into five cropping system types by appropriately grouping crop codes (Table 1, Table A3, Table A4). The five cropping system groupings included Annual Grain, Dairy Crop, Pasture, Processing Vegetable, and Mixed Vegetable (Figure 4, Figure 5). The Annual Grain group consisted of fields under corn grain, soybean, and winter wheat production. The Dairy Crop group combined corn silage and alfalfa crop codes since these are often grown in rotation. The Processing Vegetable and Mixed Vegetable distinction was made to capture differences in soil health between larger-scale single-crop vegetable production and smaller diversified vegetable production (often organic). The Pasture group was made up of different types of perennial pastures.

Table 1. Five cropping system groups were formed by combining related crop codes (n=549). Each code is followed by the associated number of soil samples in parentheses.

Cropping System	Crop Codes
Annual Grain	COG (112), SOY (71), WHT (11)
Dairy Crop	COS (83), ALE (10), ALT (7), AGE (9), AGT (8)
Process Veg.	SQW (17), BNS (13), BND (12), SWC (9), CBP (7), POT (6), TOM (6), …*
Mixed Veg.	MIX (86)
Pasture	PIT (15), PNT (11), PIE (8), GRE (6), PLT (4)

*38 samples were from crop codes with less than 4 samples.

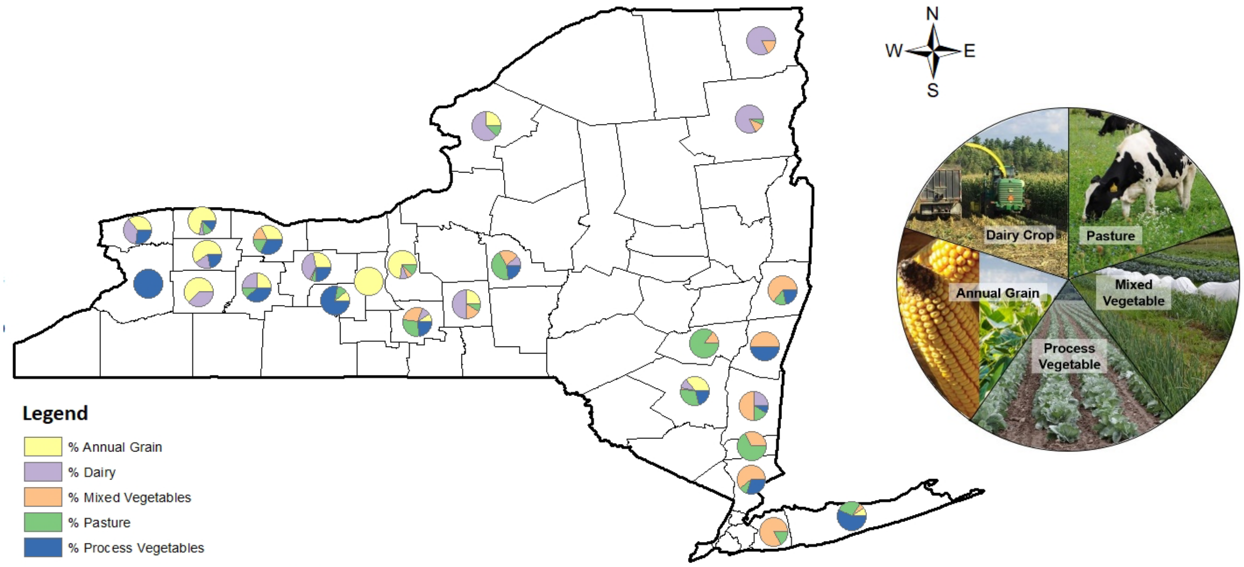

Figure 3. The NYS map shows the percentage of samples belonging to each cropping system group by county (n=549). Counties with less than five soil samples were excluded from this map. The report characterizes soil health by five types of cropping system, including Annual Grain, Dairy Crop, Pasture, small-scale Mixed vegetable operations, and larger-scale Processing Vegetable operations.

Cornell Soil Health Indicators

The Comprehensive Assessment of Soil Health (CASH) package of the Cornell Soil Health Laboratory included four biological indicators, two physical indicators, seven chemical indicators, and soil texture. Soil texture is not a soil health indicator but provides critical information about soil functioning and is key to interpreting the biological and physical soil health indicators. Detailed information and protocols for each method can be found in the Comprehensive Assessment of Soil Health Manual and in the Cornell Soil Health Laboratory Standard Operating Procedures Manual (Moebius-Clune et al., 2017; Schindelbeck et al., 2016), and are also described in the Appendix. The standard CASH package includes the following biological, physical, and chemical indicators.

Biological Properties

Soil Organic Matter (SOM): is a measure of all carbon-containing material that was derived from living organisms. The percent SOM is measured by the combustion of oven-dried soil in a 500°C furnace.

Soil Protein: is a measure of the fraction of soil organic matter which contains most of the organically bound nitrogen (N). Microbial activity can mineralize this N and make it available for plant uptake. This is measured by extraction of soil with a citrate buffer at high temperature and pressure.

Soil Respiration (Resp): is a measure of the metabolic activity of the soil microbial community. It is measured by re-wetting air-dried soil and quantifying the carbon dioxide (CO_2) released after an incubation period.

Active Carbon (ActC): is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping fuel and maintain a healthy soil food web. It is measured by quantifying potassium permanganate oxidation with a spectrophotometer.

Physical Properties

Available Water Capacity (AWC): reflects the quantity of water that a disturbed soil sample can store for plant use. AWC is the difference between water stored at field capacity and at the wilting point and is measured using pressure chambers.

Aggregate Stability (AgStab): is a measure of how well soil aggregates resist disintegration when hit by raindrops. It is measured using a standardized simulated rainfall event on a sieve containing soil aggregates between 0.25 and 2.0 mm. The fraction of soil that remains on the sieve determines the percent aggregate stability.

Surface Hardness: is a measure of the maximum penetration resistance (psi), or compaction, encountered in the soil surface (0-6 inch depth) determined using a field penetrometer (field measurement).

Subsurface Hardness: is a measure of the maximum penetration resistance (psi) encountered in the soil subsurface (6-18 inch depth) determined using a field penetrometer (field measurement).

Chemical Properties

Nutrient Analysis/pH: A standard soil test analysis package measures levels of plant nutrients and pH. Measured levels are interpreted in the assessment's framework in terms of sufficiency and excess but no crop-specific recommendations are provided.

Soil Organic Carbon Saturation Estimation

Soil texture and SOM data were used to estimate the amount of soil organic carbon (SOC) that could be stabilized on silt and clay particles to highlight the cropping systems with the greatest potential for carbon stabilization. SOM was converted to SOC by multiplying by 0.65, which is based on correlations between % SOM and % SOC. Then the carbon saturation potential for the silt and clay fraction was determined by applying a regression equation to convert the percentage of silt and clay into g silt and clay C kg^{-1} soil units (Eq. 1; Six et al., 2002).

$$\text{g silt and clay C kg}^{-1} = (\text{Silt \%} + \text{Clay \%}) \times 0.32 + 16.33 \qquad (1)$$

Statistical Analyses

ANOVA models with soil texture or cropping system as fixed effects were used to assess differences in the biological, physical, and chemical soil parameters. Multiple comparisons were made using a Tukey adjustment at $\alpha=0.05$ with the R package Agricolae (De Mendiburu, 2017). Variance component analysis was used to evaluate how well soil texture and cropping system factor levels could explain variance in different indicators. Pearson correlation coefficients were used to assess relationships among indicators. Furthermore, principal component analysis (PCA) was used to investigate relationships among soil health indicators. Principal components with eigenvalues greater than one were included in the eigenvalue analysis (Jolliffe, 2002). All statistical analyses were run using the R statistical software (R Core Team, 2019).

Results and Discussion

Overview

Soils are affected by a combination of inherent and anthropogenic factors. A soil's inherent properties are shaped over millennia by the interaction among a location's unique soil forming factors: parent material, climate, relief, biology, and time. Inherent properties such as soil texture and mineralogy exert strong controls on the amount of storable carbon and nutrients, native pH, water holding capacity, drainage, and more. However, in agriculture and many other environments, human activities have increasingly become a dominant force of change on the landscape. Tillage, crop rotations, as well as carbon and nutrient flows through erosion, organic amendments, and residue harvesting choices have dramatically altered the "natural" carbon and nutrient balances and the physical and biological health of the soil (Wills et al., 2017).

In the past 100 years, soil scientists have classified and mapped the inherent soil types across virtually all of the United States (US) of America, which is available through Web Soil Survey or SoilWeb (which is also available as an App). This inventory of the nation's naturally occurring soils has been increasingly superimposed by human management through the rate of organic matter depletion/accrual, erosion, compaction, and aggregation. Hence, the quantity and quality of soil organic matter, physical soil structure, and available water storage are dynamic properties that are changed by cultural practices. The following sections examine the effects of soil texture, cropping system, and their interaction on various biological, physical, and chemical properties.

Variance Components Analysis

The analysis of the NYS soil health dataset demonstrated that soil texture, an inherent soil property, and human management through cropping systems both exert strong controls on various soil health parameters. A variance

Table 2. Variance components analysis percentages for eight soil health indicators.

Variance Components	SOM	ActC	Protein	Resp	AgStab	AWC	Surface H	Subsurface H
	%	%	%	%	%	%	%	%
Texture	19	9	3	4	3	35	0	1.6
Cropping System	19	12	22	30	32	6	1.5	3.6
Texture x System	6	1	9	9	0	2	0	0
Error	56	78	67	57	64	57	98.5	94.7

component analysis showed how much soil health indicators were affected by either soil texture or cropping system (Table 2; Table A5). The analysis revealed that certain properties were defined mostly by soil texture while others were mostly impacted by cropping system, and yet others were impacted equally by both. Soil texture explained six times more variation in AWC than cropping system. Whereas, cropping system explained approximately 10 times more variation in AgStab, Protein, and Resp values than soil texture. Cropping system and soil texture explained an equal amount of variance in SOM and ActC. This analysis, therefore, reveals that human management especially impacts the biological indicators of labile carbon and nitrogen pools which also strongly affects the soil's structural stability, across all soil types. However, a significant amount of the variance remained unexplained (error), suggesting field-to-field varying factors are also significant. This was especially true for surface and subsurface hardness where very small percentages of variation were explained by either soil texture or cropping system.

The Effect of Soil Texture on Soil Health Indicators

Soil texture is a dominant inherent soil property that exerts strong controls on a soil's ability to function. In order to evaluate the impacts of human land management on the soil health, the effects of underlying inherent soil properties (i.e. soil texture) on biological, physical, and chemical parameters needs to be understood.

Biological

The quantity and quality of SOM is strongly controlled by a soil's textural class. Soils with higher concentrations of silt and clay (fine-textured) can store more organic matter (SOM) than sandy (coarse-textured) soils due to the large amount of surface area that can bind with organic molecules (Lützow et al., 2006). Accordingly, in the NY SH database, fine-textured soils had higher SOM, Resp, Act C, and Protein than coarse-textured soils by 79%, 59%, 56%, and 13% respectively (Table 3, Table A6). Specifically, SOM, ActC, and Resp were highest in fine-textured soils, followed by silt

Table 3. Mean values of biological soil health indicators and indices across four soil texture groups. Mean values followed by different superscripted letters are significantly different at the 0.05 error level. Values in parentheses are 1 standard deviation of the mean.

Texture	n	SOM %	ActC mg kg^{-1}	ActC/SOM %	Protein mg g^{-1}	Protein/SOM %	Resp mg CO_2 g^{-1} 4 days^{-1}
Coarse	336	2.4^{d} (1.4)	440^{d} (258)	1.9^{a} (0.5)	6.8^{a} (4.5)	28.4^{a} (7.3)	0.49^{d} (0.25)
Loam	522	3.0^{c} (1.2)	495^{c} (197)	1.7^{b} (0.4)	6.1^{b} (3.0)	20.5^{b} (5.8)	0.58^{c} (0.23)
Silt loam	544	3.5^{b} (1.4)	533^{b} (214)	1.5^{c} (0.4)	7.3^{a} (3.2)	20.9^{b} (4.5)	0.68^{b} (0.31)
Fine	54	4.3^{a} (0.9)	686^{a} (189)	1.6^{bc} (0.4)	7.7^{a} (3.7)	17.8^{c} (7.1)	0.78^{a} (0.36)
All	1456	3.1 (1.4)	504 (224)	1.7 (0.5)	6.8 (3.5)	22.4 (6.7)	0.61 (0.29)

loam, loam, and coarse-textured soils. Protein did not show the pattern of an increasing concentration in finer texture groups. This is probably due to a lower Protein extraction efficiency in soils with a higher clay content (Giagnoni et al., 2013). Additionally, Protein/SOM and ActC/SOM, two organic matter quality indices, also showed lower values for finer textured soils. Protein/SOM and ActC/SOM were 60% and 19% higher in coarse-textured soils than in fine-textured soils (Table 3, Table A6), which suggests lower relative ability to extract protein in finer textured soils. It also suggests greater proportions of high-quality "fresh" organic matter relative to the stable and mineral-bound organic matter in coarse-textured soils.

Physical

Soil texture exerted a dominant control on AWC but showed weaker relationships with the other soil physical parameters: AgStab and soil hardness. The effect of soil texture on AWC has been well studied and coarse-textured (sandy, gravelly) soils store less water because large pores between sand particles cannot hold on to water against gravity. Specifically, as sand content increases, AWC goes down ($r = -0.70$). In contrast, fine-textured (clayey) soils can store the most water, but some of that is tightly held in micropores and is unavailable to plants. Soils with intermediate textures (silt loams and loams) are known to store the most plant available water. In agreement with past results, we found that silt content was positively correlated with AWC ($r = 0.72$), and that silt loams and silty clay loam soils had the highest AWC (Brady and Weil, 2008; Table A7). Silt loam soils had 273%, 139%, 47%, and 28% higher AWC than sand, loamy sand, sandy loam, and loam soil textures (Table A7, Figure A1). We used seven texture classes due to the strong texture dependence of AWC. Fine-textured soils had very similar AWC to silt loam soils despite the different grouping because they were only marginally different (fine-textured soils had a mean clay content of 31.7 %, putting these samples just above the 27% upper limit for the silt loam texture class).

Contrary to previous findings that higher concentrations of clay content leads to greater aggregate stability (Lado et al., 2002), there was no interpretable effect of soil texture on AgStab. In fact, coarse-textured soils had a slightly higher AgStab than loam and fine-textured soils (Table 4, Table A7). This may be an artifact of the analysis methodology, where a smaller portion of material capable of passing through the 0.25 mm sieve is tested in coarse-textured soils. Additionally, the high silt contents in NY soils combined with the fact that very few samples have high clay content may make it difficult to observe this phenomenon in our data (Bradford et al., 1987; Lado et al., 2002). The most likely explanation is that the cropping system effect on AgStab is so strong that it makes it difficult to observe relationships between soil texture and AgStab.

The effects of soil texture on surface and subsurface hardness were more difficult to resolve in this dataset. A major reason is that soil hardness readings are affected by the moisture content of the soil, a factor that is difficult to constrain within the database. Despite this constraint, silt loams had a slightly higher subsurface hardness than loam soils (Table 5). Research has shown that fine-textured soils tend to have a higher penetration resistance than coarser textured soils with a similar bulk density (Daddow and Warrington, 1983).

Table 4. Mean values of physical soil health indicators across four soil texture groups. Mean values followed by different superscripted letters are significantly different at the 0.05 error level. Values in parentheses are 1 standard deviation of the mean.

Texture	n	AgStab	AWC
		%	g H_2O g^{-1} soil
Coarse	336	36.6[a] (23.3)	0.17[c] (0.06)
Loam	522	31.1[b] (21.8)	0.21[b] (0.04)
Silt loam	544	33.2[ab] (25.2)	0.27[a] (0.06)
Fine	54	28.5[b] (20.5)	0.26[a] (0.07)
All	1456	33.0 (23.5)	0.23 (0.07)

Table 5. Mean values of surface and subsurface hardness (H) across four texture groups. Different superscripted letters after mean values are significantly different at the 0.05 error level. Values in parentheses are 1 standard deviation of the mean.

Texture	n	Surface H	Subsurface H
		psi	psi
Coarse	188	177 (81)	315[ab] (123)
Loam	343	166 (85)	306[b] (103)
Silt loam	307	175 (75)	336[a] (112)
Fine	30	148 (94)	282[b] (91)
All	868	171 (81)	317 (112)

Chemical

Soil texture affects the availability of several macronutrients and micronutrients in the soil. Notably, extractable phosphorus, potassium, magnesium, and zinc levels varied across texture groups (Table 6, Table A8). Whereas extractable iron and manganese did not consistently differ among texture groups.

Extraction of phosphorus (P), and to a lesser extent zinc, is reduced in fine-textured soils compared to coarse-textured soils. Specifically, the mean for P in coarse-textured soils was 4.4 times higher than in fine-textured soils (Table 6, Table A8). This has been confirmed in the literature (Kamprath and Watson, 1980; Wuenscher et al., 2015; Zheng et al., 2003). Lower extractable P in finer textured soils is related to the ability of soils with a higher clay content or exchangeable aluminum (Al) and iron (Fe) to fix more phosphorus (Cox, 1994, Zheng et al., 2003). I.e., they have a larger buffering capacity, meaning that per unit of applied P, extractable P will rise more slowly. Wyoming is the only state in the US that uses soil texture to modify the soil's ability to fix phosphorus (Sharpley et al., 2003). Vermont uses extractable Al to modify a soils ability to fix P (Magdoff et al., 1999; University of Vermont Extension, 2018).

In contrast, extractable potassium (K) and magnesium (Mg) levels were higher in fine-textured soils compared to coarse-textured soils. The former have higher cation exchange capacities (CEC), which allows them to maintain higher levels of extractable base cations. Furthermore, the weathering of clay minerals provides a steady supply of potassium and magnesium.

Table 6. Mean values of soil chemical properties across four soil texture groups. Different superscripted letters after mean values are significantly different at the 0.05 error level. Values in parentheses are 1 standard deviation of the mean.

Texture	n	pH 1:2 H_2O	P ppm	K ppm	Mg ppm	Fe ppm	Mn ppm	Zn ppm
Coarse	336	6.4^{b} (0.7)	23.2^{a} (45.2)	93^{d} (69)	131^{c} (91)	5.6^{a} (8.7)	9.4^{b} (8.3)	2.5^{a} (7.1)
Loam	522	6.7^{a} (0.8)	16.9^{b} (24.9)	118^{c} (76)	201^{b} (108)	3.4^{b} (5.6)	11.4^{a} (6.3)	1.3^{b} (2.1)
Silt loam	544	6.3^{c} (0.6)	13.0^{bc} (11.3)	131^{b} (74)	188^{b} (97)	5.6^{a} (11.6)	12.5^{a} (9.3)	1.3^{b} (1.6)
Fine	54	6.7^{a} (0.7)	6.3^{c} (7.0)	160^{a} (84)	379^{a} (196)	3.8^{ab} (3.9)	11.2^{ab} (7.5)	1.0^{b} (1.6)
All	1456	6.5 (0.7)	16.5 (27.6)	119 (76)	187 (115)	4.8 (9.0)	11.3 (8.1)	1.6 (3.8)

The Effect of Cropping System on Soil Health Indicators

Human activities exert tremendous control over the health of the soil through the implementation of tillage, crop rotation, organic amendment, and residue harvesting practices. The cropping system categories highlighted in this analysis integrate some key differences in these various practices. *Pastures* maintain the best soil health because these fields are seldom disturbed by tillage and receive year-round root and shoot inputs, as well as manure droppings. *Mixed Vegetable* are often grown organically where compost and other organics are used to maintain soil fertility. *Dairy Cropping* systems can maintain soil health due to cycling of carbon and nutrients through manure inputs and rotations with perennial hay. In contrast, *Annual Grain* and *Processing Vegetable* systems are intensively managed and typically do not have the ability to apply enough organic amendments to replace the organic carbon that is lost each year (typically 50-80% of the carbon and nutrients are harvested and exported off the farm). Highlighting the effects of different cropping systems on biological, physical, and chemical soil health parameters can help farmers, agricultural professionals, and policymakers to identify opportunities lie to improve soil health.

Biological

Cropping systems strongly impact the *quantity* and *quality* of SOM, which were assessed using the four biological soil health indicators. Undisturbed Pasture soils accrue and maintain SOM due to year-round root and shoot inputs, potential manure droppings and an absence of tillage. As a result, Pasture systems maintained 67%, 55%, and 32%, respectively, higher SOM than Processing Vegetable, Annual Grain, and Dairy Cropping systems (Table 7). The percentage of SOM in pasture soils represents a good upper limit for what may be stored for each texture group. Small-scale diversified Mixed Vegetable farms also showed high SOM levels, presumably due to repeated additions of organic amendments such as compost or manure and intensive cover cropping. When all samples were combined regardless of texture, Pasture had the highest SOM followed by Mixed Vegetable, Dairy Crop, and Annual Grain and Processing Vegetable (Table 7). Intensive tillage and infrequent additions of organic amendments keep Annual Grain and Processing Vegetable systems with lower SOM.

Labile organic matter indicators, including ActC, Protein, and Resp, were similarly high in Pasture systems. Interestingly, Dairy Crop systems on loam textured soils had similar ActC values compared to Pasture and Mixed Vegetable systems, despite lower SOM and Protein (Figure 4), suggesting that manure applications or alfalfa in the rotation help increase ActC. Protein was consistently higher in Pasture and Mixed Vegetable farms across soil textures indicating that organic nitrogen reserves were higher in these soils. It is noteworthy that trends in ActC and Protein are not always the same across cropping systems.

Unlike ActC and Protein, Resp was consistently much higher in Pasture systems than other systems on loam and silt loam soils. While greater availability of organic substrates is likely an important explanation, Pasture soils had proportionally higher Resp rates than would be predicted from differences in SOM. For example, Pasture systems had 57% and 111% higher Resp rates than mixed veg systems, but only 5% and 35% higher SOM than Mixed Vegetable systems, on loam and silt loam soils (Table 7). Two explanations are possible. First, sampling and processing of undisturbed pasture soils in the lab (where they are sieved and crushed) allows microbes to access labile organic matter that was previously protected. A second hypothesis is that the sealed chamber alkali trap method may lead to higher respiration rates in soils with a larger fungal/bacterial ratio due to the high humidity inside the jar. In a study comparing soil respiration of soil collected under different cover crop treatments, Finney et al. (2017) found that the fungal/bacterial ratio of the sample was the best predictor of soil respiration rates in the lab.

The organic matter *quality* indices, ActC/SOM and Protein/SOM were not able to detect differences in SOM quality across different cropping systems. The only instance of a trend was the lower ActC/SOM in Pasture and Mixed Vegetable soils compared to Dairy Crop and Annual Grain soils. One problem with the ActC/SOM calculation is that it is negatively correlated with SOM, meaning that soils with higher SOM tend to have a lower ActC/SOM. It is believed that this is partly a texture effect as discussed above (fine-textured soils generally contain more SOM, but a larger fraction is stable, mineral-bound, and less biologically active).

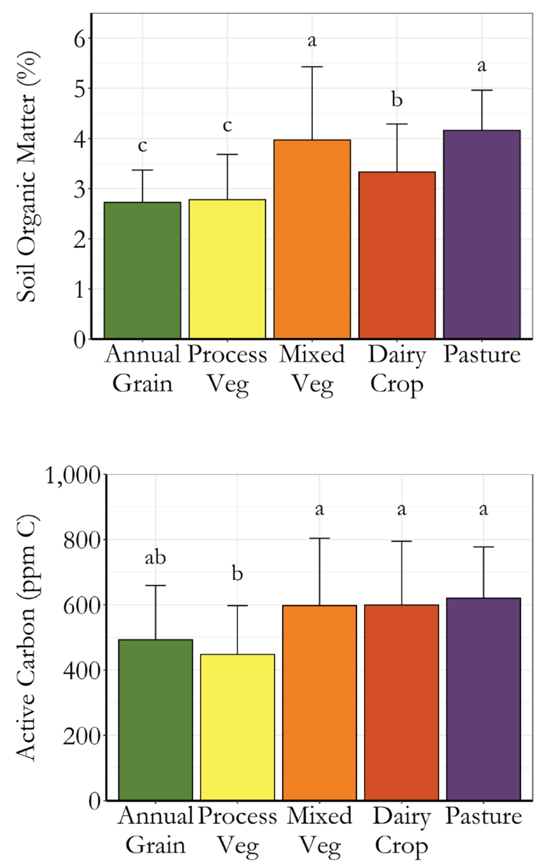

Figure 4. Mean soil organic matter and active carbon across cropping systems on **loam** textured soils. Error bars represent 1 standard deviation of the mean and letters indicate significance at the 0.05 error level.

Table 7. Mean values of soil biological properties (1 standard deviation in parentheses) by cropping system and soil texture. Mean values followed by different superscripted letters are significantly different at the 0.05 error level.

Cropping System	n	SOM	ActC	ActC/SOM	Protein	Protein/SOM	Resp
		%	mg kg^{-1}	%	mg g^{-1}	%	mg CO_2 g^{-1} 4 days^{-1}
Coarse-Textured							
Annual Grain	26	2.1^{b} (0.6)	346^{c} (130)	1.7 (0.5)	5.5^{b} (2.1)	25.9 (4.2)	0.45^{ab} (0.18)
Process Veg	22	2.0^{b} (0.8)	386^{bc} (191)	1.8 (0.7)	5.2^{b} (2.3)	25.8 (5.1)	0.38^{b} (0.25)
Mixed Veg	24	3.4^{a} (1.5)	574^{a} (279)	1.7 (0.5)	10.0^{a} (5.1)	29.1 (6.7)	0.57^{a} (0.28)
Dairy Crop	19	2.0^{b} (1.1)	400^{abc} (273)	1.9 (0.7)	5.0^{b} (2.2)	27.3 (9.7)	0.41^{ab} (0.22)
Pasture	11	3.3^{a} (0.8)	571^{ab} (167)	1.8 (0.5)	8.3^{ab} (2.2)	25.8 (7.1)	0.65^{a} (0.21)
All	102	2.5 (1.2)	443 (234)	1.8 (0.6)	6.7 (3.7)	26.9 (6.6)	0.48 (0.25)
Loam							
Annual Grain	110	2.7^{c} (0.6)	493^{ab} (166)	1.8^{a} (0.5)	5.0^{c} (1.1)	18.9^{b} (4.1)	0.51^{cd} (0.14)
Process Veg	45	2.8^{c} (0.9)	448^{b} (150)	1.7^{ab} (0.6)	5.5^{bc} (2.3)	19.9^{ab} (3.7)	0.47^{d} (0.18)
Mixed Veg	26	4.0^{a} (1.5)	598^{a} (206)	1.5^{b} (0.3)	8.8^{a} (4.5)	21.4^{a} (4.4)	0.60^{bc} (0.22)
Dairy Crop	53	3.3^{b} (1.0)	600^{a} (195)	1.8^{a} (0.4)	6.3^{b} (2.1)	19.3^{ab} (3.7)	0.65^{b} (0.20)
Pasture	11	4.2^{a} (0.8)	620^{a} (158)	1.5^{b} (0.3)	8.8^{a} (2.7)	21.1^{ab} (4.1)	0.94^{a} (0.26)
All	245	3.1 (1.0)	525 (183)	1.7 (0.5)	5.9 (2.6)	19.5 (4.0)	0.56 (0.21)
Silt Loam							
Annual Grain	52	3.4^{bc} (1.0)	526^{bc} (191)	1.6 (0.5)	6.8^{bc} (2.4)	20.0 (4.3)	0.57^{b} (0.15)
Process Veg	38	3.1^{c} (1.2)	483^{c} (227)	1.6 (0.5)	6.1^{c} (2.4)	20.5 (3.6)	0.53^{b} (0.22)
Mixed Veg	35	4.0^{b} (1.3)	623^{ab} (196)	1.6 (0.3)	8.1^{b} (2.8)	20.5 (3.6)	0.55^{b} (0.19)
Dairy Crop	28	3.8^{bc} (1.2)	575^{abc} (178)	1.5 (0.3)	7.3^{bc} (2.3)	19.1 (2.2)	0.64^{b} (0.17)
Pasture	21	5.4^{a} (1.4)	702^{a} (170)	1.3 (0.3)	10.2^{a} (2.8)	19.4 (3.6)	1.16^{a} (0.36)
All	174	3.8 (1.3)	566 (206)	1.5 (0.4)	7.4 (2.8)	20.0 (3.6)	0.64 (0.29)
Fine-Textured							
Annual Grain	7	4.1 (0.9)	615 (160)	1.5 (0.2)	6.2 (1.0)	15.3 (1.7)	0.57 (0.14)
Dairy Crop	16	4.2 (0.8)	704 (103)	1.7 (0.2)	5.8 (2.0)	13.5 (2.8)	0.64 (0.13)
All	23	4.2 (0.8)	677 (126)	1.6 (0.2)	5.9 (1.7)	14.1 (2.6)	0.56 (0.13)
All							
Annual Grain	195	2.9^{d} (0.9)	487^{b} (178)	1.7^{ab} (0.5)	5.6^{b} (1.9)	19.9^{b} (4.8)	0.52^{cd} (0.15)
Process Veg	106	2.7^{d} (1.1)	450^{b} (192)	1.7^{ab} (0.6)	5.7^{b} (2.3)	21.4^{ab} (4.6)	0.47^{d} (0.22)
Mixed Veg	86	3.9^{b} (1.5)	608^{a} (230)	1.6^{ab} (0.4)	9.0^{a} (4.2)	23.0^{a} (6.2)	0.58^{bc} (0.23)
Dairy Crop	116	3.4^{c} (1.2)	575^{a} (213)	1.7^{a} (0.4)	6.3^{b} (2.2)	19.7^{b} (6.2)	0.60^{b} (0.21)
Pasture	46	4.5^{a} (1.4)	647^{a} (167)	1.5^{b} (0.4)	9.2^{a} (2.7)	21.2^{ab} (5.6)	0.99^{a} (0.36)
All	549	3.3 (1.3)	531 (207)	1.7 (0.5)	6.6 (2.9)	20.7 (5.5)	0.58 (0.25)

Physical

The different cropping systems exerted a stronger control on AgStab than the other two physical soil health indicators: AWC and soil compaction. Pasture soils had the highest AgStab compared with than soils from other cropping systems in all texture groups. Specifically, AgStab was 2.6, 2.3, 2.0, and 1.6 times higher than Processing Vegetable, Annual Grain, Dairy Crop, and Mixed Vegetable systems, respectively (Table 8). High SOM in undisturbed Pasture systems and intact root systems and their associated arbuscular mycorrhizal fungi (AMF) help build and maintain stable macroaggregates. Meanwhile, conventional tillage has been shown to decrease aggregate stability compared to no-till and perennial systems (Nunes et al., 2018). Mixed Vegetable systems maintained 59%, 46%, and 22% higher AgStab than Processing Vegetable, Annual Grain, and Dairy Crop systems (Table 8) despite the use of intensive tillage to manage weeds and nutrients in this system (Mixed Veg. systems were often organic operations that cannot rely on herbicides for weed management). This is presumably due to the more common use of composts and other organic amendments in Mixed Vegetable systems that help to build and maintain SOM and Protein. Both SOM and Protein have a positive effect on AgStab ($r = 0.61$ *and* $r = 0.56$, *respectively*; Table A9).

Cropping systems that maintain higher % SOM levels can positively affect AWC, but this effect is stronger in coarser textured soils than other texture groups. The claim that "one percent of organic matter in the top six inches of soil would hold approximately 27,000 gallons of water per acre" is often used to promote soil organic matter management. While this number is likely an over-exaggeration of reality as evidenced by a recent study by Libohova et al. (2018) who found that this number was closer to 2,850 gallons of available water stored per acre, it is known that increasing SOM is an important strategy to increasing AWC. Furthermore, our research and other's research show that SOM was more strongly related to AWC in coarse-textured soils ($r = 0.48$) compared to loam ($r = 0.14$) or silt loam ($r = 0.12$) textured soils (Table A9). This finding demonstrates that improved organic matter management can lead to increases in AWC in coarse-textured soils to a greater extent than for loam, silt loam, and fine-textured soils. For example, coarse-textured Pasture soils had a 40%, 31%, and 62% higher AWC than coarse-textured Annual Grain, Processing Vegetable, and Dairy Crop soils. While silt loam textured Pasture soils only had 27%, 17%, and 8% higher AWC than Annual Grain, Processing Vegetable, and Dairy Crop soils.

While the effects of cropping system on soil compaction were not consistent across soil textures, two logical insights were illustrated in the data. First, in coarse-textured soils, Dairy Crop fields experienced 60% greater surface hardness issues than Annual Grain fields. High surface and subsurface compaction issues on NYS dairy farms is likely due to heavy equipment traffic that often occurs under marginally dry soil conditions. Second, when all samples were considered, Processing Vegetable farms experienced 24% greater subsurface compaction issues compared to Mixed Vegetable farms. This can be best explained by the benefits of higher SOM for reducing soil density (Table 8).

Table 8. Mean physical soil health indicator values (standard deviation in parentheses) by cropping system and soil texture. Mean values followed by different superscripted letters are significantly different at the 0.05 error level. Note that surface and subsurface hardness measurements have smaller samples sizes than AgStab and AWC and as a result some categories were excluded due to inadequate sample size.

Cropping System	n	AgStab	AWC	n	Surface H	Subsurface H
Coarse-Textured						
		%	g H_2O g^{-1} soil		psi	psi
Annual Grain	26	32.6^{bc} (16.7)	0.15ab (0.04)	25	134^{b} (92)	297 (135)
Process Veg	22	27.2^{c} (16.3)	0.16ab (0.06)	20	155^{ab} (84)	317 (140)
Mixed Veg	24	44.2^{b} (18.6)	0.18a (0.04)	10	188^{ab} (33)	264 (45)
Dairy Crop	19	29.1^{bc} (14.1)	0.13b (0.06)	15	214^{a} (89)	340 (131)
Pasture	11	64.5^{a} (24.3)	0.21a (0.07)	-	-	-
All	102	37.0 (20.9)	0.16 (0.06)	70	165 (87)	307 (127)
Loam						
Cropping System	**n**	**AgStab**	**AWC**	**n**	**Surface H**	**Subsurface H**
		%	g H_2O g^{-1} soil		psi	psi
Annual Grain	110	27.4^{c} (14.5)	0.19c (0.04)	98	171 (99)	307 (98)
Process Veg	45	25.3^{c} (17.5)	0.19c (0.04)	39	165 (85)	337 (105)
Mixed Veg	26	37.7^{b} (18.4)	0.22ab (0.03)	-	-	-
Dairy Crop	53	39.5^{b} (18.0)	0.20bc (0.05)	-	-	-
Pasture	11	64.7^{a} (18.9)	0.24a (0.04)	42	186 (82)	320 (90)
All	245	32.4 (18.7)	0.20 (0.04)	179	173 (92)	316 (98)
Silt Loam						
Cropping System	**n**	**AgStab**	**AWC**	**n**	**Surface H**	**Subsurface H**
		%	g H_2O g^{-1} soil		psi	psi
Annual Grain	52	34.3^{c} (20.2)	0.22c (0.05)	47	167 (106)	292 (100)
Process Veg	38	30.1^{c} (24.5)	0.24bc (0.05)	30	164 (79)	340 (92)
Mixed Veg	35	47.7^{b} (21.7)	0.27ab (0.06)	14	139 (70)	267 (32)
Dairy Crop	28	37.5^{bc} (22.4)	0.26ab (0.06)	18	191 (59)	283 (74)
Pasture	21	74.7a (14.4)	0.28a (0.06)	13	189 (75)	300 (61)
All	174	41.5 (25.1)	0.25 (0.06)	122	168 (87)	301 (88)
Fine-Textured						
Cropping System	**n**	**AgStab**	**AWC**	**n**	**Surface H**	**Subsurface H**
		%	g H_2O g^{-1} soil		psi	psi
Annual Grain	7	26.6 (10.1)	0.23 (0.02)	-	-	-
Dairy Crop	16	28.6 (17.3)	0.22 (0.05)	-	-	-
All	23	28.0 (15.3)	0.22 (0.05)	-	-	-
All						
Cropping System	**n**	**AgStab**	**AWC**	**n**	**Surface H**	**Subsurface H**
		%	g H_2O g^{-1} soil		psi	psi
Annual Grain	195	29.9^{cd} (16.6)	0.20b (0.05)	176	165 (100)	301^{ab} (103)
Process Veg	106	27.4^{d} (19.8)	0.20b (0.06)	90	162 (81)	332^{a} (109)
Mixed Veg	86	43.7^{b} (20.2)	0.23a (0.06)	32	156 (70)	267^{b} (48)
Dairy Crop	116	35.8^{c} (19.0)	0.20b (0.07)	90	182 (88)	305^{ab} (97)
Pasture	46	70.2^{a} (18.4)	0.25a (0.06)	29	198 (66)	286^{ab} (52)
All	549	36.2 (21.8)	0.21 (0.06)	417	170 (90)	305 (98)

Chemical

Unlike biological and physical properties, routine testing and recommendations for different crops are well established for soil chemical properties. Therefore, soil chemical properties tend to be in line with recommendations for highly managed systems such as Annual Grain production (Table 9). Pasture systems, which are less intensively managed and have lower nutrient requirements, tend to have a lower pH than Annual Grain crop and Dairy Crop systems. This is likely a geographical issue related to the higher prevalence of pastures on hilly soils with naturally lower pH in the southern parts of the state.

Phosphorus, an essential macronutrient, can pose an environmental threat to water bodies if it has built up in soils and is subject to runoff or erosion. When all samples were considered, phosphorus was highest in Mixed Vegetable systems, followed by Processing Vegetable, Dairy Crop, Annual Grain, and Pasture systems (Table 9). This indicates that the repeated application of organic amendments (compost, manure) on organic mixed vegetable farms to maintain soil fertility and health may result in excessive P buildup (especially on coarse-textured soils in our data set). But these operations also tend to be less than ten acres in size and may pose only a modest risk for water quality.

Interestingly, zinc was also consistently higher in mixed vegetable systems compared to other cropping systems, which is likely due to the high SOM levels and use of compost amendments.

Soil Health Scoring Functions for New York State

The CASH soil health assessment framework interprets laboratory results through scoring functions that rate a soil sample within a larger population of measured values. For physical and biological soil health indicators the Cornell Soil Health Laboratory uses scoring functions based on the cumulative normal distribution function that uses the mean and standard deviation values as parameters. To date, the Cornell SH Lab has scored biological and physical soil health indicators based on coarse, medium, and fine texture groups for certain indicators (Moebius-Clune et al., 2017). These scoring functions were updated in 2017 based on an analysis of a large dataset (n=5,767) containing Midwest, Northeast, and Mid-Atlantic soils (Fine et al., 2017; Moebius-Clune et al., 2017) and insights from long-term research sites in New York. This research provides the data necessary to define scoring functions for New York State's soils and allows farmers to evaluate fields relative to those with the same soil type and cropping systems.

There are inherent challenges with defining one-size-fits-all soil health scoring functions by combining data from different regions with different textures and cropping systems. van Es and Karlen (2019) illustrated that these scoring functions should not be applied outside the Midwest, Northeast, and Mid-Atlantic without careful consideration. For example, most fine-textured samples in the 2017 dataset came from Midwestern cash grain systems. This resulted in lower mean biological indicator values for fine-textured soils than they would have been if only the Northeast was considered (Fine et al., 2017).

Table 9. Mean chemical soil property values by cropping system and soil texture. Mean values followed by different superscripted letters are significantly different at the 0.05 error level.

Coarse-Textured

Cropping System	n	pH	P	K	Mg	Fe	Mn	Zn
		1:2 H_2O	ppm	ppm	ppm	ppm	ppm	ppm
Annual Grain	26	6.4	11.0^{b}	119	113	4.5^{ab}	9.2	0.8^{b}
Process Veg	22	6.1	16.4^{ab}	99	105	4.8^{ab}	7.5	1.0^{b}
Mixed Veg	24	6.3	69.9^{a}	121	169	5.5^{a}	8.0	2.1^{a}
Dairy Crop	19	6.5	15.9^{ab}	112	129	1.8^{ab}	9.3	1.0^{b}
Pasture	11	6.4	13.1^{ab}	80	172	6.1^{a}	9.6	1.4^{ab}
All	102	6.3	27.1	110	134	4.5	8.6	1.3

Loam

Cropping System	n	pH	P	K	Mg	Fe	Mn	Zn
		1:2 H_2O	ppm	ppm	ppm	ppm	ppm	ppm
Annual Grain	110	6.8^{a}	13.3^{b}	112^{b}	213^{a}	2.1^{b}	11	0.7^{b}
Process Veg	45	6.5^{ab}	28.9^{a}	131^{ab}	165^{b}	3.0^{ab}	9.9	1.1^{b}
Mixed Veg	26	6.6^{ab}	22.2^{ab}	158^{a}	208^{ab}	2.9^{ab}	12	3.5^{a}
Dairy Crop	53	6.8^{a}	18.8^{ab}	132^{ab}	234^{a}	2.0^{b}	12	1.3^{b}
Pasture	11	6.2^{b}	4.5^{b}	82^{b}	259^{a}	4.6^{a}	13	0.6^{b}
All	245	6.7	17.9	123	210	2.5	11	1.2

Silt Loam

Cropping System	n	pH	P	K	Mg	Fe	Mn	Zn
		1:2 H_2O	ppm	ppm	ppm	ppm	ppm	ppm
Annual Grain	52	6.2^{ab}	11	135	188^{ab}	4.1	10.9	0.7^{b}
Process Veg	38	6.1^{b}	17	136	146^{b}	7.6	9.9	1.1^{b}
Mixed Veg	35	6.3^{ab}	13	114	178^{ab}	4.0	12.3	3.5^{a}
Dairy Crop	28	6.5^{a}	13	147	202^{ab}	4.4	12.2	1.3^{b}
Pasture	21	6.0^{b}	8.8	113	232^{a}	14	13.0	0.6^{b}
All	174	6.2	13	130	185	6.1	11.3	1.2

All

Cropping System	n	pH	P	K	Mg	Fe	Mn	Zn
		1:2 H_2O	ppm	ppm	ppm	ppm	ppm	ppm
Annual Grain	195	6.6^{ab}	12^{b}	120^{ab}	204^{a}	3.1^{b}	10.8	0.8^{b}
Process Veg	106	6.3^{c}	21.6^{ab}	128^{ab}	147^{b}	5.0^{b}	10.6	1.4^{b}
Mixed Veg	86	6.4^{bc}	32.2^{a}	134^{a}	198^{a}	4.1^{b}	11.4	2.4^{a}
Dairy Crop	116	6.7^{a}	15.1^{b}	136^{a}	228^{a}	2.5^{b}	11.2	1.1^{b}
Pasture	46	6.1^{c}	8.6^{b}	96^{b}	225^{a}	9.3^{a}	13.5	1.0^{b}
All	549	6.5	17.4	125	199	4.0	11.2	1.3

Therefore, NYS-specific soil health scoring functions are necessary to accurately assess the effects of management within the context of the soil's inherent properties. Furthermore, cropping system information needs to be included to evaluate how a farmer's field compares to other fields under the same management system. For example, rather than hold an Annual Grain farm to the soil health standards of a Dairy Crop soil, it is more appropriate to compare Annual Grain fields amongst each other.

Based on this research the mean and standard deviation values in Tables 7 and 8 can be used to generate texture and cropping system specific scoring functions for New York farms. The NYS data suggests that separate scoring functions by texture groups are warranted for Wet Aggregate Stability, Available Water Capacity, Organic Matter, Active Carbon, Respiration, and Protein. Important differences existed between the 2017 scoring functions and the NY scoring functions for soil respiration and AWC.

Aspirational Soil Health Goals

This report includes a first attempt at developing *aspirational soil health goals* for NYS by soil texture and cropping system. Aspirational goals were defined for each soil texture and cropping system combination by selecting the 75th percentile of the distribution for each biological and physical soil health indicator (Table 10). These aspirational soil health goals provide realistic targets or goals for NYS farmers within the context of their own production environment. Nebraskan researchers are similarly working to advance soil health goals from data generated in Nebraska, which they have called the *soil health gap*. This concept has been likened to the yield gap concept that compares a field's actual yield to its yield potential. The soil health gap concept compares the amount of soil organic carbon in a native pasture to the levels under agricultural management for a given soil type (Maharjan et al., 2020). Our proposed aspirational soil health goals (Table 10) allow farmers to compare their field's soil health indicator within their own cropping system category's goal for a given soil texture, thereby providing a more realistic comparison.

Existing pH and nutrient guidelines were used to define goals for soil chemical properties (Table 11). Soil texture was not included as a modifier for soil chemical properties. The official New York and Vermont guidelines were used to define optimum pH and Modified Morgan soil test values for different systems (Cornell Cooperative Extension, 2016, University of Vermont Extension, 2018). Similar optimum ranges were defined for Annual Grain, Dairy Crop, Processing Vegetable, and Mixed Vegetable. Pasture systems can either be intensively managed or less intensively managed. Lower minimum values were selected to accommodate less intensively managed pasture systems (Table 11).

Guidelines for total heavy metals were derived from Cornell's Healthy Soils, Healthy Communities Project (Healthy Soils Healthy Communities Project, 2015) and are listed in Table 12. Maximum recommended total heavy metal concentrations were selected for human and plant toxicity concerns, depending on which arises first. Copper (Cu), nickel (Ni), and zinc (Zn) can pose toxicity issues for plants before they become concerns for human health. In contrast, arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) mainly pose threats to human health. Furthermore, median, minimum, and Q95 heavy metal concentrations from a NYS DEC survey of total heavy metals in rural NYS from "Source-Distant Surface" sites were used to aid in the interpretation of heavy metal concentrations in rural agricultural soils (New York State Department of Environmental Conservation and New York State Department of Health, 2005; Table 12).

Table 10. Aspirational soil health goals (Q75 Basis) by cropping system and soil texture for biological and physical soil health indicators. Aspirational goals for surface and subsurface hardness are 100 psi and 250 psi for all soil texture groups.

Cropping System	n	SOM	ActC	Protein	Resp	AgStab	AWC
Coarse-Textured							
		%	mg C/kg	mg/g	mg CO_2/g	%	g H_2O g^{-1} soil
Annual Grain	26	2.7	440	6.8	0.54	45	0.18
Process Veg	22	2.2	510	5.7	0.43	30	0.20
Mixed Veg	24	4.5	790	14.1	0.70	59	0.21
Dairy Crop	19	2.5	530	6.0	0.54	38	0.16
Pasture	11	3.8	674	9.5	0.78	84	0.24
Loam							
Cropping System	**n**	**SOM**	**ActC**	**Protein**	**Resp**	**AgStab**	**AWC**
		%	mg C/kg	mg/g	mg CO_2/g	%	g/g
Annual Grain	110	3.2	600	5.4	0.58	36	0.22
Process Veg	45	3.1	500	5.4	0.54	38	0.22
Mixed Veg	26	4.9	740	10.9	0.75	50	0.23
Dairy Crop	53	3.7	680	7.3	0.71	50	0.23
Pasture	11	4.8	720	10.1	1.15	76	0.26
Silt Loam							
Cropping System	**n**	**SOM**	**ActC**	**Protein**	**Resp**	**AgStab**	**AWC**
		%	mg C/kg	mg/g	mg CO_2/g	%	g/g
Annual Grain	52	4.2	710	7.2	0.68	46	0.25
Process Veg	38	3.7	610	7.1	0.62	39	0.29
Mixed Veg	35	4.4	760	9.6	0.75	62	0.30
Dairy Crop	28	4.4	740	7.9	0.72	49	0.29
Pasture	21	6.3	810	12.3	1.47	88	0.32
Fine-Textured							
Cropping System	**n**	**SOM**	**ActC**	**Protein**	**Resp**	**AgStab**	**AWC**
		%	mg C/kg	mg/g	mg CO_2/g	%	g/g
Annual Grain	7	4.6	740	7.2	0.68	46	0.24
Process Veg	*	4.0	650	7.1	0.62	39	0.27
Mixed Veg	*	4.8	800	9.6	0.75	62	0.27
Dairy Crop	16	4.7	780	7.9	0.72	49	0.24
Pasture	*	6.3	850	12.3	1.47	88	0.27

*Not enough fine-textured samples with crop codes. Interpolated based on silt loam values.

Table 11. Established soil pH and Modified Morgan extractable nutrient guidelines for New York State and Vermont.

Cropping System	pH	P	K	Mg	Fe	Mn	Zn
	1:2 H_2O	ppm	ppm	ppm	ppm	ppm	ppm
Annual Grain	6.4-7.3	4.0-21.5	100-160	51-100+	<25	<50	0.5-1.0+
Process Veg	6.4-7.3	4.0-21.5	100-160	51-100+	<25	<50	0.5-1.0+
Mixed Veg	6.4-7.3	4.0-21.5	100-160	51-100+	<25	<50	0.5-1.0+
Dairy System	6.4-7.3	4.0-21.5	100-160	51-100+	<25	<50	0.5-1.0+
Pasture	5.6-7.3	2.1-21.5	51-160	36-100+	<25	<50	0.25-1.0+

Table 3. Recommended maximum total metal concentrations for both human and plant toxicity concerns. Median, minimum, and Q95 total metal concentrations were included from NYS Rural Background.

Metal	Toxicity Concern	Recommended Maximum Concentration ppm	NYS Rural Soil (median) ppm	NYS Rural Background Level (min-Q95) ppm
Arsenic (As)	Human Toxicity	16	5	< 0.2 -12
Barium (Ba)	Human Toxicity	350	67	4-170
Cadmium (Cd)	Human Toxicity	2.5	0.4	< 0.05 – 2.4
Chromium (Cr)	Human Toxicity	36	11	1 - 20
Copper (Cu)	Plant Toxicity	50-150	12	2 - 32
Lead (Pb)	Human Toxicity	400	23	3 - 72
Mercury (Hg)	Human Toxicity	0.8	0.05	0.01 – 0.2
Nickel (Ni)	Plant Toxicity	40-60	11	0 - 25
Zinc (Zn)	Plant Toxicity	150	58	10 - 140

Soil Organic Carbon Sequestration Potential

In recent years, farmers, policy makers, and the public have grown interested in increasing soil organic carbon as a climate mitigation strategy ("carbon farming"). Soil health practices, including reduced tillage, cover crops, organic amendment additions, and perennial crops, have the potential to build and maintain soil organic carbon levels, which can help reduce carbon dioxide (CO_2) levels in the atmosphere (For a complete treatment of opportunities to mitigate climate change in NYS agriculture see: Wightman and Woodbury, 2019; Wightman and Woodbury, 2020). A recent estimate for the United States suggests that it is possible to sequester 68 Tg C yr^{-1} (250 Tg CO_2e) in croplands and grasslands with substantial investments in this area (Chambers et al., 2016). This would be equivalent to approximately 36% of total US agricultural emissions or 3.7% of total US emissions in 2018 (EPA, 2020). One important challenge to those efforts is that carbon sequestration is dependent on keeping those management practices in place (permanence). For example, if long-term no-tilled soils are switched to conventional tillage, then much of the accrued carbon can be lost relatively quickly.

An important consideration is that soils have a limited capacity to store soil organic carbon, meaning that soils can become saturated with respect to carbon. This implies that as a soil approaches its carbon saturation point, carbon inputs in the form of plant residues or organic amendments have decreased efficiency at further increasing soil organic carbon. Correspondingly, carbon inputs have the greatest efficiency to increase SOC in soils that are furthest from their carbon saturation point (Stewart et al., 2007).

Chemical adsorption of SOC to silt and clay particles is the dominant mechanism that stabilizes SOC in the soil (Six et al., 2002). Other carbon stabilization mechanisms, including physical protection within soil aggregates and biochemical recalcitrance of SOC, may also be important, but are more difficult to constrain. A soil's silt-plus-clay content has been shown to be directly related to the maximum quantity of

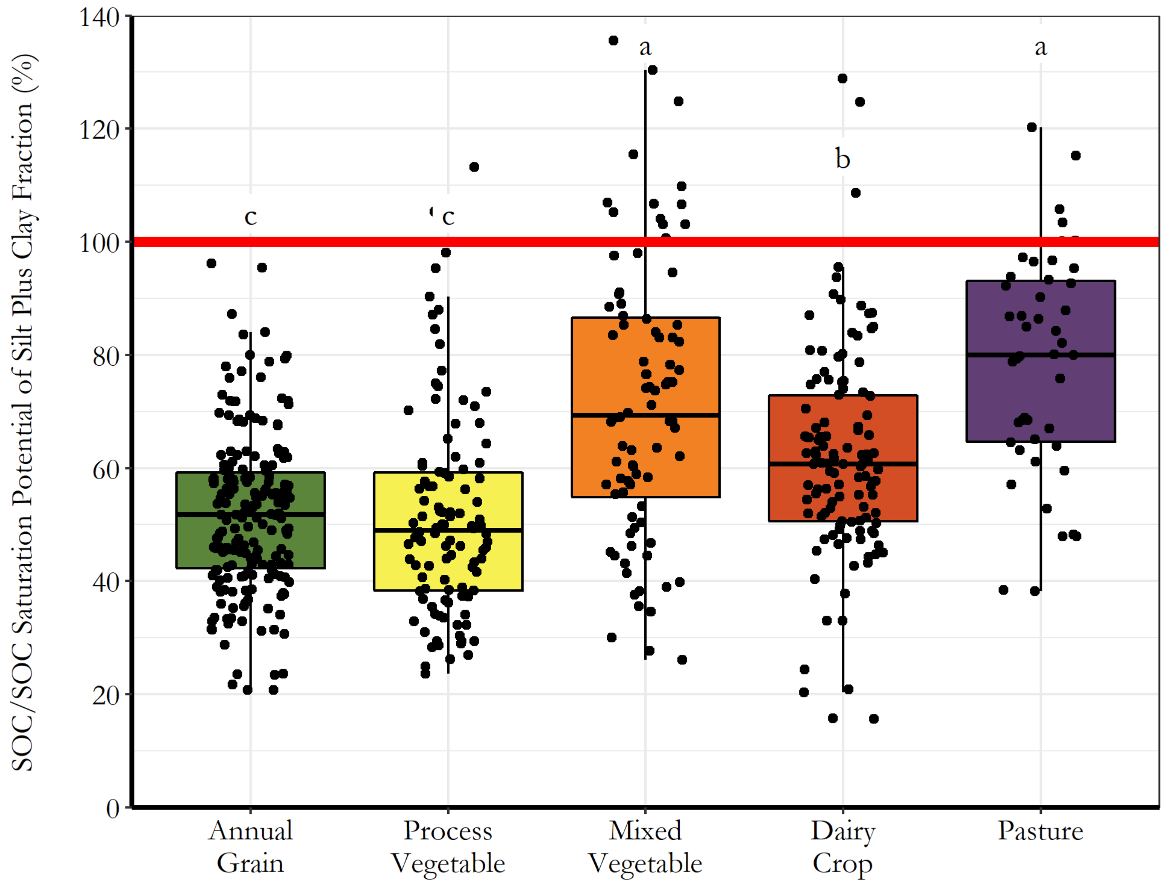

Figure 5. SOC as a fraction of the saturation potential of the silt and clay fraction across different cropping systems (based on grassland systems). The 95% confidence intervals of this regression equation linking silt and clay content to the amount store in this fraction are: Intercept: 16.33+/- 4.69 and Slope: 0.32 +/- 0.07.

SOC that can be held in the silt-plus-clay fraction in grassland soils, thereby implying saturation of this fraction (Six et al., 2002). Once this is saturated, SOC can only build up in more labile fractions of SOC that are less protected and more readily decomposed, and returned to the atmosphere as carbon dioxide. The relative organic carbon saturation of a soil, i.e., its current carbon content relative to its capacity to store carbon in the silt-plus-clay fraction, can be estimated based on the content of silt and clay particles (Figure 5; saturation = 100%).

Our results show that most fields under Annual Grain and Processing Vegetable cropping systems have much less SOC than their capacities based on silt plus clay fractions in a grassland system. Therefore, these cropping systems have the greatest potential to stabilize SOC in the silt plus clay fraction, which is the most stable fraction of SOC. Conversely, many fields in Pasture and Mixed Vegetable systems are closer to their carbon saturation levels and therefore have less potential to sequester more carbon. Dairy Crop fields are intermediate. Relative carbon saturation metrics can be used to optimize carbon allocations for soil sequestration.

Conclusions

This report provides a comprehensive attempt to characterize the soil health status of New York State soils by texture and cropping system. These efforts will enable NYS policymakers, agricultural professionals, and farmers to interpret soil health data and set soil health goals within the context of their specific soil and management environments. Increased knowledge of the effects of soil texture, the most defining inherent soil property, and cropping system on biological, physical, and chemical indicators are vital to understanding how agricultural management affects healthy soil functioning. The report highlights important differences in soil health properties across four soil texture groups and five cropping systems. Several important findings were uncovered, including a reaffirmation of the strong soil texture dependence of SOM, ActC, Respiration, and AWC. Furthermore, we demonstrated that cropping systems, through the quantity of residues returned to the soil, tillage practices, and amounts of compost or manure applied, greatly influence the health of NYS soils. Specifically, Pasture and Mixed Vegetable systems have the highest soil health, followed by Dairy Crop, and then Annual Grain and Processing Vegetable cropping systems. We also demonstrated that Respiration, Protein, and Aggregate stability soil health indicators were strongly influenced by cropping system type. A specific output of this report is new scoring functions and aspirational goals or targets by soil texture and cropping system for NYS soils.

Finally, we demonstrated that Annual Grain and Processing Vegetable cropping system fields have SOC levels that were much lower than the hypothesized saturation point of silt and clay surfaces. This means that increasing organic carbon inputs (improved organic matter management) in these systems will more efficiently increase SOC compared to Mixed Vegetable and Pasture cropping systems. Annual Grain and Processing Vegetable systems can build soil organic carbon by incorporating the types of management practices that make Dairy Crop, Mixed Vegetable, and Pasture systems more successful. This includes applications of composts and manure, integration of livestock, better rotations, cover cropping and reduced tillage. Additionally, while it may be more difficult to further increase SOC in Mixed Vegetable and Pasture systems, it will be important for NYS climate mitigation strategy to maintain their carbon levels. Also, the geography of New York's farms has carbon-surplus areas like livestock farms and urban areas interspersed with carbon-deficit lands under grain and processing vegetable production. This makes NYS well suited to move carbon between these areas to enhance carbon sequestration and soil health.

Appendix

The appendix in this report provides more detailed information on the soil health methods and results, including univariate statistics, distributions, correlations, and principal component analyses. Pearson correlation coefficient tables and principal component analyses were featured in the appendix but were not discussed in the report.

References

Bradford, J.M., J.E. Ferris and P.A. Remley. 1987. Interrill soil erosion processes: I. Effect of surface sealing on infiltration, runoff, and soil splash detachment1. Soil Science Society of America Journal 51: 1566-1571. doi:10.2136/sssaj1987.03615995005100060029x.

Brady, N.C. and R.R. Weil. 2008. The Nature and Properties of Soil. 14th ed. Pearson: Prentice Hall, Upper Saddle River.

Chambers, A., Lal, R., & Paustian, K. 2016. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. Journal of Soil and Water Conservation 71(3), 68A-74A. doi:10.2489/jswc.71.3.68A

Cornell Cooperative Extension. 2016. Cornell Guide for Integrated Field Crop Management. Cornell University, Ithaca, NY.

Cox, F.R. 1994. Predicting increases in extractable phosphorus from fertilizing soils of varying clay content. Soil Science Society of America Journal 58: 1249-1253. doi:10.2136/sssaj1994.03615995005800040036x.

Daddow, R.L. and G.E. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. Watershed Systems Development Group, USDA Forest Service, Fort Collins, CO.

De Mendiburu, F. 2017. agricolae: Statistical Procedures for Agricultural Research. R package version 1.2-8.

EPA. (2020). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018. Retrieved from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018

Fine, A.K., H.M. van Es and R.R. Schindelbeck. 2017. Statistics, scoring functions, and regional analysis of a comprehensive soil health database. Soil Science Society of America Journal 81: 589-601. doi:10.2136/sssaj2016.09.0286.

Finney, D.M., J.S. Buyer and J.P. Kaye. 2017. Living cover crops have immediate impacts on soil microbial community structure and function. Journal of Soil and Water Conservation 72: 361-373. doi:10.2489/jswc.72.4.361.

Giagnoni, L., A. Migliaccio, P. Nannipieri and G. Renella. 2013. High montmorillonite content may affect soil microbial proteomic analysis. Applied Soil Ecology 72: 203-206. doi:10.1016/j.apsoil.2013.07.010.

Healthy Soils Healthy Communities Project. 2015. Metals in urban garden soils. Cornell University, Ithaca, NY. Available at: https://ecommons.cornell.edu/bitstream/handle/1813/48147/Metals_Urban_Garden_Soils.pdf?sequence=2&isAllowed=y.

Jolliffe, I.T. 2002. Springer, London, United Kingdom.

Kamprath, E.J. and M.E. Watson. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils. In: F. E. Khasawneh, E. C. Sample and E. J. Kamprath, editors, The Role of Phosphorus in Agriculture. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. p. 433-469.

Lado, M., M. Ben-Hur and I. Shainberg. 2004. Soil wetting and texture effects on aggregate stability, seal formation, and erosion contribution from the Agricultural Research Organization, the Volcani Center, no. 607, 2004 series. Soil Science Society of America Journal 68: 1992-1999. doi:10.2136/sssaj2004.1992.

Libohova, Z., C. Seybold, D. Wysocki, S. Wills, P. Schoeneberger, C. Williams, et al. 2018. Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. Journal of Soil and Water Conservation 73: 411-421. doi:10.2489/jswc.73.4.411.

Lützow, M.v., I. Kögel-Knabner, K. Ekschmitt, E. Matzner, G. Guggenberger, B. Marschner, et al. 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. European Journal of Soil Science 57: 426-445. doi:10.1111/j.1365-2389.2006.00809.x.

Magdoff, F.R., C. Hryshko, W.E. Jokela, R.P. Durieux and Y. Bu. 1999. Comparison of phosphorus soil test extractants for plant availability and environmental assessment. Soil Science Society of America Journal 63: 999-1006. doi:10.2136/sssaj1999.634999x.

Maharjan, B., Das, S., Acharya, B.S. 2020. Soil health gap: A concept to establish a benchmark for soil health management. Global Ecology and Conservation 23, e01116.

Moebius-Clune, B.N., D.J. Moebius-Clune, R.R. Schindelbeck, K.S.M. Kurtz, H.M. van Es and A.J. Ristow. 2017. Comprehensive Assessment of Soil Health - The Cornell Framework. 3.2 ed. Cornell University, Geneva, NY. Available at http://soilhealth.cals.cornell.edu/training-manual/.

New York State Department of Environmental Conservation and New York State Department of Health. 2005. Concentrations of selected analytes in rural New York State surface soils: A summary report on the statewide rural surface soil survey. Albany, NY. Available at https://www.dec.ny.gov/docs/remediation_hudson_pdf/appendixde.pdf.

Nunes, M.R., H.M. van Es, R. Schindelbeck, A.J. Ristow and M. Ryan. 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328: 30-43. doi:10.1016/j.geoderma.2018.04.031.

Ogden, C.B., H.M. van Es and R.R. Schindelbeck. 1997. Miniature rain simulator for field measurement of soil infiltration. Soil Science Society of America Journal 61: 1041-1043. doi:10.2136/sssaj1997.03615995006100040008x.

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Schindelbeck, R.R., B.N. Moebiues-Clune, D.J. Moebius-Clune, K.S. Kurtz and H.M. van Es. 2016. Cornell University comprehensive assessment of soil health laboratory standard operating procedures. Available at: http://soilhealth.cals.cornell.edu/resources.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, et al. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. Journal of Soil and Water Conservation 58: 137-152.

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

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry, 86(1), 19-31. doi:10.1007/s10533-007-9140-0

University of Vermont Extension. 2018. Nutrient recommendations for field crops in Vermont. University of Vermont.

USDA-NRCS, 2020. Soil Health. Soil Health Division. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.

Van Es, H.M. and D.L. Karlen. 2019. Reanalysis validates soil health indicator sensitivity and correlation with long-term crop yields. Soil Science Society of America Journal 83: 721-732. doi:10.2136/sssaj2018.09.0338.

Wightman, J.L., Woodbury, P.B. 2019. Understanding greenhouse gas benefits of soil health practices in New York State. Cornell University. Available at: http://blogs.cornell.edu/woodbury/publications/

Wightman, J.L., Woodbury, P.B. 2020. New York Agriculture and Climate Change: Key Opportunities for Mitigation, Resilience, and Adaptation. Final Report on Carbon Farming project for the New York State Department of Agriculture and Markets. Cornell University. Available at: http://blogs.cornell.edu/woodbury/publications/.

Wills, S.A., C.O. Williams, M.C. Duniway, J. Veenstra, C. Seybold and D. Presley. 2017. Human land-use and soil change. In: L. T. West, M. J. Singer and A. E. Hartemink, editors, The Soils of the USA. Springer International Publishing, Cham. p. 351-371.

Wuenscher, R., H. Unterfrauner, R. Peticzka and F. Zehetner. 2015. A comparison of 14 soil phosphorus extraction methods applied to 50 agricultural soils from Central Europe. Plant Soil Environment 61: 86-96.

Zheng, Z., L.E. Parent and J.A. MacLeod. 2003. Influence of soil texture on fertilizer and soil phosphorus transformations in Gleysolic soils. Canadian Journal of Soil Science 83: 395-403. doi:10.4141/S02-073.

Appendix

Cornell Soil Health Indicator Methodology (Detailed)

Biological Soil Health Indicators

The Cornell Soil Health Laboratory measures four biological soil health indicators that provide information about the quantity and quality of organic matter and the activity of microorganisms. These indicators include soil organic matter (SOM), active carbon (ActC), soil protein (Protein), and soil respiration (Resp). SOM consists of the total amount (*quantity*) of living and dead carbon containing material found in soil. A large portion of this SOM can remain stable for hundreds to thousands of years. SOM was analyzed by analyzed by mass loss on ignition in a muffle furnace at 500 °C for two hours.

ActC is a measure of the easily decomposable fraction of SOM and is an indicator of the amount of food that is available to fuel the soil food web. ActC was measured as permanganate oxidizable carbon, measured in duplicate, by reacting a 2.5 g soil sample with 20 mL 0.02 M potassium permanganate ($KMnO_4$) solution (pH 7.2). Extracts were shaken for 2 minutes at 120 rpm and then allowed to settle for exactly 8 minutes. An aliquot of solution was diluted 100-fold before absorbance readings were taken at 550 nm using a handheld spectrophotometer (Hach, Loveland, CO). Sample absorbance was calibrated with a $KMnO_4$ standard curve and converted to mg ActC per kg soil using the equation of Weil et al. (2003). The ratio of ActC over SOM was used to assess soil organic matter *quality* (Eq. A1).

$$\%\ \text{ActC/SOM} = \left(\frac{\text{ActC}}{\text{SOM}}\right) \times (100) \qquad \text{(A1)}$$

Protein is a measure of the protein-like substances in the soil, which represents the largest pool of organic nitrogen in the soil. Unlike potassium, calcium, and magnesium, the majority (approximately >90-95 %) of total nitrogen in the topsoil is bound in organic matter. Therefore, testing for inorganic nitrogen can only provide a snapshot of available nitrogen at the time of sampling. Protein provides a low-cost way to assess the size of the soil organic nitrogen pool. Microorganisms can mineralize part of this organic nitrogen pool and make it available for plant uptake. Protein was measured by extracting a 3.0 g soil sample with a 0.02 M sodium citrate at pH 7. The extract was then quantified by bicinchoninic acid assay against a bovine serum albumin standard curve for soil protein concentration after a sequence of centrifugation and autoclaving steps (Nunes et al., 2018; Wright and Upadhyaya, 1996). The ratio of Protein over SOM was used as another index of soil organic matter *quality* (Eq. A2).

$$\%\ \text{Protein/SOM} = \left(\frac{\text{Protein}}{\text{SOM}}\right) \times (100) \qquad \text{(A2)}$$

Soil respiration measures the metabolic activity of the soil microbial community, which is closely related to the amount of SOM that is available for microorganisms. Respiration helps assess how actively microorganisms are performing their essential functions such as the mineralization of soil organic nitrogen into inorganic, plant available, forms of nitrogen. Resp was measured after a four-day incubation using an alkali trap to measure CO_2 production. Soil samples weighing 20 g were placed in a perforated aluminum weighing boat and put inside a glass jar sitting atop two staggered Whatman qualitative filter papers. A preassembled alkali trap placed onto the weigh boat and the beaker was filled with 9 mL of 0.5 M KOH. Distilled water (7.5 mL) was pipetted alongside the jar to facilitate rewetting of the sample via capillary rise. The amount of CO_2 respired and absorbed by the KOH trap over the course of incubation was determined by measuring the change in electrical conductivity of the solution with an OrionTM DuraProbeTM 4-Electrode Conductivity Cell (ThermoFisher Scientific, Inc., Waltham, MA). The necessary background correction for atmospheric CO_2 was quantified using blank incubations with no soil (Nunes et al., 2018).

Physical Soil Health Indicators

The Cornell Soil Health Laboratory measures two physical soil health indicators that provide information about surface soil structure and plant available water. Wet aggregate stability (AgStab) is a measure of the ability of soil aggregates to resist falling apart when wetted and hit by raindrops. AgStab was measured by using a rainfall simulator fitted with Teflon capillaries generating 0.6 mm water drops (Ogden et al., 1997). Soil samples were prepped by shaking soil for 10 s on a mechanical shaker with stacked sieves of 2 and 0.25 mm to collect aggregates between 0.25-to-2 mm. A single layer of aggregates was spread on a 0.25 mm mesh sieve, which was placed 0.5 m below the rainfall simulator to apply 2.5 J of energy over a 5-minute period. AgStab was determined as the fraction of soil remaining on the sieve, correcting for solid particles > 0.25 mm.

Available water capacity (AWC) is a measure of the amount of plant available water a soil can store. AWC is measured as the difference between water content at field capacity and water content at the permanent wilting point. Saturated soil subsamples were equilibrated to pressures of -10 kPa (field capacity) and -1500 kPa (permanent wilting point) on porous ceramic pressure plates in pressure chambers (Soil Moisture Equipment Corp., Goleta, CA).

Additionally, the lab recommends that surface (0-6 in) and subsurface (6-18 in) penetrometer measurements are taken at the time of soil sampling to assess compaction in the field. Surface soil compaction limits infiltration, rooting, and proliferation of soil organisms, which can lead to increased runoff, erosion, and poor water storage, while subsurface compaction leads to poor drainage, aeration, and deep rooting. Research has indicated that most plant roots cannot readily penetrate soil with penetrometer readings above 300 psi.

Chemical Soil Health Indicators

The Cornell Soil Health test includes seven chemical measurements, including soil pH and Modified Morgan Extractable phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn), and zinc (Zn). Soil pH was measured in a 1:2 soil:water slurry. Modified Morgan Extractable nutrients were extracted with a Modified Morgan solution (ammonium acetate plus acetic acid, pH 4.8) and then run using inductively coupled plasma optical emission spectrometry (SPECTRO Analytical Instruments Inc., Mahwah, NJ). All nutrient contents were reported in units of mg kg^{-1} soil (ppm). Soil chemical properties such as pH and major macronutrients (P and K) have been thoroughly studied across NYS and robust interpretations exist for most crops. A total heavy metal screening is available as an add-on to the standard assessment if heavy metals are thought to be a concern (especially in urban environments).

New York State Soil Health Dataset Background Information Tables

Table A1. Mean (StdDev) for the percent of sand, silt, and clay in each texture group.

Texture Group	n	Sand %	Silt %	Clay %
Coarse	336	66.1 (11.3)	26.4 (9.8)	7.5 (2.7)
Loam	522	41.7 (5.8)	43.3 (5.0)	14.9 (4.8)
Silt loam	544	22.6 (10.9)	61.5 (8.0)	15.9 (4.7)
Fine	54	15.3 (11.5)	52.8 (13.9)	31.9 (4.8)

Table A2. The number and percentage of total samples belonging to different soil orders in each soil texture group.

Coarse		
Soil Suborder	n	% Total
Aquepts	5	3
Udepts	85	54
Psamments	45	28
Aqualfs	5	3
Udalfs	13	8
Loam		
Soil Suborder	n	% Total
Aquepts	8	4
Udepts	124	61
Aqualfs	7	3
Udalfs	60	29
Silt Loam		
Soil Suborder	n	% Total
Aquepts	27	9
Udepts	191	66
Aqualfs	21	7
Udalfs	45	16

Table A3. Mean (StdDev) for the percent of sand, silt, and clay in each cropping system by soil texture group

Coarse

Cropping System	n	Sand %	Silt %	Clay %
Annual Grain	26	62.2 (7.7)	29.5 (6.3)	8.2 (2.2)
Process Veg	22	65.8 (12.4)	27.1 (11.8)	7.1 (1.5)
Mixed Veg	24	62.8 (10.0)	30.0 (9.3)	7.2 (1.9)
Dairy Crop	19	70.6 (12.8)	21.9 (9.9)	7.4 (3.5)
Pasture	11	57.1 (8.4)	34.6 (8.2)	8.3 (1.7)
All	102	64.1 (11.0)	28.2 (9.8)	7.6 (2.3)

Loam

Cropping System	n	Sand %	Silt %	Clay %
Annual Grain	110	40.5 (5.2)	43.6 (3.8)	16.0 (4.1)
Process Veg	45	43.4 (5.0)	42.6 (4.2)	14.0 (4.0)
Mixed Veg	26	42.6 (5.5)	44.2 (6.1)	13.2 (3.9)
Dairy Crop	53	42.6 (6.1)	41.3 (7.4)	16.1 (5.8)
Pasture	11	40.0 (5.2)	46.1 (4.1)	13.9 (3.3)
All	245	41.7 (5.5)	43.1 (5.2)	15.2 (4.6)

Silt Loam

Cropping System	n	Sand %	Silt %	Clay %
Annual Grain	52	25.8 (7.6)	58.5 (7.1)	15.8 (3.5)
Process Veg	38	29.5 (5.9)	56.7 (5.5)	13.8 (3.2)
Mixed Veg	35	31.1 (6.9)	55.4 (3.8)	13.6 (4.7)
Dairy Crop	28	26.3 (7.1)	57.8 (4.9)	15.9 (3.9)
Pasture	21	24.6 (8.4)	58.1 (5.8)	17.3 (4.8)
All	174	27.6 (7.4)	57.3 (5.7)	15.1 (4.1)

Fine

Cropping System	n	Sand %	Silt %	Clay %
Annual Grain	7	14.6 (5.9)	51.8 (3.7)	33.6 (5.7)
Dairy Crop	16	28.5 (9.9)	35.8 (10.8)	35.8 (5.5)
All	23	24.3 (10.9)	40.6 (11.8)	35.1 (5.5)

All

Cropping System	n	Sand %	Silt %	Clay %
Annual Grain	195	38.5 (13.4)	46.0 (10.4)	15.5 (5.8)
Process Veg	106	42.9 (15.3)	44.5 (12.9)	12.6 (4.6)
Mixed Veg	86	43.6 (15.1)	44.8 (12.2)	11.6 (4.7)
Dairy Crop	116	41.4 (17.0)	41.2 (13.9)	17.4 (9.5)
Pasture	46	35.5 (15.9)	49.3 (11.3)	15.2 (6.6)
All	549	40.5 (15.2)	44.8 (12.2)	14.7 (6.8)

Table A4. The number and percentage of total samples belonging to different soil orders in each cropping system.

Annual Grain		
Soil Order	n	% Total
Alfisols	35	56
Entisols	2	3
Inceptisols	25	40
Dairy Crop		
Soil Order	n	% Total
Alfisols	23	64
Entisols	6	17
Inceptisols	7	19
Mixed Vegetable		
Soil Order	n	% Total
Alfisols	13	28
Inceptisols	33	70
Histosols	1	2
Pasture		
Soil Order	n	% Total
Alfisols	6	29
Entisols	1	5
Inceptisols	14	67
Process Vegetable		
Soil Order	n	% Total
Alfisols	24	40
Entisols	8	13
Inceptisols	28	47

Variance Components Analysis Table (Detailed)

Table A5. Variance component analysis for individual biological and physical SH indicators

Components	DF	VC	%Total	SD	CV(%)
SOM (%)					
Texture	3	0.3	19.2	0.6	18.0
Cropping System	4	0.3	18.4	0.6	17.6
Texture x System	12	0.1	6.0	0.3	10.0
Error	529	1.0	56.3	1.0	30.7
ActC (mg kg^{-1})					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	4133	9.1	64.3	12.1
Cropping System	4	5285	11.6	72.7	13.7
Texture x System	12	650	1.4	25.5	4.8
Error	529	35378	77.8	188.1	35.4
Protein (mg g^{-1})					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	0.3	3.0	0.5	8.0
Cropping System	4	2.1	22.0	1.4	21.8
Texture x System	12	0.8	8.4	0.9	13.4
Error	529	6.2	66.6	2.5	37.9
Respiration (mg CO_2 g^{-1} 4 day^{-1})					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	0.0	3.8	0.1	8.9
Cropping System	4	0.0	30.1	0.1	25.0
Texture x System	12	0.0	9.1	0.1	13.7
Error	529	0.0	57.1	0.2	34.5
AWC (g g^{-1})					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	1.4E-03	34.8	0.0	17.9
Cropping System	4	2.4E-04	6.0	0.0	7.4
Texture x System	12	6.9E-05	1.7	0.0	4.0
Error	529	2.3E-03	57.4	0.0	23.0
AgStab (%)					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	14.9	2.9	3.9	10.6
Cropping System	4	166.3	32.0	12.9	35.6
Texture x System	12	1.4	0.3	1.2	3.3
Error	529	336.5	64.8	18.3	50.6
Surface Hardness (psi)					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	0	0	0	0
Cropping System	4	125.3	1.5	11.2	6.6
Texture x System	11	0	0	0	0
Error	397	8009.8	98.5	89.5	52.8
Subsurface Hardness (psi)					
Components	DF	VC	%Total	SD	CV(%)
Texture	3	164.1	1.6	12.8	4.2
Cropping System	4	367	3.6	19.2	6.3
Texture x System	11	0	0	0	0
Error	397	9527	94.7	97.6	32.0

Table A6. Biological soil health indicators and indices across four soil texture groups. Mean values followed by different letters are significantly different at the 0.05 error level.

SOM (%)										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	2.4d	1.4	0.2	7.4	1.0	1.3	2.1	3.2	4.6
Loam	522	3.0c	1.2	0.9	7.3	1.6	2.3	2.8	3.6	4.7
Silt loam	544	3.5b	1.4	0.8	7.5	1.8	2.4	3.5	4.4	5.4
Fine	54	4.3a	0.9	2.5	7.8	3.2	3.7	4.3	4.6	5.1
All	1456	3.1	1.4	0.2	8.1	1.4	2.1	3.0	4.1	5.0
ActC (mg kg^{-1})										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	440d	258	20	1251	158	237	388	585	812
Loam	522	495c	197	66	1245	245	361	472	624	758
Silt loam	544	533b	214	153	1259	274	350	519	708	814
Fine	54	686a	189	122	1057	451	602	691	777	918
All	1456	504	224	20	1259	224	329	480	656	807
Protein (mg g^{-1})										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	6.8a	4.5	0.5	26.8	2.8	3.3	5.4	8.8	13.6
Loam	522	6.1b	3.0	2.0	22.4	3.4	4.1	5.2	7.1	10.7
Silt loam	544	7.3a	3.2	2.4	20.7	4.1	4.7	6.6	9.5	11.7
Fine	54	7.7a	3.7	1.9	18.6	3.7	4.7	7.3	9.7	11.5
All	1456	6.8	3.5	0.5	26.8	3.3	4.3	5.7	8.5	11.8
Respiration (mg CO_2 g^{-1})										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	0.49d	0.25	0.01	1.41	0.23	0.31	0.43	0.6	0.82
Loam	522	0.58c	0.23	0.17	1.60	0.34	0.43	0.54	0.69	0.88
Silt loam	544	0.68b	0.31	0.17	2.18	0.37	0.45	0.61	0.86	1.12
Fine	54	0.78a	0.36	0.19	1.82	0.41	0.49	0.68	1.07	1.27
All	1456	0.61	0.29	0.01	2.18	0.31	0.41	0.54	0.75	1.00
% ActC/SOM										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	1.9a	0.5	0.2	4.4	1.3	1.5	1.8	2.1	2.4
Loam	522	1.7b	0.4	0.2	3.7	1.2	1.4	1.7	1.9	2.1
Silt loam	544	1.5c	0.4	0.5	3.8	1.1	1.3	1.5	1.7	2.0
Fine	54	1.6bc	0.4	0.4	2.9	1.3	1.4	1.7	1.8	2.1
All	1456	1.7	0.5	0.2	4.4	1.2	1.4	1.6	1.9	2.1
% Protein/SOM										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	28.4a	7.3	8.5	63.8	20.6	23.8	27.9	31.7	37.4
Loam	522	20.5b	5.8	6.0	57.8	14.3	16.1	20.0	24.1	27.3
Silt loam	544	20.9b	4.5	6.7	38.7	15.7	18.0	20.7	23.8	26.2
Fine	54	17.8c	7.2	6.0	36.9	10.5	12.1	15.8	22.4	28.2
All	1456	22.4	6.7	6.0	63.8	14.8	17.9	21.7	25.9	30.5

Table A7. Physical soil health indicators across four soil texture group. Additionally, AWC data is also presented across seven texture groups to demonstrate the texture sensitivity of this variable. Mean values followed by different letters are significantly different at the 0.05 error level.

AgStab (%)										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	36.4a	23.3	2.3	87.2	7.6	15.9	34.6	55.9	70.5
Loam	522	31.1b	21.8	0.8	93.1	6.3	13.3	26.5	44.5	67.8
Silt loam	544	32.0ab	25.2	1.1	96.3	6.3	11.8	25.4	51.0	71.9
Fine	54	27.0b	18.8	5.5	86.8	11.6	14.8	20.5	32.8	52.1
All	1456	33.0	23.5	0.8	96.3	6.6	13.6	27.1	49.1	70.2
AWC (g g^{-1})										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	0.17c	0.06	0.02	0.33	0.10	0.13	0.17	0.21	0.24
Loam	522	0.21b	0.04	0.07	0.36	0.15	0.18	0.21	0.24	0.26
Silt loam	544	0.27a	0.06	0.07	0.41	0.19	0.23	0.28	0.31	0.35
Fine	54	0.26a	0.07	0.10	0.40	0.17	0.20	0.24	0.32	0.36
All	1456	0.23	0.07	0.02	0.41	0.14	0.18	0.22	0.27	0.32
AWC (g g^{-1}) with seven texture groups										
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
sand	14	0.07d	0.03	0.02	0.15	0.04	0.05	0.07	0.08	0.11
loamy sand	53	0.11d	0.04	0.04	0.23	0.07	0.09	0.12	0.14	0.15
sandy loam	269	0.18c	0.05	0.08	0.33	0.13	0.15	0.18	0.21	0.24
loam	511	0.21b	0.05	0.10	0.25	0.14	0.19	0.21	0.24	0.24
silt loam	544	0.27a	0.04	0.10	0.36	0.16	0.18	0.21	0.24	0.26
silty clay loam	35	0.28a	0.06	0.07	0.41	0.19	0.23	0.28	0.31	0.35
clay loam	16	0.20bc	0.08	0.14	0.40	0.19	0.23	0.30	0.35	0.37
All	1456	0.23	0.07	0.02	0.41	0.14	0.18	0.22	0.27	0.32

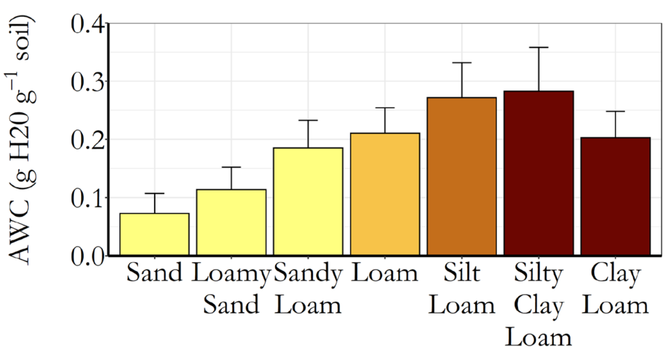

Figure A1. Mean AWC across seven soil texture classes. Error bars represent 1 std deviation.

Table A8. Chemical soil health indicators across four soil texture groups. Mean values followed by different letters are significantly different at the 0.05 error level.

					pH					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	6.4b	0.7	3.7	8.9	5.5	6.0	6.4	6.9	7.2
Loam	522	6.7a	0.8	4.3	8.1	5.7	6.2	6.6	7.3	7.7
Silt loam	544	6.3c	0.6	4.5	7.7	5.5	5.9	6.3	6.6	6.9
Fine	54	6.7a	0.7	4.6	7.9	5.6	6.2	6.8	7.2	7.4
All	1456	6.5	0.7	3.7	8.9	5.6	6.0	6.4	6.9	7.4
					P (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	23.2a	45.2	0.0	518.5	3.6	6.3	14.3	23.2	38.0
Loam	522	16.9b	24.9	1.0	335.3	3.3	5.5	10.2	19.7	32.6
Silt loam	544	13.0bc	11.3	1.0	81.0	3.3	5.6	9.9	17.0	25.1
Fine	54	5.5c	3.8	1.0	19.0	1.5	2.8	5.0	6.6	10.0
All	1456	16.5	27.6	0.0	518.5	3.2	5.4	10.6	19.3	31.9
					K (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	93d	69	3	435	27	47	78	117	173
Loam	522	118c	76	10	592	54	72	95	140	203
Silt loam	544	131b	74	16	680	60	82	117	158	212
Fine	54	153a	61	54	313	74	116	139	188	237
All	1456	119	76	3	680	48	71	101	146	203
					Mg (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	131c	91	8	444	43	69	100	168	259
Loam	522	201b	108	9	621	83	113	176	284	360
Silt loam	544	188b	97	17	511	85	119	160	243	330
Fine	54	358a	145	56	850	211	292	342	415	500
All	1456	187	115	8	1350	69	102	157	256	355
					Fe (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	5.6a	8.7	0.3	81.3	1.1	1.8	3.2	5.6	11.7
Loam	522	3.4b	5.6	0.1	68.3	0.6	1.1	1.8	3.7	6.7
Silt loam	544	5.6a	11.6	0.3	142.8	1.1	1.6	2.9	5.5	10.8
Fine	54	3.8ab	4.0	0.6	19.3	1.1	1.4	2.3	4.2	8.8
All	1456	4.8	9.0	0.1	142.8	0.9	1.4	2.5	4.7	9.7
					Mn (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	9.4b	8.3	0.2	66.7	2.9	4.6	7.6	11.1	16.2
Loam	522	11.4a	6.3	1.0	56.1	4.4	7.8	10.6	13.7	18.6
Silt loam	544	12.5a	9.3	1.6	152.8	4.4	7.5	11.0	15.9	21.2
Fine	54	10.7ab	7.0	4.0	34.1	5.5	6.6	8.0	12.1	16.5
All	1456	11.3	8.1	0.2	152.8	3.9	6.7	9.9	13.9	19.7
					Zn (ppm)					
Texture	n	mean	sd	min	max	Q10	Q25	Q50	Q75	Q90
Coarse	336	2.5a	7.1	0.0	103.7	0.3	0.6	1.3	1.9	4.7
Loam	522	1.3b	2.1	0.1	34.7	0.3	0.5	0.8	1.5	2.4
Silt loam	544	1.3b	1.6	0.0	24.2	0.4	0.6	1.0	1.6	2.3
Fine	54	0.8b	0.6	0.1	2.5	0.2	0.3	0.6	1.2	1.9
All	1456	1.6	3.8	0.0	103.7	0.3	0.5	1.0	1.6	2.6

Density Plots for Biological and Physical Soil Health Indicators

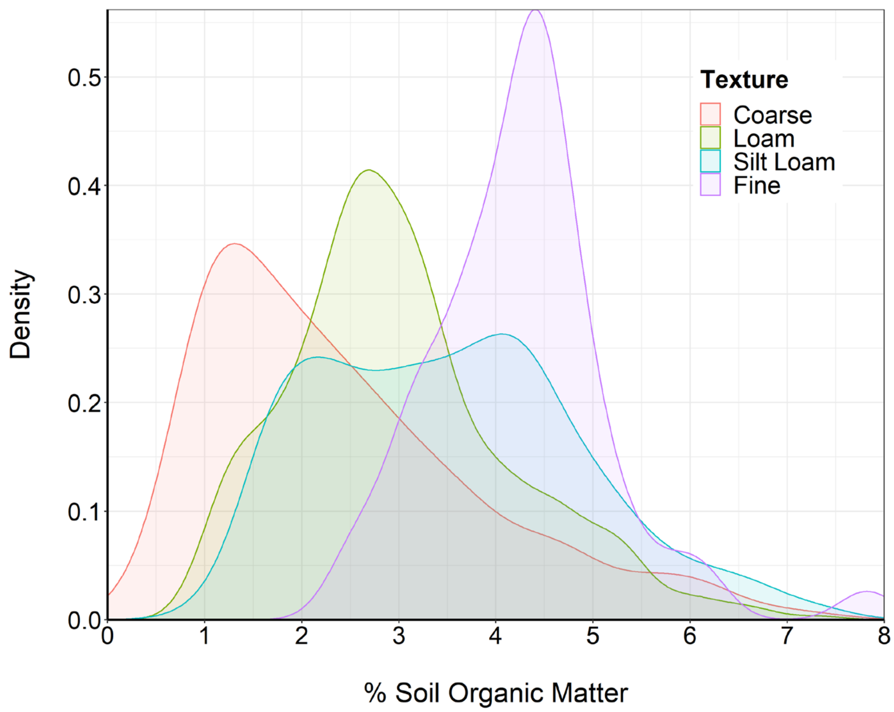

Figure A2. Density plot for % soil organic matter within coarse, loam, silt loam, and fine texture groups.

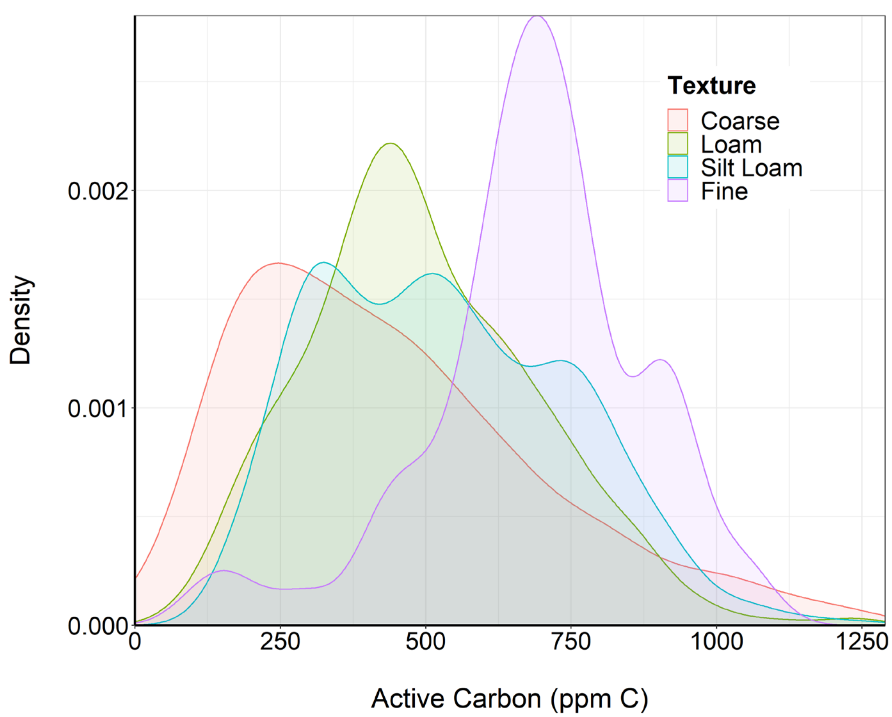

Figure A3. Density plot for active carbon within coarse, loam, silt loam, and fine texture groups.

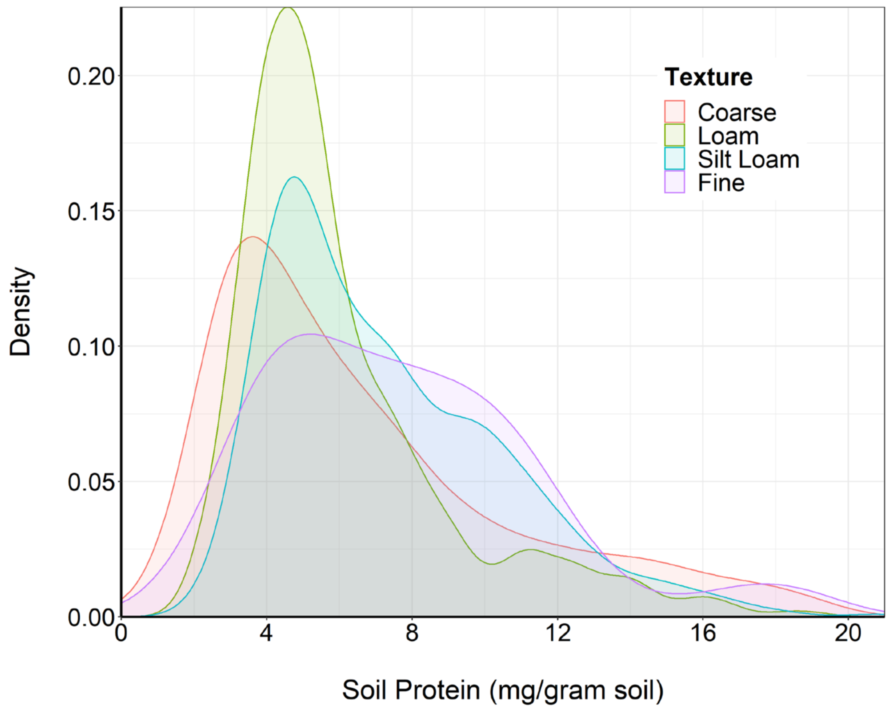

Figure A4. Density plot for soil protein within coarse, loam, silt loam, and fine texture groups.

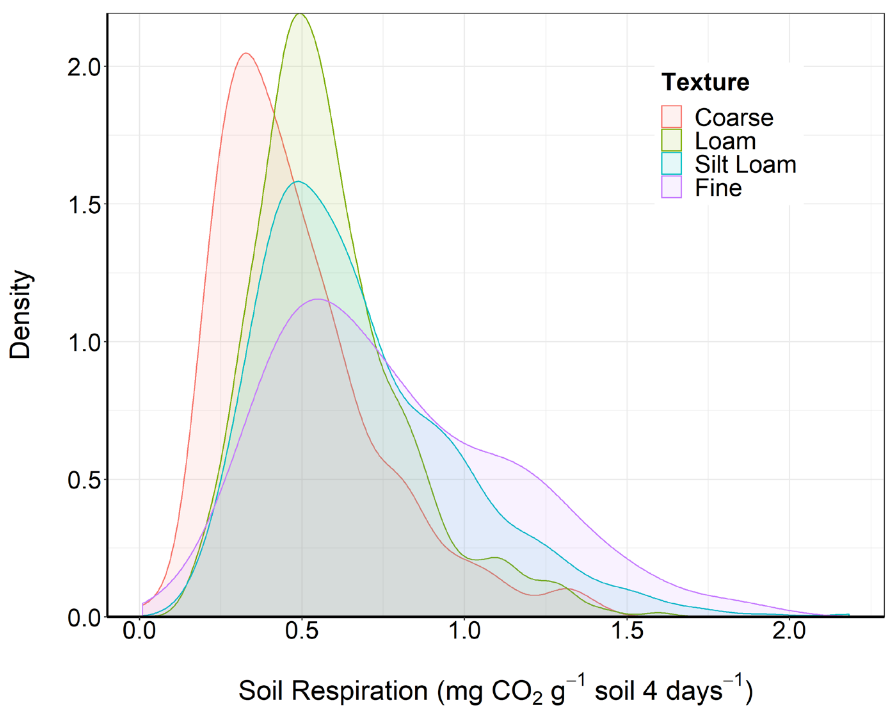

Figure A5. Density plot for soil respiration within coarse, loam, silt loam, and fine texture groups.

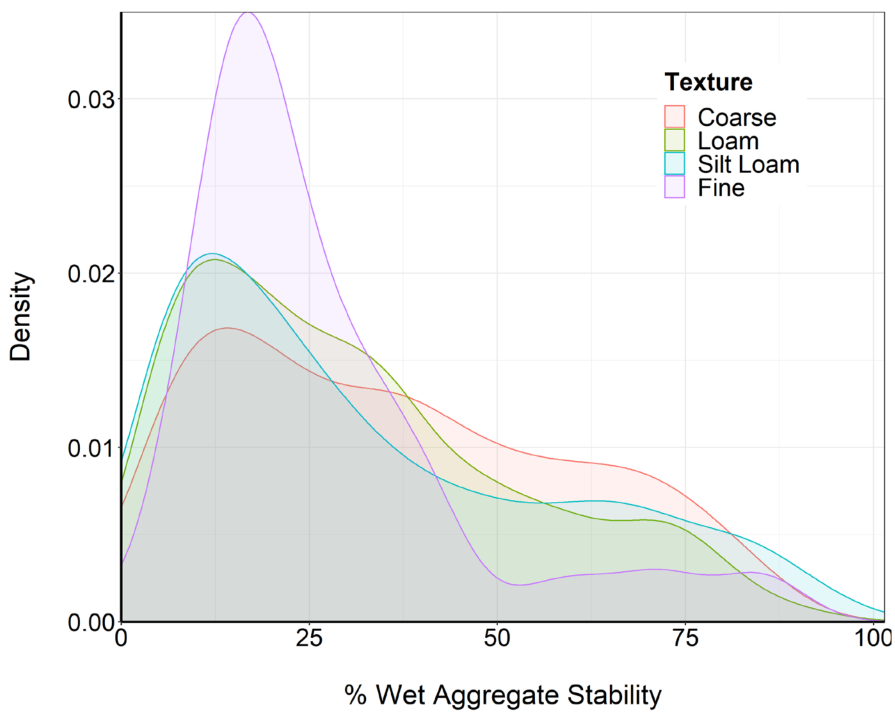

Figure A6. Density plot for % wet aggregate stability within coarse, loam, silt loam, and fine texture groups.

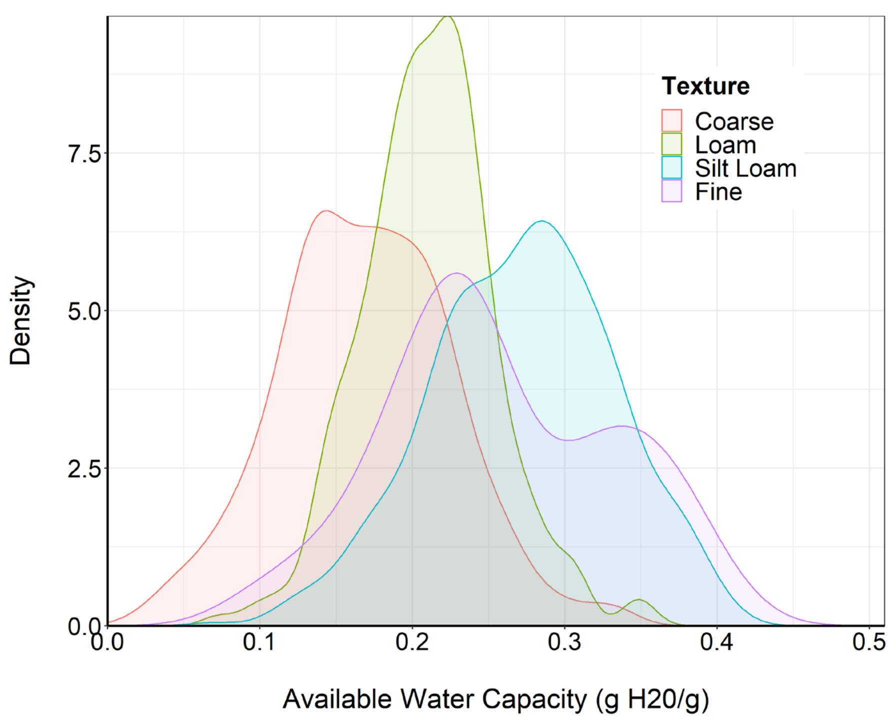

Figure A7. Density plot for available water capacity within coarse, loam, silt loam, and fine texture groups.

Relationships Among Indicators

Thus far the analysis has focused on the effects of texture and cropping system on individual soil health indicators. This section focuses on understanding the relationship among the biological, physical, and chemical attributes included in this analysis. Pearson product-moment correlation coefficients between indicators were calculated for the whole dataset and for each texture group, resulting in five correlation matrices (Table A9-A13). Ninety-four out of 117 Pearson correlation coefficients were significant ($p<0.05$; Table A9).

Strong correlations existed between the biological indicators: SOM with AC ($r = 0.81$), SOM with Prot ($r = 0.78$), SOM with Resp ($r = 0.72$), AC with Prot ($r = 0.74$), and Prot with Resp ($r = 0.63$), which was similarly found in Fine et al. (2017). Aggregate stability was moderately well correlated to SOM ($r = 0.61$) and Protein ($r = 0.56$), which reinforces the benefits of maintaining and building SOM on promoting stable aggregates (Table A9).

SOM was more strongly related to AWC in coarse-textured soils ($r = 0.48$; Table A10) compared to loam ($r = 0.14$; Table A11) or silt loam ($r = 0.12$; Table A12) textured soils. This suggests that improved organic matter management can lead to greater AWC increases in coarse-textured soils than in finer textured soils. A recent study utilizing the National Cooperative Soil Survey Characterization Database concluded similarly (Libohova et al., 2018). Interestingly, Protein content appeared to be slightly more correlated with AWC than SOM in loam, silt loam, and fine-textured soils (Tables A11-A13).

Magnesium was the only chemical property that was positively related to physical, biological, and chemical properties. Magnesium exhibited positive correlations ($r \geq 0.5$) to clay content, SOM, ActC, and pH (Table A9). There were correlation coefficients that were greater than 0.50 when certain texture subsets were considered. For example, extractable Fe was negatively correlated with pH ($r = 0.50$) in loam textured soils.

Principal component analyses were used to further assess relationships among soil health indicators (n=1,458). Five principal components (PC) explained 75% of the total variance in the data (Figure A8; Table A14). PC1 accounted for 34% of the variance and had high positive loadings mostly for biological indicators (OM > ActC > Resp > Protein > Mg > AgStab). PC2 represented 15% of the variance mostly through chemical indicators with both high positive loadings (Fe > AgStab) and high negative loadings (pH > Mg). PC3 (10%) had high negative loadings for some chemical indicators (P > Zn > K). PC4 (9%) had a high positive loading for AgStab and high negative loading for AWC and K. PC5 (7%) had high negative loadings for chemical indicators Mn followed by Zn (Table A14). A visualization of the first two PCs illustrated that PC1 was able to help distinguish among texture groups. Silt loam and fine-textured soils were capable of having higher biological indicator values compared to coarse-textured soils (Figure A8).

Principal component analyses were also conducted on the subset of data that had cropping system information (n=542; Figure A9; Table A15). Visualization of the first two PCs showed that PC1 was able to help distinguish among cropping systems (Figure A9-A12). Annual Grain and Processing Vegetable systems were constrained to the left of PC1 with lower biological indicators. While pasture and Mixed Vegetable systems were able to achieve/maintain higher biological indicators. Dairy Crop systems were located intermediate to the systems with lower biological health and higher biological health. Similarly, PC2 was able to separate the highly managed systems (Annual Grain, Processing Vegetable, and Dairy Crop systems) from less intensively managed Pasture systems, which tend to have a lower pH and inversely higher extractable Fe.

Pearson Correlation Coefficients Among Soil Health Indicators Tables

Table A9. Pearson correlations among soil health indicators for all samples from New York with $p<0.05$ (n=1,458). Pearson correlation coefficients were bolded if they are greater than 0.50.

	Sand	Silt	Clay	AWC†	AgStab	SOM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	**-0.70**	**0.72**	0.38													
AgStab	0.11		-0.13													
OM	-0.41	0.33	0.42	0.36	**0.61**											
Protein	-0.14	0.14	0.10	0.33	**0.56**	**0.78**										
Resp	-0.41	0.37	0.35	0.46	0.45	**0.72**	**0.63**									
ActC	-0.28	0.21	0.34	0.33	0.46	**0.81**	**0.74**	**0.65**								
pH		-0.07	0.21		-0.14	0.05	-0.07	0.16	0.24							
P	0.14	-0.10	-0.17				0.14		0.12	0.07						
K	-0.28	0.28	0.16	0.25		0.31	0.28	0.22	0.32	0.07	0.33					
Mg	-0.39	0.24	**0.57**	0.26	0.10	**0.54**	0.32	0.47	**0.58**	**0.52**	0.06	0.31				
Fe				0.11	0.26	0.19	0.26	0.14		-0.38		-0.11	-0.16			
Mn	-0.18	0.17	0.13	0.15	0.21	0.30	0.21	0.43	0.19			0.14	0.12	0.24		
Zn	0.11	-0.09	-0.12		0.07	0.10	0.14		0.09		0.16					

†AWC, available water capacity; AgStab, wet aggregate stability; SOM, soil organic matter; Protein, soil protein, Resp, soil respiration during a 4-day incubation; ActC, active carbon.

Table A10. Pearson correlations among soil health indicators for coarse-textured soils from New York with $p<0.05$ ($n=336$). Pearson correlation coefficients were bolded if they are greater than 0.50.

	Sand	Silt	Clay	AWC†	AgStab	SOM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	**-0.64**	**0.60**	0.49													
AgStab																
OM	-0.30	0.22	0.43	0.48	**0.65**											
Protein	-0.17	0.11	0.29	0.40	**0.61**	**0.85**										
Resp	-0.32	0.25	0.45	0.49	**0.51**	**0.76**	**0.66**									
ActC	-0.21	0.14	0.36	0.44	**0.56**	**0.88**	**0.82**	**0.71**								
pH			0.24			0.22		0.24	0.19							
P						0.29	0.23	0.11	0.28	0.12						
K	-0.40	0.38	0.33	0.30		0.42	0.28	0.35	0.35	0.21	0.33					
Mg	-0.34	0.25	**0.51**	0.44	0.32	**0.67**	**0.54**	**0.60**	**0.64**	0.47	0.29	**0.53**				
Fe				0.11	0.24	0.21	0.28	0.13	0.15	-0.36						
Mn			0.24		0.12	0.18		0.34	0.12	0.34		0.27	0.35	0.20		
Zn						0.22	0.13		0.18	0.16						

†AWC, available water capacity; AgStab, wet aggregate stability; SOM, soil organic matter; Protein, soil protein, Resp, soil respiration during a 4-day incubation; ActC, active carbon.

Table A11. Pearson correlations among soil health indicators for loam textured soils from New York with $p<0.05$ (n=522). Pearson correlation coefficients were bolded if they are greater than 0.50.

	Sand	Silt	Clay	AWC†	AgStab	SOM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	-0.11	0.29	-0.17													
AgStab			-0.14													
OM	-0.28	0.11	0.23	0.14	**0.66**											
Protein			-0.11	0.28	**0.65**	**0.79**										
Resp	-0.21	0.13	0.12	0.24	**0.54**	**0.68**	**0.57**									
ActC	-0.22		0.19	0.13	**0.54**	**0.78**	**0.62**	**0.64**								
pH	-0.22		0.35	-0.13	-0.14		-0.20	0.22	0.26							
P			-0.12			0.14	0.15		0.14							
K		0.09			0.10	0.34	0.32	0.16	0.31	-0.09	0.49					
Mg	-0.38		0.45			0.40	0.10	0.43	0.49	**0.65**	0.12	0.11				
Fe	0.13		-0.14	0.25	0.31	0.21	0.37	0.11		**-0.50**		-0.11	-0.33			
Mn	-0.10			0.14	0.22	0.35	0.29	0.43	0.31	-0.10	0.14	0.29	0.11	0.20		
Zn			-0.11	0.11	0.10	0.20	0.27	0.12	0.09	-0.10	0.26	0.13		0.09	0.16	

†AWC, available water capacity; AgStab, wet aggregate stability; SOM, soil organic matter; Protein, soil protein, Resp, soil respiration during a 4-day incubation; ActC, active carbon.

Table A12. Pearson correlations among soil health indicators for fine-textured soils from New York with $p<0.05$ (n=56). Pearson correlation coefficients were bolded if they are greater than 0.50.

	Sand	Silt	Clay	AWC†	AgStab	SOM	Protein	Resp	ActC	pH	P	K	Mg	Fe	Mn	Zn
AWC	**-0.59**	**0.55**														
AgStab				-0.30												
SOM				0.25	**0.56**											
Protein	-0.49	**0.51**	-0.30	**0.67**		**0.60**										
Resp	**-0.50**	**0.53**	-0.36	**0.65**	0.31	**0.53**	**0.77**									
ActC				**0.53**		**0.61**	**0.78**	**0.63**								
pH					-0.29				0.39							
P		0.29	-0.30		0.15	0.46	**0.51**	0.30	**0.50**	0.40						
K	-0.24			0.34		**0.51**	**0.65**	0.26	**0.63**	0.41	**0.79**					
Mg			0.49			**0.54**	0.29		0.43	0.27	**0.61**	**0.56**				
Fe	-0.24			0.30			0.34	0.27		-0.34						
Mn					0.28	0.39	0.31	0.31			0.47		0.28	0.40		
Zn	**-0.52**	**0.54**	-0.34			0.48	**0.59**	0.32	0.49		**0.87**	**0.79**	**0.60**		0.39	

†AWC, available water capacity; AgStab, wet aggregate stability; SOM, soil organic matter; Protein, soil protein, Resp, soil respiration during a 4-day incubation; ActC, active carbon.

Principle Component Analyses by Soil Texture and Cropping System Plots and Tables

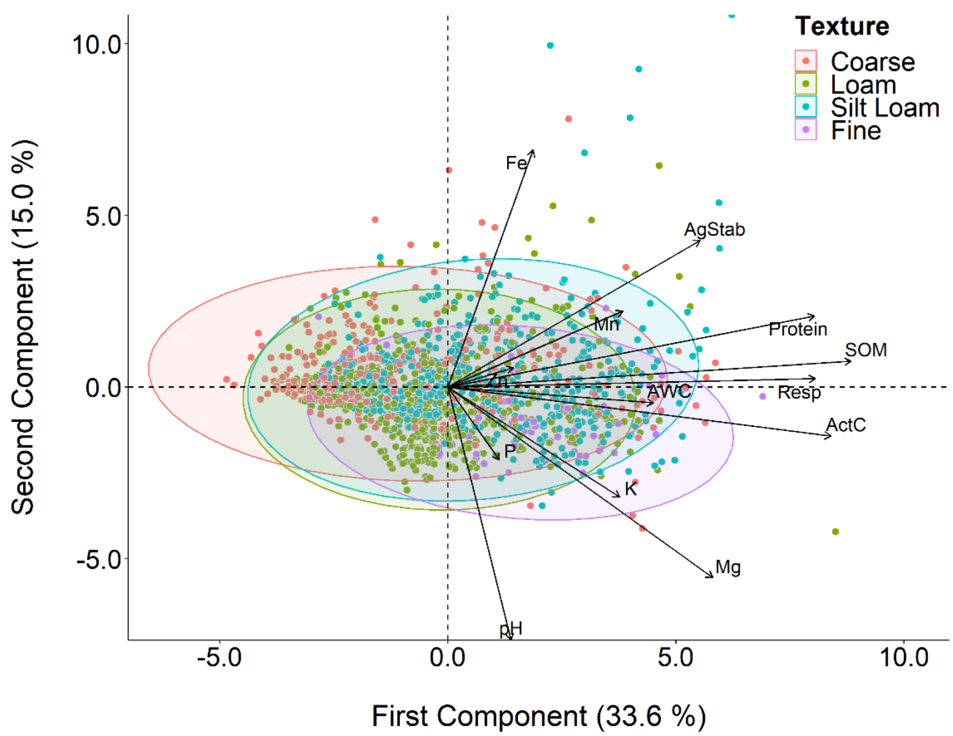

Figure A8. Principal component analysis (PCA) of New York Comprehensive Assessment of Soil Health (CASH) Database (n=1,458).

Table A13. Eigenvalue analysis of the first six principal components for all samples.

Variable	PC1	PC2	PC3	PC4	PC5
AWC	0.225	-0.035	0.083	-0.653	0.049
AgStab	0.276	0.320	0.043	0.462	0.132
SOM	0.442	0.057	0.041	0.088	0.122
Protein	0.402	0.155	-0.121	0.098	0.187
Resp	0.403	0.018	0.172	-0.097	-0.165
ActC	0.420	-0.107	0.019	0.145	0.123
pH	0.069	-0.552	0.192	0.231	-0.298
P	0.056	-0.159	-0.684	0.037	0.043
K	0.188	-0.240	-0.428	-0.347	0.216
Mg	0.290	-0.416	0.190	0.034	-0.026
Fe	0.093	0.517	-0.019	-0.153	-0.080
Mn	0.192	0.166	0.043	-0.239	-0.684
Zn	0.072	0.042	-0.468	0.236	-0.526
Eigenvalue	4.374	1.947	1.329	1.157	0.962
Proportion	0.336	0.150	0.102	0.089	0.074
Cumulative	0.336	0.486	0.588	0.677	0.751

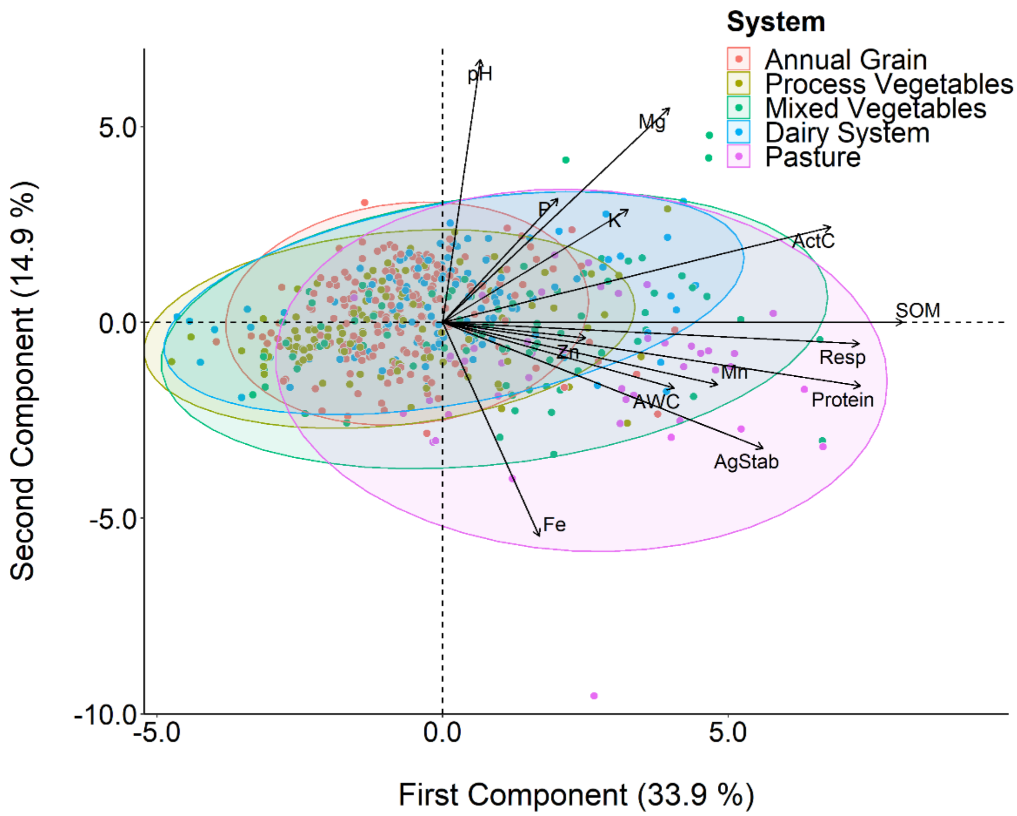

Figure A9. Principal component analysis (PCA) of New York Comprehensive Assessment of Soil Health (CASH) samples with cropping system information (n=542).

Table A14. Eigenvalue analysis of the first six principal components for all samples with cropping system information.

Variable	PC1	PC2	PC3	PC4	PC5
AWC	0.218	-0.151	0.037	-0.532	0.651
AgStab	0.298	-0.295	0.217	0.423	-0.158
SOM	0.439	-0.016	0.077	0.093	0.101
Protein	0.400	-0.133	-0.093	0.258	0.110
Resp	0.394	-0.078	0.218	-0.013	-0.109
ActC	0.373	0.174	0.146	0.092	0.098
pH	0.048	0.536	0.310	-0.111	-0.269
P	0.115	0.279	-0.501	0.090	-0.181
K	0.200	0.275	-0.444	-0.139	0.132
Mg	0.238	0.425	0.189	-0.218	-0.061
Fe	0.087	-0.448	-0.141	-0.393	-0.380
Mn	0.270	-0.115	-0.122	-0.403	-0.484
Zn	0.155	0.023	-0.504	0.222	0.055
Eigenvalue	4.405	1.931	1.403	0.953	0.852
Proportion	0.339	0.149	0.108	0.073	0.066
Cumulative	0.339	0.487	0.595	0.669	0.734

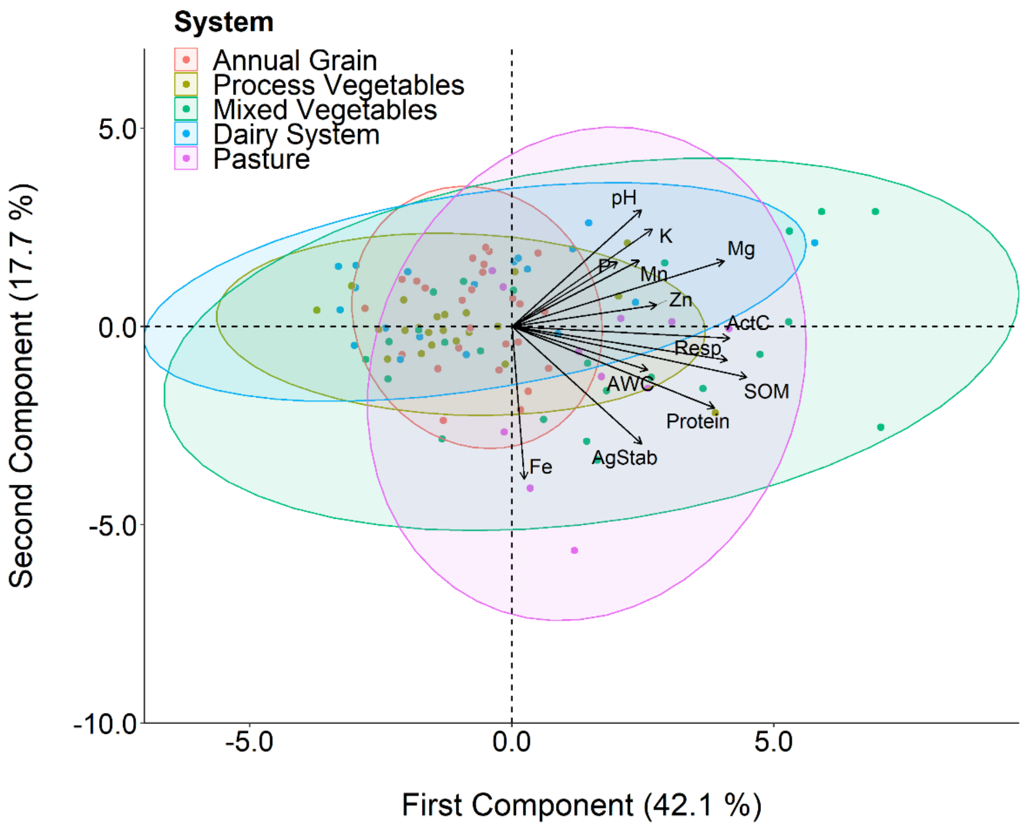

Figure A10. Principal component analysis (PCA) of New York Comprehensive Assessment of Soil Health (CASH) samples with coarse texture and cropping system information (n=102).

Fappend Eigenvalue analysis of the first six principal components for coarse-textured soils with cropping system information.

Variable	PC1	PC2	PC3	PC4	PC5
AWC	0.228	-0.148	0.111	-0.532	0.614
AgStab	0.217	-0.401	0.226	0.237	-0.257
SOM	0.394	-0.173	0.028	-0.069	-0.138
Protein	0.340	-0.278	-0.054	-0.055	-0.269
Resp	0.361	-0.114	0.225	0.150	0.022
ActC	0.365	-0.040	-0.035	-0.174	-0.180
pH	0.217	0.398	0.382	-0.113	-0.093
P	0.177	0.220	-0.533	-0.208	-0.322
K	0.235	0.334	-0.274	0.044	0.277
Mg	0.356	0.224	0.063	-0.129	0.113
Fe	0.021	-0.521	-0.295	0.118	0.376
Mn	0.214	0.225	0.205	0.621	0.284
Zn	0.243	0.074	-0.493	0.355	0.094
Eigenvalue	5.470	2.310	1.282	0.974	0.812
Proportion	0.421	0.178	0.099	0.075	0.062
Cumulative	0.421	0.598	0.697	0.772	0.834

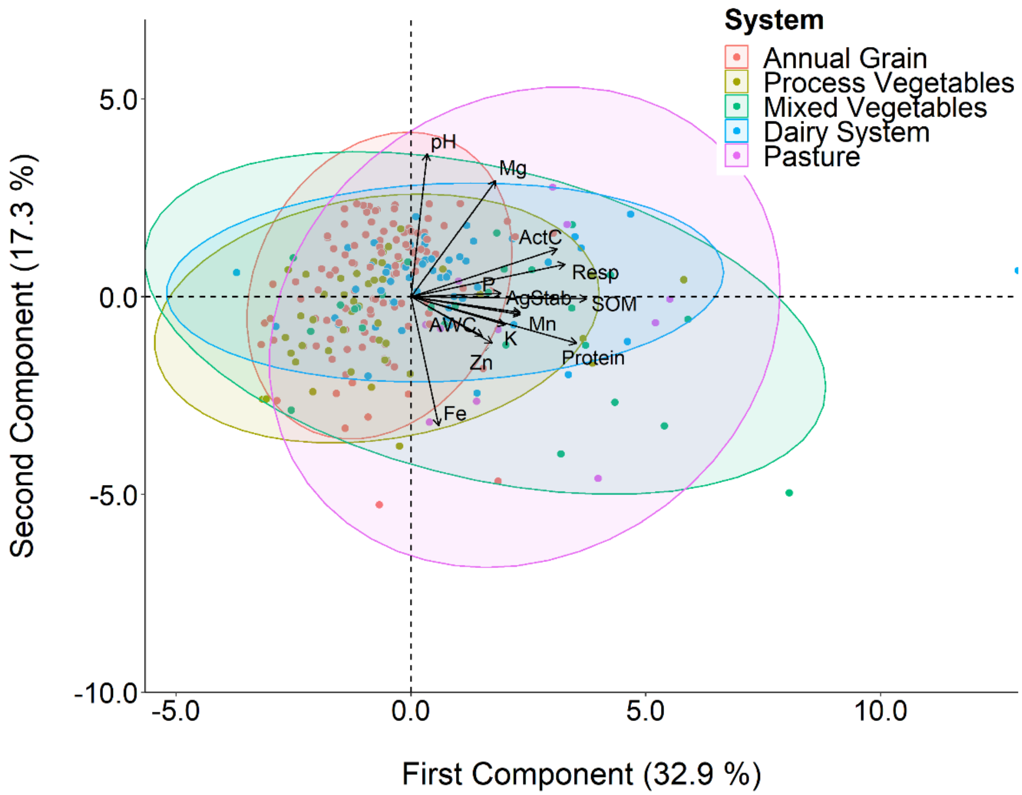

Figure A11. Principal component analysis (PCA) of New York Comprehensive Assessment of Soil Health (CASH) samples with loam texture and cropping system information (n=245).

Table A15. Eigenvalue analysis of the first six principal components for loam textured soils with cropping system information.

Variable	PC1	PC2	PC3	PC4	PC5
AWC	0.177	-0.159	0.109	-0.799	0.353
AgStab	0.270	-0.063	0.445	0.322	-0.218
SOM	0.433	-0.008	0.085	0.083	0.116
Protein	0.409	-0.187	0.100	0.086	0.124
Resp	0.380	0.132	0.279	-0.119	-0.055
ActC	0.361	0.193	0.094	-0.053	-0.047
pH	0.040	0.579	-0.061	-0.033	0.046
P	0.222	0.014	-0.579	-0.027	-0.009
K	0.232	-0.113	-0.514	-0.081	-0.210
Mg	0.209	0.469	-0.092	-0.076	-0.005
Fe	0.069	-0.521	0.025	-0.129	-0.239
Mn	0.270	-0.071	-0.178	0.036	-0.497
Zn	0.201	-0.187	-0.206	0.441	0.666
Eigenvalue	4.273	2.245	1.515	0.974	0.797
Proportion	0.329	0.173	0.117	0.075	0.061
Cumulative	0.329	0.501	0.618	0.693	0.754

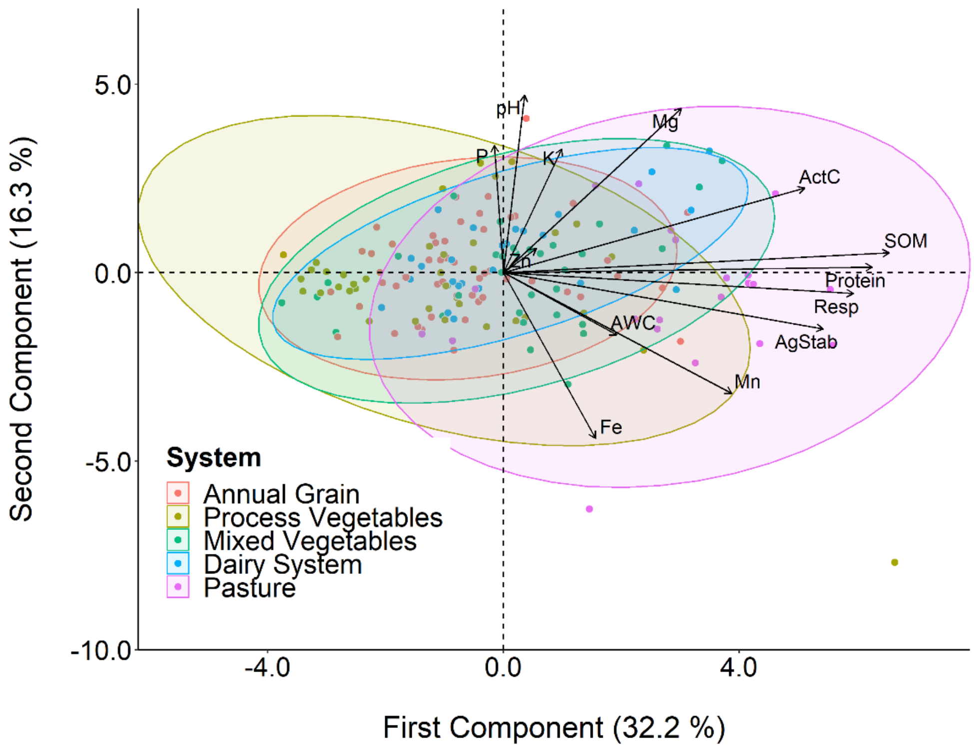

Figure A12. Principal component analysis (PCA) of New York Comprehensive Assessment of Soil Health (CASH) samples with silt loam texture and cropping system information (n=174).

Table A16. Eigenvalue analysis of the first six principal components for silt loam textured soils with cropping system information.

Variable	PC1	PC2	PC3	PC4	PC5
AWC	0.133	-0.164	0.120	-0.875	0.303
AgStab	0.380	-0.145	-0.109	0.181	-0.108
SOM	0.457	0.051	-0.031	0.091	-0.074
Protein	0.438	0.014	0.125	-0.019	0.017
Resp	0.415	-0.055	-0.071	-0.070	-0.070
ActC	0.359	0.218	-0.083	-0.004	0.010
pH	0.022	0.463	-0.315	-0.247	0.086
P	-0.004	0.331	0.534	0.042	0.253
K	0.076	0.321	0.496	0.210	0.312
Mg	0.208	0.427	-0.242	0.040	0.051
Fe	0.108	-0.432	0.139	0.176	0.359
Mn	0.270	-0.316	0.120	0.059	0.036
Zn	0.040	0.062	0.472	-0.215	-0.765
Eigenvalue	4.189	2.118	1.656	0.956	0.840
Proportion	0.322	0.163	0.127	0.074	0.065
Cumulative	0.322	0.485	0.613	0.686	0.751