# Empirical approach for developing production environment soil health goals, New York, USA

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## Abstract

Defining quantitative soil health goals can support efforts to improve soil quality and meet broader ecosystem services goals, while simultaneously helping field-level benchmarking of soil health on farms. But soil health metrics in agricultural systems require edaphic context, notably climate, soil type (soil texture and classification), as well as cropping system. Soil samples (n=1,328) from New York State (USA) with Land Resource Regions (LRR), texture, and cropping system information were analyzed for eight physical and biological soil health indicators (soil organic matter, permanganate-oxidizable carbon, respiration, protein, available water capacity, wet aggregate stability, and penetration resistance from 0-15 and 15-45 cm), and population distribution functions were determined. Production environment soil health (PESH) goals were derived for four soil texture groups and six cropping systems by proposing the 75$^{\text{th}}$ and 90$^{\text{th}}$ percentile for each factorial class. Finer-textured soils and Pasture and Mixed Vegetable cropping systems generally had the highest values for soil health goals, followed by Dairy Crop and Orchard systems, then Annual Grain, and lastly Processing Vegetable systems. Long Island (LRR-S) had soil organic matter PESH goals that were on average 0.7 % lower than the rest of New York State (LRRs-L&R). This implies that regional PESH goals within a state or region may be warranted if edaphic context is considerably different.

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**Keywords:** soil health, soil texture, cropping system, land resource region, soil health benchmarks, soil organic matter, soil organic carbon, Inceptisols, Alfisols

**Abbreviations:**

AWC, available water capacity; WAS, wet aggregate stability; SOM, soil organic matter; SOC, soil organic carbon; SIC, soil inorganic carbon; Protein, soil protein, Resp, soil respiration from 4-day incubation; POXC, permanganate-oxidizable carbon; PR15, penetration resistance from 0-

15 cm; PR45, penetration resistance from 15-45 cm; SH, soil health; CASH, Comprehensive Assessment of Soil Health; SHAPE, Soil Health Assessment Protocol and Evaluation; PESH, Production Environment Soil Health; LRR, Land Resource Region; MLRA, Major Land Resource Area; NYS, New York State; LRR-L, Lake States Fruit, Truck Crop, and Dairy Region; LRR-R, Northeastern Forage and Forest Region; LRR-S, Southern Atlantic Slope Diversified Farming Region.

# 1. INTRODUCTION

## 1.1. Interpreting Soil Health Data

Soil health concepts, practices, and testing are rapidly being adopted around the world. This growing interest reflects a heightened appreciation of the role that soils play in providing essential ecosystem services, as well as concerns about the increasingly important influence human activities, including agriculture, have on soil health (SH). This includes the recent efforts to ramp ramp up agricultural practices that build soil organic carbon (SOC) as a climate mitigation and adaptation strategy. A recent estimate for the United States (US) 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), equivalent to approximately 36% of total US agricultural emissions or 3.7% of total US emissions in 2018 (EPA, 2020).

Although quality standards have been developed to protect water and air in the USA (EPA, 2023), very few analogous metrics exist to promote the protection of soil quality or health. Defining quantitative soil health goals can support efforts to improve soil quality and meet humanity's broader climate mitigation and water quality goals, while simultaneously helping benchmark soil health at the individual field level. However, useful comparisons between farms require context with respect to regional soil types, climate, and cropping system in order to calibrate management. The New York State legislature passed a Soil Health and Climate Resiliency Act that includes a mandate to the establish of “voluntary soil health standards” (New York State Senate, 2022). This work aims to address this need.

Conventional extractable soil nutrient contents (in soil fertility tests) are typically interpreted through a research base that establishes the optimum and suboptimum soil test values for different crops. Fertility guidelines then aim to reach optimum levels of each nutrient for a given crop (Magdoff and van Es, 2021). The concept of soil health is more holistic and refers to the overall well-being of the soil environment. Interpretation frameworks for new biological and physical indicators are rapidly evolving and currently use soil texture groupings because of the known differences in soil organic matter (SOM), SOC, and other SH indicators across soils of different texture classes (Amsili et al., 2021; Fine et al., 2017; Nunes et al., 2021). Finer-textured soils tend to have higher inherent levels of SOC than coarser-textured ones, due to the greater capacity of fine silt and clay to stabilize SOC through chemical adsorption and physical protection (Schmidt et al., 2011; von Lützow et al., 2006). Additionally, in a previous study in New York State (NYS), we found that texture group was a more useful categorical predictor of SOM than taxonomic suborder or drainage class (Figure S1).

Emerging large SH datasets are now allowing for the interpretation of SH indicators across regions, soil textural classes, soil taxonomy, climate, and management effects (Fine et al., 2017; Nunes et al., 2020). A Bayesian interpretation approach for SOC was recently developed using texture, suborder classes, and mean annual temperature and precipitation (Soil Health Assessment Protocol and Evaluation (SHAPE; n=14,680; Nunes et al., 2021), which provides a valuable baseline for setting regional SH goals based on inherent soil and climate parameters. However, SHAPE does not currently account for different cropping systems.

Several studies have compared SOC and other SH indicators between annual cropland and adjacent undisturbed systems (Beniston et al., 2014; DeGryze et al., 2004; Kaye et al., 2005; Martens et al., 2004; Mishra et al., 2010; VandenBygaart et al., 2003) that function as local SH benchmarks. Maharjan et al. (2020) introduced the Soil Health Gap concept as the "difference between soil health (SOC in this case) in an undisturbed native virgin soil and current soil health in a cropland in a given agroecosystem". This benchmarking approach, however, raises questions about the actual benchmark conditions, the very limited presence of sites with undisturbed virgin soil, and whether comparison to virgin systems offers realistic and achievable goals for farmers. Alternatively, the Soil Health Target concept aims to identify SH targets based on sites that have implemented SH management systems over a long period of time (>10 years; Looker, 2021). This approach relies on expert judgement about what constitutes the SH management system and the duration that SH management system has been in place.

Alternatively, scoring functions can be employed to establish SH goals based on peer groupings. Scoring functions transform measured indicator values into SH scores (Andrews et al., 2004; Karlen et al., 2019), generally using cumulative normal distribution functions. The Comprehensive Assessment of Soil Health (CASH) framework (Moebius-Clune et al., 2017) uses scoring functions based on empirical data where individual sample results are evaluated relative to a larger population of samples. These scoring functions in effect apply fuzzy logic (McBratney and Odeh, 1997) to SH test results rather than the discrete optimum-suboptimum approach or gap approaches. Scoring functions are more meaningful if they are based on samples from similar production environment groupings, i.e., when they account for inherent site characteristics (climate and soil type) and cropping systems. An empirical approach for defining production environment soil health (PESH) goals for NYS was developed by estimating the 75$^{th}$ percentile value within soil texture and cropping system groupings (Amsili et al., 2020). Also, Drexler et al. (2022) developed SOC standards for Germany by defining both lower and upper benchmarks (12.5$^{th}$ and 87.5$^{th}$ percentiles, respectively) for 33 strata that were defined by a combination of land use, soil texture, C/N ratio, and mean annual precipitation factor levels.

Global interest in improving soil health to reverse soil degradation, sustainably intensify agriculture, and mitigate and adapt to climate change requires guidance on SH and SOC goals for farmers, policymakers, and other stakeholders. Considering this global and local context, the objectives of this research were to (i) establish population-based PESH goals for NYS (LRR-L&R) by soil texture and cropping system (production environments), (ii) compare resulting values, and (iii) evaluate different regional PESH goals within NYS. Our approach to defining PESH goals for NYS can serve as a template for other regions of the US and world.

## 2. MATERIALS AND METHODS

### 2.1. Dataset

A dataset on SH indicators was compiled from 1,328 soil samples (0-15 cm depth) from across NYS that were collected and analyzed between 2014-2021. Samples came from one of three Land Resource Regions in NYS, including Lake States Fruit, Truck Crop, and Dairy Region (LRR-L), Northeastern Forage and Forest Region (LRR-R), and North Atlantic Slope Diversified Farming Region (LRR-S). Within NYS, LRR-L is equivalent to the Ontario-Erie Plain and

Finger Lakes Major Land Resource Area (MLRA), which has predominantly Alfisol and Inceptisol soil orders. And LRR-S is equivalent to the Long Island-Cape Cod Coastal Lowland MLRA, where Inceptisols and Entisols are the dominant soil orders. Hence LRR-S in this study is same as Long Island, which includes Nassau and Suffolk Counties. Whereas LRR-R combines three MLRAs, including Glaciated Allegheny Plateau and Catskill Mountains (MLRA-140), St. Lawrence-Champlain Plain (MLRA-142), and New England and Eastern New York Upland Southern (MLRAS-144A; Figure S2). The dominant soil order in LRR-R is Inceptisols, but there are also small amounts of Entisols and Alfisols. The United States Department of Agriculture has defined LRRs and MLRAs based on patterns of physiography, geology, climate, soils, and land uses (United States Department of Agriculture - Natural Resources Conservation Service, 2022). In NYS, mean annual precipitation ranges between 800-1,270 mm and mean annual temperature ranges between 12-18°C.

The SH indicator dataset (n=1,328) was derived from routine soil sample submissions to the Cornell Soil Health Laboratory, with the majority of samples collected and submitted by trusted researchers and agricultural professionals (n=1,102). This final dataset was compiled from a larger database by removing urban, manufactured, landscaped, and muck soils to make interpretations more applicable for agricultural soils. Soils with SOM values greater than the 98$^{th}$ percentile of SOM content (7.4, 7.6, 7.6, and 8.1 % for coarse, loam, and silt loam, and fine textures, respectively) were filtered out to ensure all heavily amended soils were removed, which tended to include high tunnels and small Mixed Vegetable Farms less than one acre in size. Finally, any repeated submissions (e.g. from the same field or research experiment) were also removed from the database. In the end, most of the samples (n=1,244) came from commercial farm fields, but the remaining samples (n=84) came from eleven research experiments that contained 44 unique treatments differing in tillage, organic matter inputs, or both. Samples were analyzed for soil texture and a suite of SH indicators according to the CASH protocol (Moebius-Clune et al., 2017). These included four biological and four physical indicators: soil organic matter (SOM) by loss on ignition (NY-Method: 500ºC for 2 hr with correction factor); permanganate oxidizable carbon (POXC) using $KMnO_4$ and colorimetric readings at 550 nm; soil protein (Protein) using citrate extraction, autoclaving, and bicinchoninic acid protein assay; soil respiration (Resp) quantified as emitted $CO_2$ after soil wetting and 4-day incubation; wet aggregate stability (WAS) based on soil aggregate breakdown under simulated rainfall; available water capacity (AWC) as the gravimetric soil water content difference between −10 kPa and −1500 kPa water potential in pressure chambers; and surface (0-15 cm; PR15) and subsurface hardness (15-45 cm; PR45) using a soil penetrometer (Schindelbeck et al., 2016). A portion (32%) of the dataset had SOC measurements on them (n=428). For the remaining samples, SOC was predicted from SOM by applying the following regression equations by 0.69(SOM)-0.03, 0.70(SOM)-0.31, 0.70(SOM)-0.31, and 0.65(SOM)-0.26 for coarse, loam, silt loam, and fine textures respectively, based on best fit linear regression models between SOM (NY method) and SOC developed from a continental U.S. dataset also derived from the Cornell Soil Health Laboratory containing both measurements (Figure S3, n=5,063). Total C in this dataset was measured with a Primacs SNC-100 Combustion Analyzer (Skalar, Buford, GA). Samples with a pH above 6.5 were run through a modified calcimeter procedure to determine soil inorganic carbon (SIC; Fonnesbeck et al., 2013) and to calculate SOC (SOC=Total C-SIC). The combination of measured and predicted SOC values are presented here as *predicted SOC*.

Analytical protocols are summarized in Amsili et al. (2021) with further details in Schindelbeck et al. (2016).

Soil samples also included crop code information denoting the current and past crops (3-years) in the rotation (Dairy One, 2020). These were grouped into six cropping system types, Annual Grain, Processing Vegetable, Dairy Crop, Mixed Vegetable, Orchard, and Pasture (Table 1). The Dairy Crop category denotes dairy cropping systems that include forage crops such as corn silage or alfalfa in rotation as feed for dairy cows. The majority of samples in the Pasture category were indeed pastures, but hayland samples were also included. The geographic distribution in part represents regional specializations within the state, with higher prevalence of vegetable crops and pastures in the southeastern part, dairy crops in the northern, central, and western parts, and annual grains and processing vegetables in the central and western part (Figure 1; Amsili et al., 2021). These six cropping system categories were chosen based on the available dataset and don’t reflect all possible cropping systems or approaches to agriculture in NYS.

**Table 1.** Six cropping system groups were formed by combining related crops (n=1,328). Each crop is followed by the associated number of soil samples in parentheses. The original crop codes used to derive the crop type and the scientific names are present in the footnote below the table.

| **Cropping System** | **Crops**[1,2] |
|---|---|
| Annual Grain | corn grain (174), soybean (100), wheat (40), dry beans (16), wheat straw (8) |
| Processing Veg | sweet corn (20), snap beans (15), pumpkins (13), tomato (11), cabbage transplanted (10), winter squash (9), potato (7) |

| | |
|---|---|
| Dairy Crop | corn silage (174), alfalfa (25), alfalfa grass (24), clover grass (12) |
| Mixed Veg | mixed vegetable (261) |
| Orchard | apple (172), peach (13) |
| Pasture | pasture rotational grazing (73), grasses (37), pasture with native grasses (25), pasture with legumes (19) |

[1] COG=corn grain (*Zea mays)*, SOY=soybean (*Glycine max)*, WHT=wheat (*Triticum aestivum)*, BND=dry beans (*Phaseolus vulgaris*), WHS=wheat straw, SWC=sweet corn (*Zea mays* convar. *saccharata* var. *rugosa),* SQW=winter squash (*Cucurbita spp.*), BNS=snap beans (*Phaseolus vulgaris*), PUM=pumpkin (*Cucurbita pepo*), CBP=cabbage transplanted (*Brassica oleracea*), TOM=tomato (*Solanum lycopersicum*), POT=potato (*Solanum tuberosum*), COS=corn silage, ALE/ALT=alfalfa (*Medicago sativa*), AGE/AGT=alfalfa grass, CGT=clover grass, MIX=mixed vegetable, APP=apple (*Malus domestica*), PCH=peach (*Prunus persica)*, PIT/PIE=pasture rotational grazing, PNT=pasture with native grasses, GRE/GRT=grasses, PLT=pasture with legumes.

[2]84 samples were from crop codes with less than 5 samples.

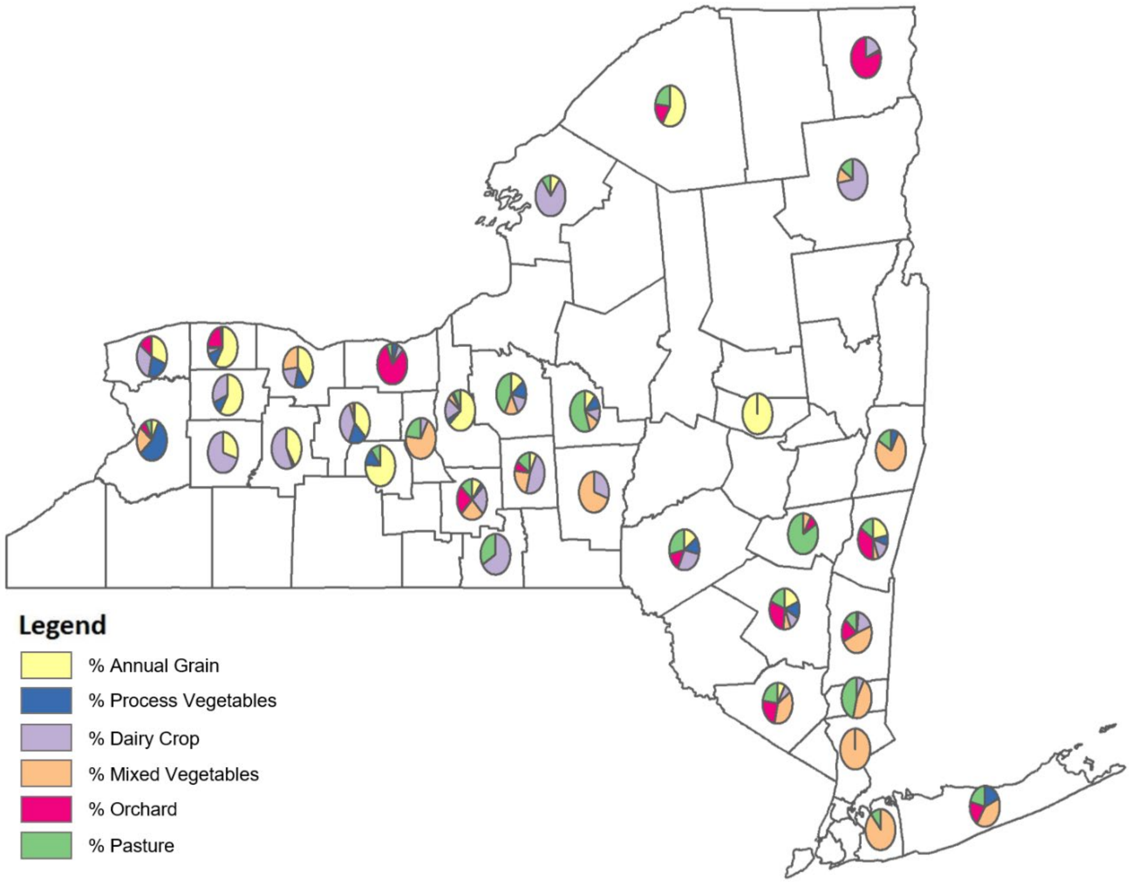


**Figure 1.** Geographic distribution of the six cropping systems included in the analysis.

### 2.2. Production Environment Soil Health Goal Approach

The soil samples submitted to the Cornell Soil Health Laboratory further include a range of management conditions and use of SH building or degrading practices (e.g., tillage intensity, cover cropping, perennial sod crops, organic amendments, etc.). Preliminary analysis (discussed below) indicated that Long Island (LRR-S) was sufficiently different from the rest of NYS (LRR-L&R) to require separate scoring functions and PESH goals. Therefore, cumulative normal distribution scoring functions and PESH goals for all indicators were calculated for NYS without Long Island (LRR-L&R).

The first step was to parameterize the cumulative normal distribution scoring functions for each of the SH indicators of interest. Mean and standard deviations were estimated for 24 subgroup populations of all possible combinations of four soil texture groups and six cropping system types (Table 1). The four soil texture groups consisted of coarse-textured (loamy sand and sandy loam), loam (loam and sandy clay loam), silt loam, and fine-textured (clay loam, silty clay loam, and clay). Medium-textured classes were separated as they represent the majority of agricultural lands in NYS and consistent differences in SH indicators were observed between loam and silt loam texture classes. Two texture classes had limited sample sizes: sandy clay loam and clay with each only having 7 and 3 observations, respectively. These 24 subgroup populations represent different production environments, thereby integrating soil texture and cropping system variables. Next, PESH goals were calculated as the 75$^{th}$ and 90$^{th}$ percentile of the distribution for each biological and physical SH indicator in each of 24 sub groupings (Figure 2). Therefore, these PESH goals are empirically shown as achievable because 25% and 10% of the soil samples within each class have attained them.

Furthermore, PESH goals for SOM at both the 75$^{th}$ and 90$^{th}$ percentiles were compared among LRR-L (n=596), LRR-R (n=472), and LLR-S (n=264; equivalent to Long Island) across coarse, loam, and silt loam soil textures. Fine-textured samples were excluded from this comparison because no fine-textured samples were collected from Long Island. This comparison was carried out due to the important differences in soil type and or climate across these regions, which could make assessing the effects of management on SH difficult if site inherent properties are too different. Summary statistics (mean, standard deviation, and quantiles) were calculated by region, texture, and cropping system. ANOVA models with LRR as fixed effects were used to assess differences in SOM across groups that shared the same soil texture and cropping system. Multiple comparisons were made using a Tukey adjustment at α=0.05 with the R package Agricolae (De Mendiburu, 2017). Statistical analyses and figures were run using the R statistical software (R Core Team, 2021).

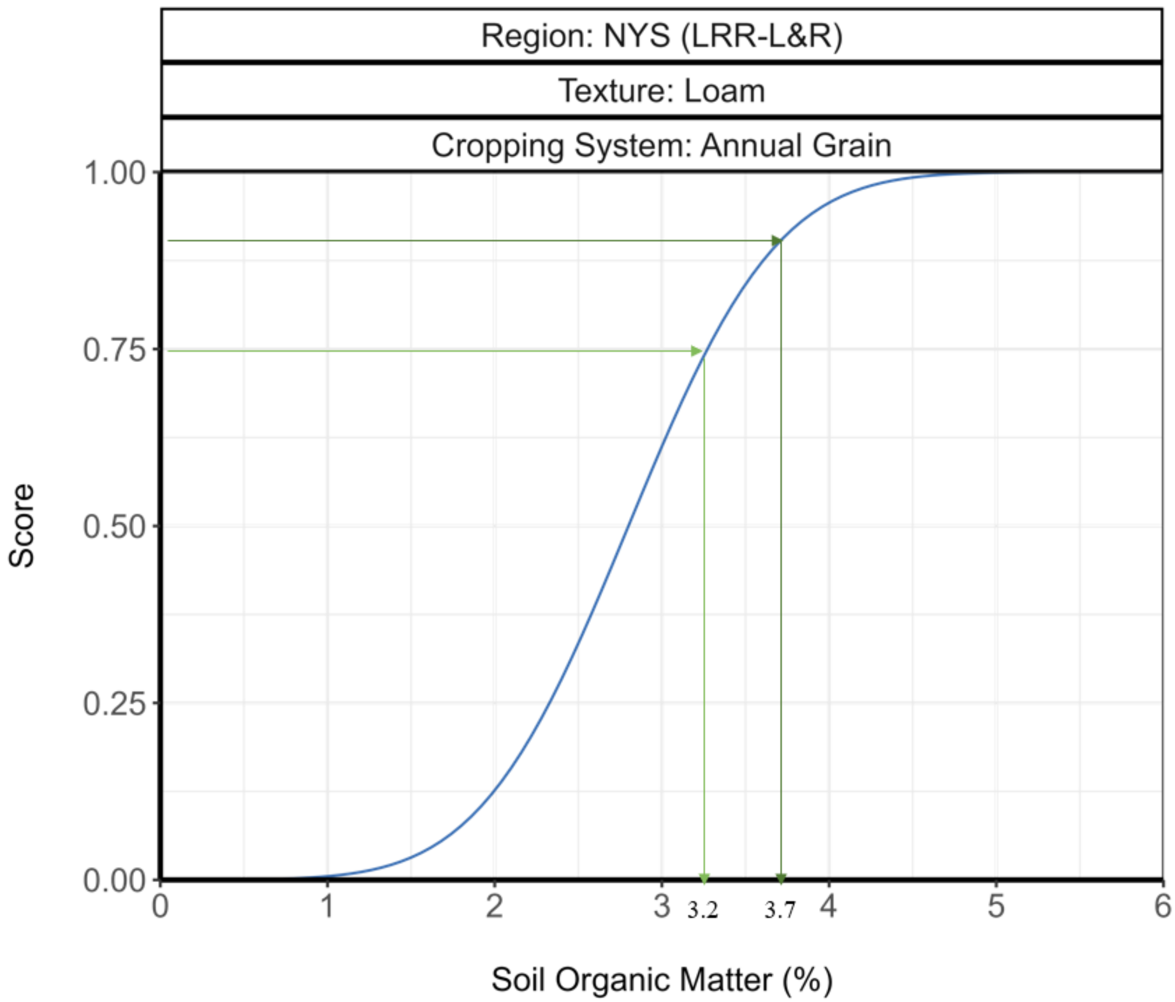


**Figure 2.** An illustration of the approach to calculate soil health goals at the 75th and 90th percentile of biological and physical SH indicators. This example is for SOM in Annual Grain systems on loam textured soils in LRRs L and R in New York State.

## 3. RESULTS AND DISCUSSION

### 3.1. Production Environment Soil Health Scoring Functions

This NYS SH dataset provided the foundation to define empirical scoring functions for SOM, predicted SOC, POXC, protein, WAS, and AWC for 24 production environments (all possible combinations of four soil texture and six cropping system groups) in NYS (Table 2). PESH scoring functions, as presented here are parameterized to integrate information about cropping system, which represents the next level of SH interpretation as it goes beyond solely inherent site characteristics (soil texture, soil taxonomy, region, and climate) and has been shown to be a relevant factor impacting soil health outcomes (Amsili et al., 2021; Augarten et al., 2023; Marshall et al., 2021). Most likely, PESH scoring functions are only applicable at regional scales due to the vast numbers of strata that would be required to accommodate both site inherent properties and regionally unique cropping systems across the continental US. Therefore, regional scoring systems have the advantage that they can include cropping system information, which helps to constrain what management practices can realistically be implemented by farmers. This is particularly important for regions like the Northeast US, which hosts a high diversity of annual and perennial cropping systems.

Soil health scoring functions from 24 production environments provides the foundation to calculate PESH goals. Due to inconsistent effects of cropping systems on penetration resistance, we used established penetration resistance scoring functions for PR15 and PR45. Mean and standard deviation values were 1130 kPa and 650 kPa for PR15 and 2070 kPa and 760 kPa for PR45, respectively (Moebius-Clune et al., 2017). Additionally, since our dataset is relatively small for fine-textured soils, PESH scoring functions for this texture grouping were poorly constrained and were also interpolated based on silt loam scoring functions. For fine-textured cropping system categories with less than 10 samples, we made three assumptions to interpolate those scoring functions: 1) for biological indicators, PESH scoring function means should be slightly higher than those from silt loam soils and available data for annual grain and dairy crop systems set how much higher; 2) for aggregate stability, PESH scoring functions would be the same as those for silt loam soils; and 3) for available water capacity, PESH scoring functions would be the same as when fine-textured samples were pooled. Similar to SHAPE scoring functions (Nunes et al., 2021), PESH scoring functions for NYS will be refined over time as sample sizes for certain production environments become larger.

**Table 2.** Mean values (standard deviation; SD) for biological and physical soil health indicators across four soil texture groups in NYS without Long Island (LRR-L&R). These mean and SD values are the parameters required for the cumulative normal distribution scoring functions specific to cropping system and soil texture (production environment).

| Cropping System | n | SOM | Pred. SOC | POXC | Protein | Resp | WAS | AWC |
|---|---|---|---|---|---|---|---|---|
| | | % | % | mg C/kg | mg/g | mg $CO_2$/g | % | g $H_2O$/g soil |
| | | | | **Coarse-Textured** | | | | |
| **Annual Grain** | 37 | 2.2 (0.6) | 1.4 (0.4) | 428 (143) | 5.5 (1.6) | 0.45 (0.16) | 33.7 (17.0) | 0.16 (0.03) |
| **Processing Veg** | 20 | 1.9 (1.0) | 1.3 (0.7) | 363 (201) | 5.0 (2.3) | 0.37 (0.26) | 25.1 (19.8) | 0.17 (0.05) |
| **Dairy Crop** | 29 | 2.8 (1.4) | 1.9 (1.0) | 551 (270) | 6.7 (2.7) | 0.54 (0.28) | 39.9 (22.5) | 0.16 (0.07) |
| **Mixed Veg** | 29 | 3.4 (1.3) | 2.3 (0.9) | 579 (243) | 9.8 (4.3) | 0.57 (0.26) | 43.6 (18.3) | 0.18 (0.06) |
| **Orchard** | 44 | 2.4 (0.8) | 1.6 (0.6) | 552 (231) | 6.7 (3.0) | 0.44 (0.21) | 38.4 (19.2) | 0.17 (0.05) |
| **Pasture** | 16 | 3.1 (0.8) | 2.1 (0.5) | 531 (142) | 7.8 (1.9) | 0.62 (0.20) | 63.8 (23.0) | 0.20 (0.06) |
| **All** | 175 | 2.6 (1.1) | 1.8 (0.8) | 506 (224) | 6.9 (3.2) | 0.49 (0.24) | 39.3 (21.5) | 0.17 (0.05) |
| | | | | **Loam** | | | | |
| **Annual Grain** | 209 | 2.8 (0.7) | 1.7 (0.5) | 545 (158) | 5.5 (1.7) | 0.53 (0.15) | 26.4 (15.5) | 0.20 (0.03) |
| **Processing Veg** | 38 | 2.7 (0.7) | 1.6 (0.6) | 440 (124) | 5.1 (1.4) | 0.46 (0.17) | 21.2 (17.5) | 0.20 (0.03) |
| **Dairy Crop** | 133 | 3.2 (1.0) | 2.0 (0.7) | 617 (154) | 6.6 (2.1) | 0.65 (0.19) | 30.5 (20.6) | 0.21 (0.03) |
| **Mixed Veg** | 62 | 4.0 (1.4) | 2.5 (1.0) | 667 (217) | 8.8 (4.0) | 0.62 (0.27) | 37.3 (17.7) | 0.22 (0.03) |
| **Orchard** | 51 | 2.7 (0.8) | 1.7 (0.6) | 543 (167) | 6.5 (1.9) | 0.50 (0.19) | 33.5 (19.7) | 0.20 (0.04) |
| **Pasture** | 38 | 4.0 (1.0) | 2.5 (0.7) | 638 (200) | 8.2 (2.6) | 0.86 (0.33) | 61.1 (20.0) | 0.23 (0.03) |
| **All** | 531 | 3.1 (1.0) | 1.9 (0.7) | 576 (176) | 6.4 (2.5) | 0.59 (0.22) | 31.5 (20.2) | 0.21 (0.03) |
| | | | | **Silt Loam** | | | | |
| **Annual Grain** | 79 | 3.6 (1.0) | 2.2 (0.7) | 618 (202) | 7.6 (3.1) | 0.65 (0.24) | 36.9 (21.8) | 0.23 (0.05) |
| **Processing Veg** | 21 | 3.5 (1.1) | 2.2 (0.8) | 554 (166) | 6.9 (2.6) | 0.57 (0.27) | 37.4 (26.7) | 0.23 (0.05) |
| **Dairy Crop** | 52 | 3.9 (1.1) | 2.5 (0.8) | 628 (168) | 7.8 (2.4) | 0.67 (0.19) | 38.8 (23.2) | 0.26 (0.05) |
| **Mixed Veg** | 58 | 4.3 (1.1) | 2.7 (0.8) | 685 (187) | 9.2 (2.9) | 0.65 (0.23) | 48.9 (23.6) | 0.27 (0.05) |
| **Orchard** | 48 | 3.7 (1.0) | 2.3 (0.8) | 633 (161) | 8.7 (3.1) | 0.70 (0.29) | 46.5 (19.2) | 0.27 (0.05) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Pasture** | 60 | 5.2 (1.1) | 3.3 (0.8) | 684 (164) | 10.0 (2.5) | 1.11 (0.38) | 74.2 (17.0) | 0.27 (0.05) |
| **All** | 318 | 4.1 (1.2) | 2.6 (0.9) | 642 (181) | 8.5 (3.0) | 0.74 (0.32) | 47.9 (25.3) | 0.26 (0.05) |
| **Fine-Textured** | | | | | | | | |
| **Annual Grain** | 12 | 3.9 (0.8) | 2.2 (0.5) | 650 (150) | 6.3 (1.0) | 0.53 (0.20) | 36.9 (21.8) | 0.23 (0.04) |
| **Processing Veg** | * | 3.9 (0.8) | 2.3 (0.8) | 650 (150) | 6.3 (1.0) | 0.53 (0.20) | 31.1 (23.2) | 0.23 (0.04) |
| **Dairy Crop** | 23 | 4.3 (0.8) | 2.5 (0.4) | 730 (120) | 6.7 (2.3) | 0.60 (0.14) | 38.8 (23.2) | 0.23 (0.04) |
| **Mixed Veg** | * | 4.2 (1.2) | 2.5 (0.8) | 730 (120) | 6.7 (2.3) | 0.60 (0.14) | 38.6 (24.0) | 0.23 (0.04) |
| **Orchard** | * | 4.2 (1.0) | 2.5 (0.6) | 730 (120) | 6.7 (2.3) | 0.60 (0.14) | 43.1 (20.5) | 0.23 (0.04) |
| **Pasture** | 4* | 4.8 (1.7) | 2.8 (0.9) | 740 (210) | 8.4 (2.6) | 1.23 (0.18) | 68.5 (22.9) | 0.23 (0.04) |
| **All** | 40 | 4.2 (0.9) | 2.5 (0.6) | 700 (145) | 6.8 (2.1) | 0.64 (0.24) | 31.0 (21.2) | 0.23 (0.04) |

### 3.2. Production Environment Soil Health Goals

This research focuses on developing a framework for empirically defining PESH goals by soil texture, cropping system, and geography (LRR) thereby providing realistic targets for farmers within the context of their farming environment. We developed PESH goals based on the 75th and 90th percentile of the production environment group's distribution to support broader policy discussions around the most appropriate metrics for voluntary SH standards. Although our geographic focus is on NYS, this framework can be applied to any production environment where SH data are sufficient to develop a peer population-based analysis (i.e., a large enough representative dataset to allow for comparison of individual sample results against their peers, results of all samples from the same production environment).

PESH goals in NYS (Table 3) were highest in finer textured soils for SOM, POXC, and Resp in order of fine-textured = silt loam > loam > coarse-textured. Finer textured soils have a greater ability to retain and stabilize SOM against decomposition than coarse-textured soils (von Lützow et al., 2006). Protein goals did not follow this trend, likely due to the effects of lower protein extraction efficiency in soils with higher clay content (Amsili et al., 2021; Giagnoni et al., 2013). Wet aggregate stability (WAS) goals were also not strongly affected by soil texture group. Available water capacity (AWC goals) were highest for silt loam soils, conforming to established knowledge (Brady and Weil, 2008; Libohova et al., 2018; Table 4). Since surface (0-15 cm; PR15) and subsurface hardness (15-45 cm; PR45) follow a less-is-better scoring function (Moebius-Clune et al., 2016), PESH goals were based on the 25th and 10th percentile values of the generalized scoring functions, which are 690 kPa and 350 kPa, respectively, for PR15, and 1550 kPa and 1100 kPa, respectively, for PR45.

Cropping systems were equally influential in shaping aspirational SH goals when compared to soil texture. Pastures, Mixed Vegetable, and Dairy Crop systems allow for the highest biological and physical PESH goals, followed by Orchard systems. Pasture systems naturally maintain greater biological and physical health due to continuous perennial carbon inputs and an absence of cultivation, whereas Mixed Vegetable and Dairy Crop systems improve SH largely through cover cropping, perennial forages, and organic matter inputs. Orchard systems had intermediate PESH goals presumably because some have quite poor soil health due to chemical fallow groundcover management that does not return OM inputs to the soil (Merwin et al., 1994), while others maintain higher soil health by utilizing woodchip mulch to provide weed control and build SOM. Processing Vegetable and to a lesser extent Annual Grain systems were associated with lower biological and physical SH goals as the harvest and removal of much of the aboveground biomass and use of tillage generates off-farm carbon and nutrient flows without adequate replacement. Interestingly, for silt loam textures, SH goals for Dairy Crop and Mixed Vegetable systems appeared to converge with those for Annual Grain and Processing Vegetables.

By having PESH goals farmers may be more encouraged to implement management practices that build soil health because a more achievable target can be reached. For example, if a farmer currently has SOM levels of 2.0% but within the same soil texture class and cropping system has the ability to reach 4.0%, it is empirically proven that they can reach this goal within the context of their soil type, climate, and cropping system. With the help of an agriculture service provider, this farmer can determine what changes in practices are needed to build SOM and improve overall soil health.

One potential limitation of the empirical framework for defining PESH goals as the $75^{th}$ or $90^{th}$ percentile is that soils at the $75^{th}$ or $90^{th}$ percentile may still represent low soil health. Therefore, it is important that the sample population for each production environment includes fields that have had long-term implementation of best practices relevant to that cropping system. While this is not a limitation for this dataset, where many of NYS's most innovative regenerative farmers and long-term research experiments are well represented, this is would be a concern for PESH goals that were developed from unrepresentative datasets.

**Table 3.** Production environment soil health goals (Q75 and Q90 basis) by cropping system and soil texture for biological SH indicators for NYS without Long Island (LRR-L&R).

| Cropping System | n | Q75 SOM | Q90 SOM | Q75 Pred. SOC | Q90 Pred. SOC | Q75 POXC | Q90 POXC | Q75 Protein | Q90 Protein | Q75 Resp | Q90 Resp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | % | % | % | mg C/ kg | mg C/ kg | mg/g | mg/g | mg $CO_2$/g | mg $CO_2$/g |
| **Coarse-Textured** | | | | | | | | | | | |
| **Annual Grain** | 37 | 2.6 | 2.8 | 1.8 | 1.9 | 494 | 620 | 6.5 | 7.5 | 0.53 | 0.58 |
| **Processing Veg** | 20 | 2.2 | 2.8 | 1.5 | 1.9 | 509 | 603 | 6.7 | 7.7 | 0.42 | 0.60 |
| **Dairy Crop** | 29 | 3.7 | 4.3 | 2.5 | 3.1 | 668 | 954 | 8.5 | 9.4 | 0.63 | 0.85 |
| **Mixed Veg** | 29 | 4.6 | 5.0 | 3.0 | 3.4 | 790 | 900 | 12.5 | 15.0 | 0.65 | 1.00 |
| **Orchard** | 44 | 2.7 | 3.0 | 2.0 | 2.1 | 685 | 843 | 7.6 | 9.6 | 0.48 | 0.54 |
| **Pasture** | 16 | 3.4 | 4.2 | 2.3 | 2.9 | 575 | 735 | 9.0 | 9.6 | 0.75 | 0.87 |
| **All** | 175 | 3.1 | 4.2 | 2.1 | 2.9 | 629 | 836 | 8.1 | 11 | 0.58 | 0.78 |
| **Loam** | | | | | | | | | | | |
| **Annual Grain** | 209 | 3.2 | 3.7 | 2.0 | 2.3 | 651 | 757 | 5.9 | 7.2 | 0.61 | 0.69 |
| **Processing Veg** | 38 | 3.1 | 3.5 | 1.9 | 2.1 | 508 | 579 | 5.6 | 6.5 | 0.53 | 0.66 |
| **Dairy Crop** | 133 | 3.6 | 4.5 | 2.3 | 2.9 | 688 | 775 | 7.4 | 8.8 | 0.72 | 0.89 |
| **Mixed Veg** | 62 | 4.9 | 5.6 | 3.2 | 3.6 | 847 | 927 | 10.8 | 14.7 | 0.70 | 0.86 |
| **Orchard** | 51 | 3.2 | 3.7 | 2.1 | 2.3 | 617 | 731 | 7.2 | 9.0 | 0.58 | 0.76 |
| **Pasture** | 38 | 4.8 | 5.2 | 2.9 | 3.4 | 731 | 895 | 9.7 | 11.8 | 1.12 | 1.27 |
| **All** | 531 | 3.6 | 4.5 | 2.2 | 2.9 | 680 | 811 | 7.2 | 9.4 | 0.68 | 0.84 |
| **Silt Loam** | | | | | | | | | | | |
| **Annual Grain** | 79 | 4.2 | 5.2 | 2.7 | 3.3 | 758 | 856 | 8.7 | 11.4 | 0.72 | 0.87 |
| **Processing Veg** | 21 | 4.2 | 4.8 | 2.7 | 3.0 | 651 | 690 | 7.7 | 8.9 | 0.76 | 0.91 |
| **Dairy Crop** | 52 | 4.4 | 5.6 | 2.8 | 3.6 | 725 | 859 | 8.6 | 11.7 | 0.77 | 0.92 |
| **Mixed Veg** | 58 | 5.0 | 5.9 | 3.1 | 3.9 | 800 | 912 | 10.7 | 13.1 | 0.79 | 0.94 |
| **Orchard** | 48 | 4.5 | 4.8 | 2.8 | 3.1 | 746 | 834 | 9.7 | 12.1 | 0.89 | 1.08 |
| **Pasture** | 60 | 5.9 | 6.5 | 3.8 | 4.3 | 801 | 862 | 11.4 | 12.7 | 1.37 | 1.64 |
| **All** | 318 | 4.9 | 5.8 | 3.1 | 3.8 | 774 | 883 | 10.0 | 12.5 | 0.89 | 1.19 |
| **Fine-Textured** | | | | | | | | | | | |
| **Annual Grain** | 12 | 4.2 | 4.7 | 2.4 | 2.8 | 659 | 822 | 7.2 | 7.4 | 0.62 | 0.70 |
| **Processing Veg** | * | 4.2 | 4.7 | 2.4 | 2.8 | 659 | 822 | 7.2 | 7.4 | 0.62 | 0.70 |
| **Dairy Crop** | 23 | 4.7 | 5.1 | 2.8 | 3.3 | 784 | 924 | 7.9 | 8.8 | 0.69 | 0.80 |
| **Mixed Veg** | * | 4.7 | 5.1 | 2.8 | 3.3 | 784 | 924 | 7.9 | 8.8 | 0.69 | 0.80 |
| **Orchard** | * | 4.7 | 5.1 | 2.8 | 3.3 | 784 | 924 | 7.9 | 8.8 | 0.69 | 0.80 |
| **Pasture** | 4 | 5.9 | 6.5 | 3.8 | 4.2 | 797 | 857 | 11.3 | 12.6 | 1.37 | 1.63 |
| **All** | 37 | 4.6 | 5.2 | 2.8 | 3.1 | 777 | 913 | 7.8 | 8.9 | 0.70 | 1.06 |

*Groups with fewer than 10 in the fine-textured categories were interpolated based off silt loam values.

**Table 4.** Production environment soil health goals (Q75 and Q90 basis) by cropping system and soil texture for physical SH indicators for NYS without Long Island (LRR-L&R). Soil health goals for PR15 and PR45 are presented in the section 3.2.

| Cropping System | n | Q75 WAS % | Q90 WAS % | Q75 AWC g $H_2O$/g soil | Q90 AWC g $H_2O$/g soil |
|---|---|---|---|---|---|
| | | **Coarse-Textured** | | | |
| **Annual Grain** | 37 | 47.7 | 58.3 | 0.19 | 0.20 |
| **Processing Veg** | 20 | 28.0 | 43.9 | 0.21 | 0.23 |
| **Dairy Crop** | 29 | 49.7 | 71.6 | 0.21 | 0.24 |
| **Mixed Veg** | 29 | 57.7 | 69.1 | 0.22 | 0.24 |
| **Orchard** | 44 | 48.0 | 65.9 | 0.19 | 0.20 |
| **Pasture** | 16 | 84.5 | 86.1 | 0.23 | 0.28 |
| **All** | 175 | 52.4 | 72.2 | 0.20 | 0.23 |
| | | **Loam** | | | |
| **Annual Grain** | 209 | 34.5 | 44.5 | 0.22 | 0.24 |
| **Processing Veg** | 38 | 33.2 | 44.1 | 0.22 | 0.23 |
| **Dairy Crop** | 133 | 54.9 | 70.1 | 0.28 | 0.30 |
| **Mixed Veg** | 62 | 69.6 | 74.5 | 0.30 | 0.34 |
| **Orchard** | 51 | 42.9 | 68.3 | 0.22 | 0.23 |
| **Pasture** | 38 | 76.1 | 81.9 | 0.25 | 0.26 |
| **All** | 531 | 41.0 | 62.9 | 0.23 | 0.24 |
| | | **Silt Loam** | | | |
| **Annual Grain** | 79 | 54.7 | 70.1 | 0.26 | 0.30 |
| **Processing Veg** | 21 | 50.4 | 72.7 | 0.28 | 0.29 |
| **Dairy Crop** | 52 | 54.9 | 70.1 | 0.28 | 0.30 |
| **Mixed Veg** | 58 | 69.6 | 74.5 | 0.30 | 0.34 |
| **Orchard** | 48 | 59.1 | 72.3 | 0.31 | 0.34 |
| **Pasture** | 60 | 87.1 | 92.0 | 0.30 | 0.32 |
| **All** | 318 | 70.1 | 83.3 | 0.29 | 0.32 |
| | | **Fine-Textured** | | | |
| **Annual Grain** | 12 | 54.7 | 70.1 | 0.25 | 0.26 |
| **Processing Veg** | * | 50.4 | 72.7 | 0.25 | 0.26 |
| **Dairy Crop** | 23 | 54.9 | 70.1 | 0.25 | 0.26 |
| **Mixed Veg** | * | 69.6 | 74.5 | 0.25 | 0.26 |
| **Orchard** | * | 59.1 | 72.3 | 0.25 | 0.26 |
| **Pasture** | 4 | 87.1 | 92.0 | 0.25 | 0.26 |
| **All** | 40 | 70.3 | 84.0 | 0.25 | 0.26 |

*Cropping system goals in the fine-textured categories were assumed to be the same as the silt loam category for aggregate stability and the same as All fine-textured samples for AWC.

### 3.3. Comparing PESH Goals (Q75 vs Q90)

While targeting the 75th percentile is a sound approach for identifying achievable SH goals, choosing a higher quantile (e.g., 90th percentile) may be of interest for certain subgroup populations to provide a more aspirational SH goal. The Q90 goal was 15.9%, 17.5%, 20.8%, 23.2%, 31.1%, and 8.0% higher than the Q75 goal for SOM, POXC, Protein, Resp, WAS, and AWC, respectively (Table 3; Table 4). A concern is that certain subgroup populations with narrow distributions might not contain those systems with aspirational soil health practices and outcomes at the 75th percentile. In those cases, choosing the 90th percentile as the PESH goal may remedy that situation. For SOM, the percent and absolute difference between the 90th and 75th percentile was 16.9% and 0.55% for Annual Grain and Processing Vegetable systems, but was 22.8% and 0.9% for Dairy Crop systems. This indicates that choosing the 90th percentile instead of the 75th percentile might be more appropriate for Annual Grain and Processing Vegetable systems, especially on coarse and loam textures where the differences between Q75 and Q90 were more pronounced for other systems. Ultimately, providing both Q75 and Q90 PESH goals gives agricultural professionals, farmers, and policymakers options about which goal seems to be the most appropriate for their specific situation.

### 3.4. Regional Goals within New York State

The development of PESH goals for NYS without Long Island (LRR-L&R) provides a first step forward to defining appropriate standards for NYS glaciated soils and cropping systems, but further regionalization of PESH goals may be necessary. The US Department of Agriculture's LRR and Major Land Resource Area concepts, regions defined by similarities in physiography, geology, climate, soils, and land use, were used to explore this question. Comparisons of SOM means and PESH goals across LRRs demonstrated that Long Island (LRR-S) had the most distinct soil health outcomes across cropping systems compared to other regions, and thereby requires separate scoring functions and PESH goals (Table 5; Table S1; hence the decision to remove Long Island samples from Figures 2-4).

PESH goals for SOM (Q75) for Long Island subgroup populations had on average 0.7 % lower SOM than their corresponding subgroup populations from the rest of NYS (Table 5; Table S1; Figure 3). These differences between Long Island and the rest of NYS appeared larger in loam and silt loam texture groups than for coarse-textured soils (Table 5; Table S1). Long Island's generally coarser textured soils (higher sand and lower clay content; Aller et al., 2022) and warmer climate are important factors that likely contribute to a lower inherent ability for Long Island's soils to retain SOM against decomposition compared to the rest of NYS (Guo et al., 2006; von Lützow et al., 2006). The soils of Long Island were formed from sorted sand and gravel glacial outwash parent materials that are characteristic of the southern edge of Pleistocene glaciers (Warner et al., 1975). Specifically, loam and silt loam groups on Long Island had 5% less clay than those same texture groups from the rest of NYS. These differences in clay content increased at the upper end of the distribution of clay content in loam and silt loam soils. The mean annual temperature on Long Island is also approximately 3.3 °C warmer than all other agricultural areas in the rest of NYS. While the effects of temperature on microbial decomposition of SOM are difficult to unravel, topsoil SOC concentrations appear to decrease as mean annual temperature increases within certain ranges (Guo et al., 2006). Also, Long Island has a long history of intensive processing vegetable production including lima beans, cauliflower, and potatoes (Bond, 1954; Faber, 1975; Lazarus and White, 1984), which might be a third factor contributing to low topsoil SOM values. Continuous processing vegetable production involves intensive soil disturbance and few organic matter inputs to the soil, which can lead to lower SOM concentrations over time (Angers et al., 1999). These soil, climatic, and land use history differences are likely explanations for the overall lower SOM values for Long Island compared to similar production environments (texture x cropping system) in the rest of NYS (Table 5; Table S1).

More subtle differences were revealed between LRR-L (equivalent to the Ontario-Erie Plain and Finger Lakes Major Land Resource Area) and LRR-R in Dairy Crop systems, but not the other cropping systems (Table S1; Table S2). SOM PESH goals (Q75) for Dairy Crop systems in LRR-R were on average 0.9% higher than for those in LRR-L. These differences were significant in loam and silt loam texture groups, but not for coarse textured soils (Table S1; Table S2). When examined at the MLRA level, these same differences in Dairy Crop systems were seen between the Ontario-Erie Plain and Finger Lakes MLRA and the Glaciated Allegheny Plateau and Catskill Mountain MRLA (Table S2). The crop sequences for Dairy Crop systems indicated that those in the Ontario-Erie Plain and Finger Lakes MLRA were more likely to have soybeans in the dairy rotation, which was rare for the Glaciated Allegheny Plateau and Catskill Mountain MRLA. At this point, there is insufficient data to determine if separate SH scoring functions and PESH goals are required for LRR-L and LRR-R.

**Table 5.** Mean values (standard deviation; SD) and Production Environment Soil Health goals (Q75 and Q90 basis) by cropping system and soil texture for soil organic matter compared between Long Island (LRR-S) and the rest of NYS (LRR-L&R). Letters indicate differences in soil organic matter across regions within the same texture and cropping system categories ($P<0.05$).

| | NYS (LRR-L&R) | | | | Long Island (LRR-S) | | | |
|---|---|---|---|---|---|---|---|---|
| **Cropping System** | **n** | **Mean (SD) SOM** | **Q75 SOM** | **Q90 SOM** | **n** | **Mean (SD) SOM** | **Q75 SOM** | **Q90 SOM** |
| | | % | % | % | | % | % | % |
| **Coarse** | | | | | | | | |
| **Annual Grain** | 37 | 2.2 (0.6) | 2.6 | 2.8 | - | - | - | - |
| **Processing Veg** | 20 | 1.9a (1.0) | 2.2 | 2.8 | 25 | 1.7a (0.4) | 2.1 | 2.2 |
| **Dairy Crop** | 29 | 2.8 (1.4) | 3.7 | 4.3 | - | - | - | - |
| **Mixed Veg** | 29 | 3.4a (1.3) | 4.6 | 5.0 | 46 | 3.3a (1.9) | 4.0 | 6.3 |
| **Orchard** | 44 | 2.4b (0.8) | 2.7 | 3.0 | 9* | 3.3a (1.8) | 4.1 | 5.5 |
| **Pasture** | 16 | 3.1a (0.8) | 3.4 | 4.2 | 28 | 2.0b (0.7) | 2.5 | 3.0 |
| **All** | 176 | 2.6 (1.1) | 3.1 | 4.3 | 108 | 2.6 (1.5) | 3.1 | 5.1 |
| **Loam** | | | | | | | | |
| **Annual Grain** | 209 | 2.8 (0.7) | 3.2 | 3.7 | - | | - | - |
| **Processing Veg** | 38 | 2.7a (0.7) | 3.1 | 3.5 | 10 | 2.2a (0.3) | 2.5 | 2.6 |
| **Dairy Crop** | 133 | 3.2 (1.0) | 3.6 | 4.5 | - | | - | - |
| **Mixed Veg** | 64 | 4.0a (1.4) | 4.9 | 5.6 | 26 | 2.6b (0.9) | 2.9 | 3.5 |
| **Orchard** | 51 | 2.7a (0.8) | 3.2 | 3.7 | 16 | 2.4a (0.7) | 3.3 | 3.7 |
| **Pasture** | 38 | 4.0a (1.0) | 4.8 | 5.2 | 8* | 2.2b (0.6) | 2.1 | 2.8 |
| **All** | 533 | 3.1 (1.0) | 3.6 | 4.5 | 60 | 2.4 (0.7) | 2.6 | 3.3 |
| **Silt Loam** | | | | | | | | |
| **Annual Grain** | 79 | 3.6 (1.0) | 4.2 | 5.2 | - | - | - | - |
| **Processing Veg** | 21 | 3.5a (1.1) | 4.2 | 4.8 | 13 | 2.9a (1.0) | 3.5 | 4.1 |
| **Dairy Crop** | 52 | 3.9 (1.1) | 4.4 | 5.6 | - | - | - | - |
| **Mixed Veg** | 58 | 4.3a (1.1) | 5.0 | 5.9 | 38 | 2.6b (0.7) | 3.0 | 3.7 |
| **Orchard** | 48 | 3.7a (1.0) | 4.5 | 4.8 | 25 | 2.8b (0.6) | 3.1 | 3.7 |
| **Pasture** | 62 | 5.2a (1.1) | 5.9 | 6.5 | 20 | 3.2b (0.8) | 3.6 | 4.0 |
| **All** | 320 | 4.1 (1.2) | 4.9 | 5.8 | 96 | 2.8 (0.8) | 3.3 | 3.9 |

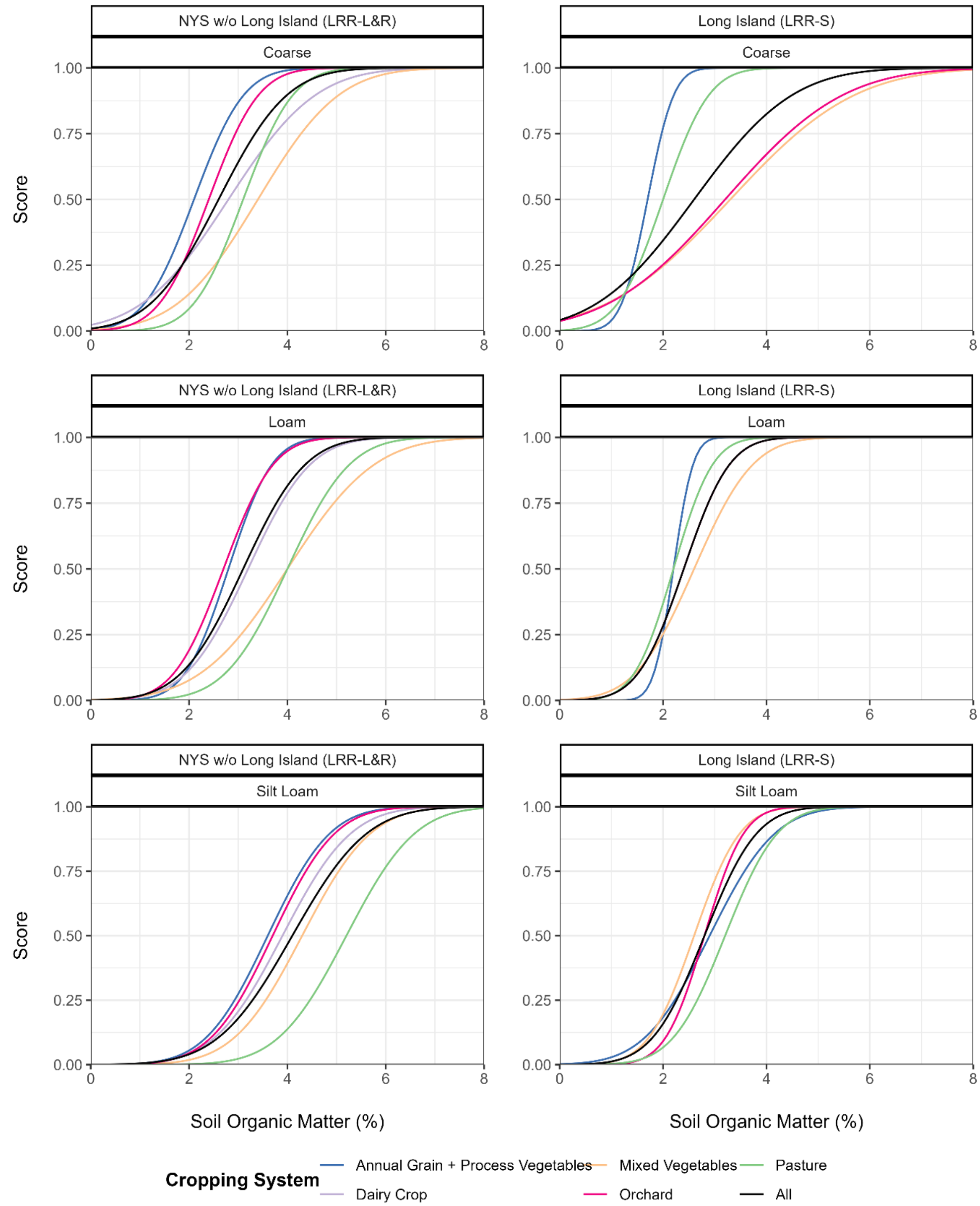


**Figure 3.** Scoring functions for soil organic matter for two regions in NYS and three soil texture classes. Scoring functions were presented for Annual Grain + Process Vegetables, Dairy Crop, Mixed Vegetables, Orchard, Pasture, and All data within each texture group. Annual Grain and Process Vegetable data was grouped since cumulative normal distribution functions were quite similar for those systems. There were no Annual Grain or Dairy Crop systems on Long Island (LRR-S).

## 4. CONCLUSIONS

Increased interest in soil health and building soil organic carbon requires benchmarks for assessing progress within the context of region, climate, soil type, and cropping system (production environment). PESH goals which regionally group together soil texture and cropping system can provide more realistic soil health goals to help growers calibrate their management. Realistic PESH goals for Pasture, Mixed Vegetable, and Dairy Crop systems are different than those for Annual Grain and Processing Vegetable systems across soil texture groups, mostly as a result of fundamentally different agronomic management practices (i.e., tillage and amount of organic carbon inputs) that are implemented in these systems. The development of separate PESH goals for areas within a state is justified if significant differences in soil type and climate exist, which was the case for Long Island compared to the rest of NYS.

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