Effects of Crop Management Practices on the Soil Health Indicators—Water Stable Aggregates and Soil Organic Matter

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Abstract

Soil health is integral in maintaining crop productivity, so we evaluated impacts of crop rotations on soil health using two no-till six-year rotations incorporating annual cover crops and perennials and a no-till corn/soybean rotation. This study was conducted in the Northeastern Sustainable Agriculture Research and Education (NESARE) Sustainable Dairy Cropping System at the Agricultural Research Farm at Rock Springs in State College, Pennsylvania. All crop entries are planted each year in 0.25 acre plots with four replicates that are randomized within crop rotation. We hypothesized that water stable aggregates (WSA) and soil organic matter (SOM) would be higher in crop rotations with more continuous live root cover provided by annual cover crops or perennials compared to rotations with only summer annual crops. This is because live roots help bind together soil particles and support microbial and fungal processes that increase WSA and SOM, and perennial roots contain more carbon than annuals. Ten soil cores were collected per split-plot at 0-5cm and at both 0-5cm and 5-15cm depths to measure WSA and SOM, respectively. We found that after three years, at the 0-5 cm soil depth, soil organic matter was significantly increased and water stable aggregates significantly higher in soil where corn was preceded by perennials compared to the soil of corn with prior annual cover crops or in rotation without cover crops, which were not statistically different from each other. Based on these results, recommendations can be provided to Northeastern dairy farmers on increasing their soil health by adding perennials to their rotations to ensure their productive soil's longevity.

Introduction/Literature Review

There is a limited amount of new land that can be cultivated because much of what is available cannot support agriculture (Duiker, 2011). This is due to less than ideal conditions such as the land's susceptibility to erosion, poor fertility and nutrient holding capacity, and even laws that have been put in place to protect forested lands from disappearing. Therefore, more emphasis has been placed on maintaining soil health for the long term on intensively cultivated farmland to support increasing global food demand (Westcott and Trostle, 2012). Soil health is the capacity of a soil to function and support life. It is often evaluated as an indicator of an agroecosystem's ability to be productive over time because it influences soil water holding capacity, nutrient holding capacity and cycling, and gas exchange, which can influence long-term crop productivity and resilience to climactic stress. Two soil properties that are often measured to evaluate soil health include soil organic matter (SOM) and water stable aggregates (WSA) (Karlen et al., 1997). Organic matter is any of the dead and dying plant materials such as roots, leaves, and stems, as well as animals and other organisms that are left on the soil surface. Soil microbes can break down these materials into simpler elements and compounds that can be used by the plants. A water stable aggregate is a group of soil particles that bind together to resist disintegration by water. The portion of the aggregate that holds together when water passes over and through it is considered water stable, while particles that crumble off are considered unstable.

Soil organic matter offers many benefits to soil health, and certain management practices have been shown to increase the amount of organic matter returned to the soil. Concerning soil function, the organic acids and compounds found in soil organic matter, provide many soil benefits, such as increasing cation-exchange capacity, helping to bind soil particles into aggregates, increasing water-holding capacity, and helping to buffer pH (Brady and Weil, 1996). Higher soil organic matter levels also help support diverse subsurface activities like nutrient availability and microbial activity (Brady and Weil, 1996). Management practices such as annual tillage, short–term crop stands, and fallowing croplands are methods that adversely influence soil organic matter by reducing the production or availability of organic matter (Duiker, 2011). Conversely, soil organic matter can be maintained or possibly increased using reduced tillage or no tillage, as well as applying nutrients like manure, fertilizer, or compost, and even diverse cropping systems that incorporate perennials and legumes (Duiker, 2011; Ogunwole, 2008). Although, unlike synthetic fertilizer, manure contains soil microorganisms, which are organic materials and nutrients that drive plant and microbial metabolism and provide additional organic matter to the soil when crops and organisms die (Ogunwole, 2008). Another management practice affecting soil organic matter is the use of cover crops that replenish carbon rich organic matter through root exudates, interactions with microorganisms, and glomalin-producing mycorrhizal fungi, which are carbon-binding agents (Jastrow, Miller, and Lussenhop, 1997). These beneficial cover crops provide continuous plant cover throughout the year and put live roots into the ground, thereby enhancing soil organic matter. Other studies also support the practice of using cover crops to enhance organic matter (Duiker, 2011; Ogunwole, 2008), but fewer investigate changes over time between different crop rotations incorporating a variety of species.

Water aggregate stability directly and indirectly influences many soil processes and higher percentages of WSA can be promoted in cropping systems in several ways. Higher percentages of WSA are associated with greater carbon storage capacity, increased water infiltration ability, improved root growth, and even resistance to compaction (Brady and Weil, 1996; Grover and Karsten, 2008). Continuous tillage and leaving the soil surface bare after harvesting negatively affect the stability of these aggregates (Ogunwole, 2008). However, current research suggests that the following management practices promote aggregate stability: no till or reduced tillage management, cropping systems that keep plants in the ground for longer periods of time, leaving plant residues on soil surfaces to increase organic matter, and applications of manure amendments (Grover and Karsten, 2008; Ogunwole, 2008). Live root systems have also been identified as a key player in promoting the formation of water stable aggregates by contributing soil organic matter, increasing microbial activity, and helping bind together soil particles, in conjunction with soil microbes, fungal hyphae, and sticky polysaccharides (Miller and Jastrow, 1998). Although there are water stable aggregates present in rotations without cover crops, they do not tend to increase over time because there are not constant live roots. A number of studies have investigated the effects of cropping systems and the presence of live roots on water stable aggregates, but few have considered the differences between individual crop roots within the system. For instance, perennials put more nutrient resources and carbohydrates into developing root systems that are equipped to store nutrients and spread deeper and farther through the soil for longer-term establishment than annuals. Additionally, perennial root systems that can be dense and thick, fine, or fibrous contribute organic matter, promote microbial activity, and are in the ground longer, all of which enhance aggregate stability (Brady and Weil, 1996). By contrast, annuals focus energy and nutrient allocations on moving from germination to seed production quickly, thus, fewer resources are allocated towards extensive development of root systems, resulting in smaller root zones that are in the ground for less of the year.

The soil health indicators, SOM and WSA, were evaluated in cropping systems under variable management practices in the Northeast Sustainable Agriculture Research and Education (NESARE) sustainable dairy cropping systems project, which was initiated in 2010 at Penn State University (PSU). The project is an interdisciplinary research effort funded by a grant awarded by the United States Department of Agriculture NESARE funds. Goals of this project include making a dairy farm sustainable by minimizing off-farm inputs, lessening environmental impacts, and remaining lucrative while increasing soil health and biodiversity. Currently, in its fifth year of crop rotation and data collection, the project utilizes a host of management practices to evaluate 1) pest management strategies, which compare a standard herbicide regiment to practices that reduce herbicides (i.e. tillage, banding herbicide, using a high residue cultivator, and adding annual companion crops) 2) manure management practices by assessing injection versus broadcasting manure, and 3) a nutrient management component looking at manure versus synthetic fertilizer applications. Such multiyear cropping system research has the potential to examine the relationship of diverse management practices and the effect that each of those decisions, both individual and combined, have on indicators of agroecosystem sustainability.

The goal of this research was to examine the effect that selected crops and their rotations had on two soil health indicators (i.e. water stable aggregates and soil organic matter), over a three-year period. Soil in corn plots were sampled in 2013, and previously in 2010, in the three different crop rotations; the corn was preceded by annual cover crops, perennial crops, or no cover crop. In examining these soil health indicators, the following hypotheses were proposed: 1) Soil of corn in crop rotations implementing continuous plant cover will have more organic matter and higher percentages of water stable aggregates in the first 0-5 cm as opposed to soil of corn in a simple rotation without continuous cover, and 2) Soil of corn that was preceded by continuous perennial root cover will have more organic matter and higher percentages of water stable aggregate in the first 0-5 cm than corn that was preceded by continuous annual root cover.

Materials and Methods

Site Description

In 2010, the NESARE Sustainable Dairy Cropping System launched on 16 acres of the PSU Agronomy Farm at the Russell E. Larson Agricultural Research Farm at Rock Springs. Typically, Centre County Pennsylvania experiences an average of 40 inches of rainfall per year. Mean climactic conditions in January reach lows of 17 F degrees with temperatures reaching the high 80s in July. Though not completely uniform, the vast majority of soil at the experimental site is a Murrill channery silt loam (Fine-loamy, mixed mesic Typic Hapludults) that slopes 0-3% with some Buchanan channery silt loam (3-8% slope) and some Hagerstown silt loam (3-8% slope).

Cropping Systems

The experiment included three crop rotations of two six-year diverse crop rotations and a two-year control rotation. Every phase of the crop rotation was planted each year for a total of 14 crop entries that were randomized within each rotation and replicated in four blocks for a total of 56 main plots (120 feet by 90 feet). Each main treatment plot was divided into split-plots (60 feet by 75 feet). Thus, two management practices were compared within each rotation in a nested split-plot design. In the pest management comparison, one split-plot was treated as standard herbicide, including a herbicide application at standard rates, spraying cover crops, two broadcast and post-emergent herbicide treatments, and a broadleaf herbicide if necessary (Figure 1). For comparison, the other split-plot was managed with a combination of other practices designed to reduce herbicide applications. The reduced herbicide practices included tillage once in six years to terminate alfalfa, spraying and rolling cover crops, banding herbicide over the crop row rather than broadcasting across the entire field with high residue cultivation twice between the crop rows, and the addition of annual small grain crops to the new seeding of alfalfa and orchard grass. In the manure management comparison, one split-plot was broadcasted with dairy manure while the other was injected with dairy manure. Finally, the nutrient management comparison differed with one split-plot treated with broadcasted manure or fertilizer and the other with injected dairy manure or fertilizer. Prior to planting any experimental rotations, in the fall of 2009 all of the fields were planted with a rye cover crop to ensure that the project treatments would not be affected by previous crop history. All of the cropping systems have been operated under no-tillage management except in the reduced herbicide grain rotation, when tillage is used to terminate alfalfa once every six years. In the case of the corn plots where soil was sampled in 2013, the tillage event had occurred in 2011.

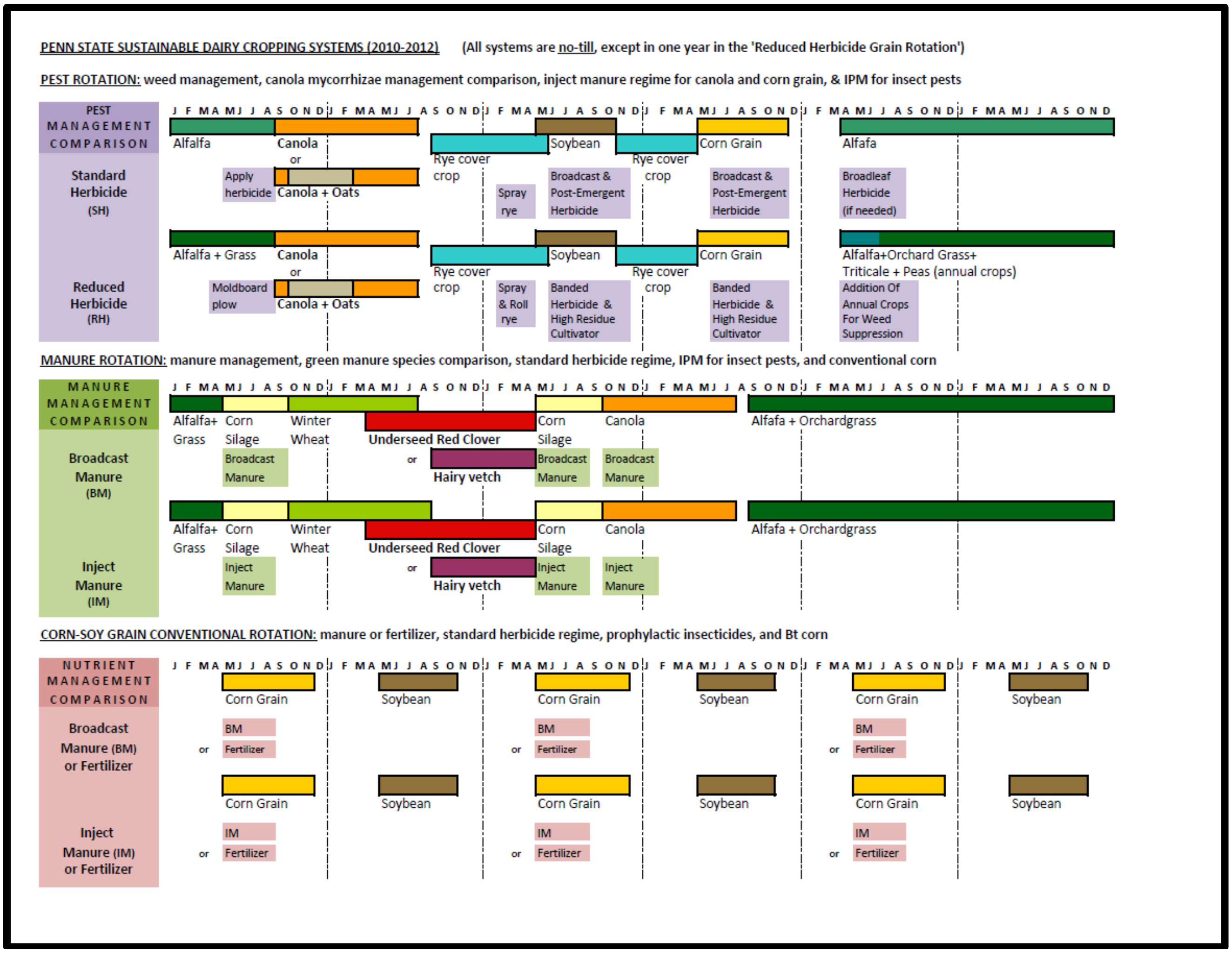

Figure 1: NESARE cropping system rotation from 2010-2012.

Aggregate Stability

Ten random composite soil samples were collected from each split-plot at a 0-15 cm depth. After collection, the samples were stored in airtight containers and moved to a cooler as soon as possible until processing. To begin processing, soil samples were sieved at field moisture and dried. Then, ten grams of soil was placed into a sieve apparatus for 1-2 mm particles and dunked into water for five minutes followed by dunking into a chemical dispersing solution (2g Na- hexametaphosphate/ 1 L DI water). Materials that passed through the sieves in the first few minutes were dried down and weighed, then labeled as the unstable aggregates. Next, a rubber-tipped probe was used for dispersing sand particles from the soil. The sand remained on the sieve while the soil fell into a collection bin. The soil was then dried down and weighed for sand corrected stable aggregate mass. Percent water stable aggregates were then calculated ([SandCorrect Ag/(SandCorrect Ag + Unstable aggregate)]*100).

Soil Organic Matter

A JMC Backsaver Soil Sampler was used to extract all soil cores for analysis. For soil organic matter, ten random soil cores were collected per main treatment at 0-5 cm and 5-15 cm depths, and composited into a single sample for each depth. After being finely ground, the soil samples were sent to the North Carolina State Soil Testing Lab where they were analyzed for elemental carbon. We used the equation developed by Ranney (1969) to convert percent carbon to percent organic matter (Percent organic matter = 0.35 + 1.80 x percent organic carbon).

Statistical Analysis

The statistical analysis software (SAS) was used to conduct an analysis of variance (ANOVA) on the data using the mixed procedure (PROC MIXED). The averaged data from an entire main plot for corn crops in each rotation were compared using Tukey's test and differences were considered significantly different at $p<0.05$ for soil organic matter and $p<0.01$ for water stable aggregates.

Results

Soil Organic Matter

In 2010, which marked the beginning of the NESARE cropping system prior to initiating treatments, there were no statistical differences in soil organic matter in either the 0-5 cm or 5-15 cm depths between the three rotations that we compared. In 2013, again the soil organic matter did not differ among the rotations at the 5-15 cm soil depth, but it did so at the 0-5 cm depth. Therefore, the remaining results and discussion will focus on soil organic matter in the 0-5 cm depth. At 0-5 cm, soil organic matter differed significantly ($p<0.05$) in the soil of corn rotations preceded by perennials compared to the soil of corn with prior annual cover crops (Figure 2). At 0-5 cm, soils of corn rotations with prior perennials had an average of 3.67% organic matter, while soil where annual cover crops were in place before corn had an average of 3.05%, which is 20% less organic matter.

At 0-5 cm, there was no significant difference between the corn in the no-cover crop rotation compared to the rotations that had prior annual cover crops or prior perennials. Soils that had no cover crops in rotation with corn measured an average of 3.18% organic matter.

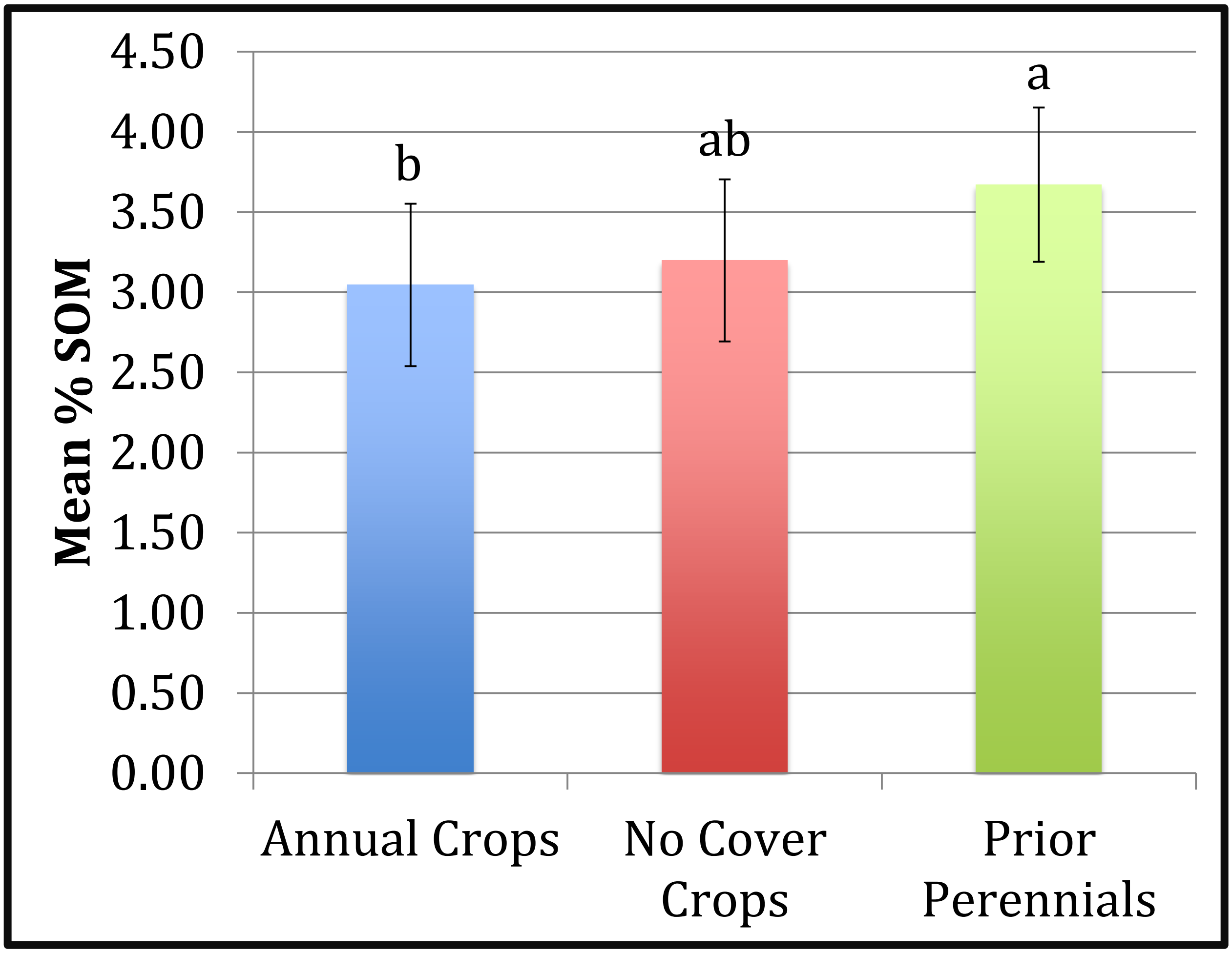

Figure 2: Mean % soil organic matter (SOM) at 0-5 cm depth in 2013. Different letters (a, b) indicate treatments that differ significantly at $p<0.05$.

For organic matter difference 2013-2010, the rotation effect between corn that was preceded by perennials compared to prior annual cover crops was significant (Figure 3). However, when no cover was compared to just previous annual cover crops, statistically, the numbers did not differ significantly. Soil in corn with prior perennials had a 70% increase in mean organic matter from 2010 to 2013, while the soil with prior annual cover crops only increased by 4%. Where there were no cover crops, soil organic matter decreased by 6%.

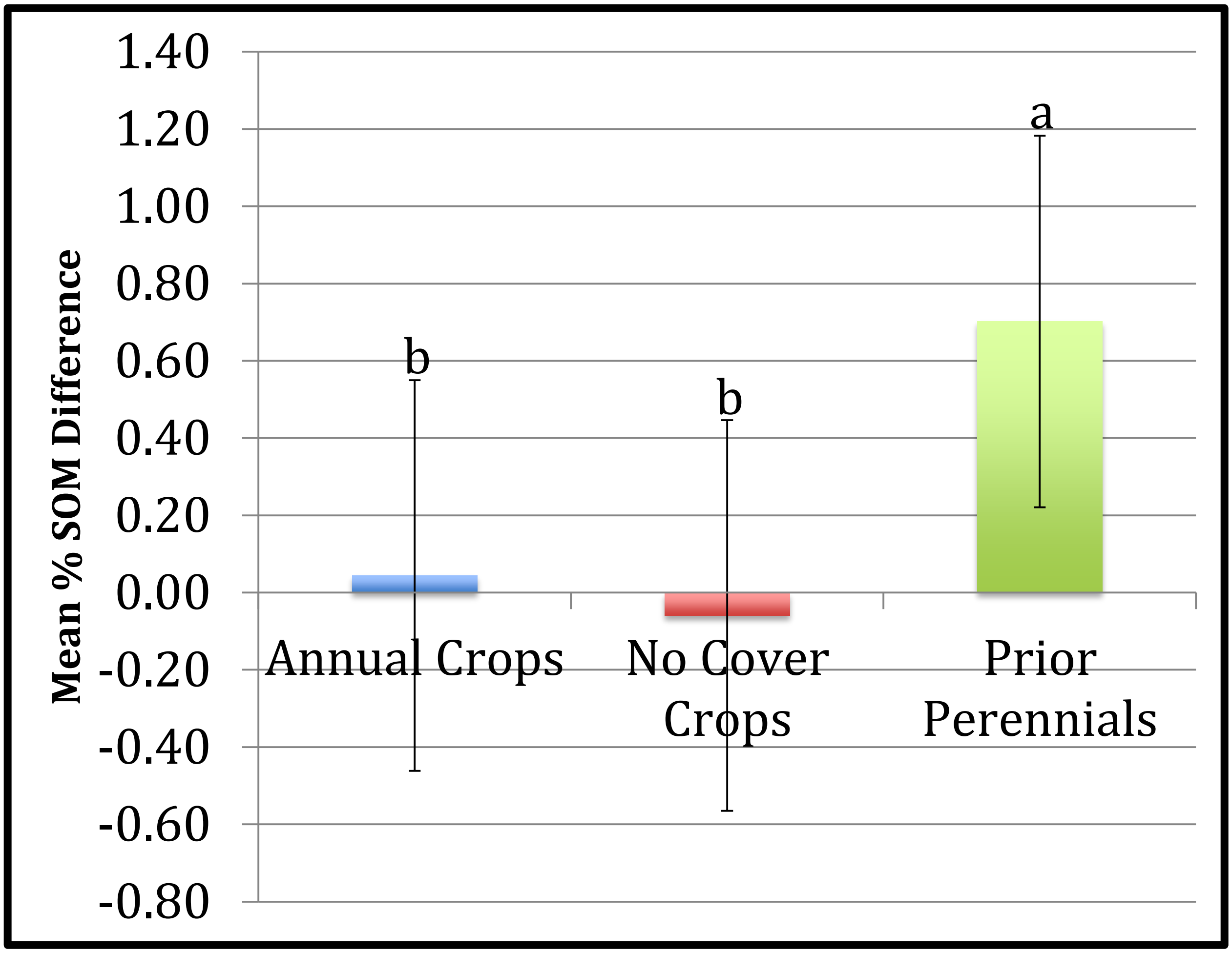

Figure 3: Mean % soil organic matter (SOM) difference from 2010 to 2013 at 0-5 cm depth. Different letters (a, b) indicate treatments that differ significantly at $p<0.05$.

Water Stable Aggregates

Again, when comparing 2010 data, there were no statistical differences in percent water stable aggregates in the rotations we compared. In 2013, water stable aggregates differed significantly ($p<0.01$) in the soil of corn rotations preceded by perennials and those with prior annual cover crops or no cover crop (Figure 4). The soils of corn in rotation with prior perennials had an average of 45.19% water stable aggregates while corn with prior annual cover crops only had an average of 38.21%, totaling an 18% difference in water stable aggregates. The soils of the no cover crop control averaged 39.18% water stable aggregates, which is 15% less water stable aggregates than the soils of corn with prior perennials. There was no statistical difference between rotations not using cover crops compared to rotations that had prior annual cover crops.

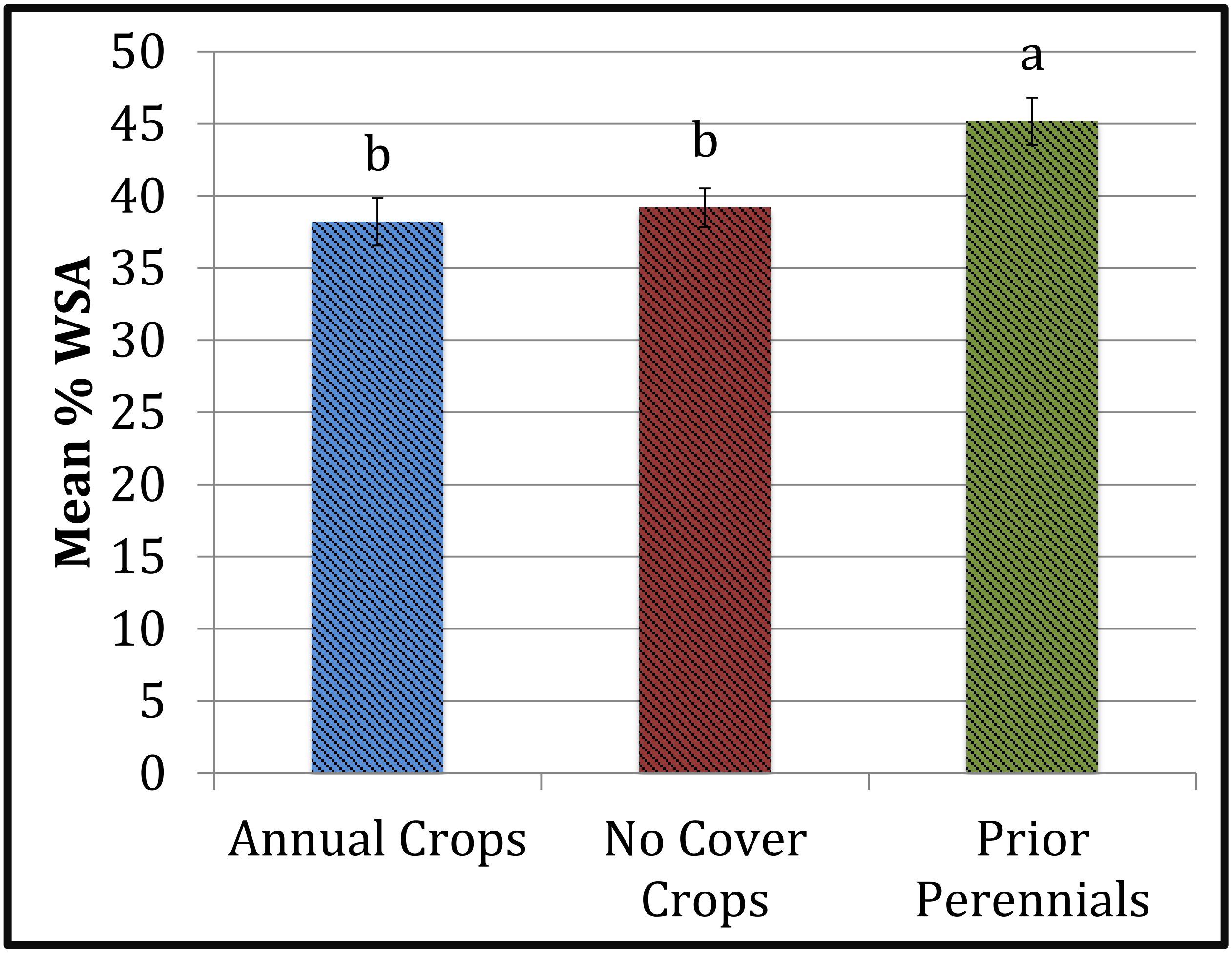

Figure 4: Mean % water stable aggregates (WSA) in 2013 at 0-15 cm depth. Different letters (a, b) indicate treatments that differ significantly at $p<0.01$.

Discussion

Soil is the foundation of crop production, and thus preserving the soil's health on existing farmland is paramount to support continually rising populations and global food demand in the long run (Westcott and Trostle, 2012). In this study, we looked at the two soil health indicators, soil organic matter and water stable aggregates. One of our primary findings is that after just three years, soil organic matter was significantly increased at the 0-5 cm soil depth (Figure 3) and water stable aggregates were significantly higher in soil where corn was in rotation with perennials compared to rotations with prior annual cover crops or in rotations without cover crops, which were not statistically different from one another (Figure 3, 4).

Soil Organic Matter

Our hypothesis stating that soil organic matter would be higher in corn rotations with continuous plant cover as opposed to corn in a simple rotation without continuous cover was not supported. We expected that the treatments in rotation with annual cover crops and perennials would have more soil organic matter than the no cover crop control because the former two treatments had live roots in the ground for more months of the year. There was no statistical difference, however, between the no cover crop rotation, and the annual cover crop and perennial rotations (Figure 2). These results could be due to three possible confounding factors, the first being tillage. Tilling the soil incorporates organic matter lying on the soil surface by turning it under, making it more accessible to the soil microbes (Brady and Weil, 1996; Duiker, 2011). With more access, the microbes can break down the organic matter much more quickly compared to when it is being slowly decomposed on the soil surface. In 2011, in the reduced herbicide treatment in the pest rotation (Figure 1), which is the corn in rotation with annual cover crops, there was a tillage event to kill a perennial alfalfa stand instead of spraying herbicide before winter canola was planted (Figure 1). This tillage event could explain why we saw lower percentages of organic matter in soils where corn was preceded by annual cover crops, but does not explain why we saw the same levels of SOM in our perennials preceding corn treatment, where no tillage occurred.

The second confounding factor that could explain the lack of difference between all three treatments is the method of soil sampling used. As part of the NESARE experiment, there was a comparison between broadcast and injected manure in the rotation that included perennials or no cover crop and once in the rotation with annual cover crops (Figure 1). Soil samples were collected randomly from both of those treatments. However, there is some evidence to suggest that random soil sampling does not provide an adequate representation of nutrients in the manure injected sites (R. Meinen, personal communication). The manure injector injects manure in bands that are spaced 30 inches apart in the soil. Thus, when random sampling was used, there is a chance that none of the samples were on or around that injection site and the soil data would show less organic matter than was present across the field. There is also a smaller chance that one could have sampled right on the band, causing an overestimation in the average organic matter in the soil. These bands of concentrated manure organic matter likely increased the variability of the soil organic matter data.

Finally, a third factor that could explain why soil organic matter was statistically equivalent in soil where corn was in rotation with annual cover crops and in soil in the no cover crop control was organic matter rich corn stover (Brady and Weil, 1996). Even though there were long fallow periods with no live roots present contributing organic matter between crop entries in the no cover crop control, there was a significant amount of corn stover left on the soil surface. In a no-till system, soil organic matter is not plowed under, and thus accumulates in the top 0-5 cm of the soil, breaking down very slowly. The other rotations did not include corn grain that left corn stover on the soil, and the rotation with annual cover crops prior to corn used canola, soybean, and rye cover crop as the annuals, which did not leave behind a lot of residue for the soil microbes to break down. Further, the rye cover crop was planted late in the fall (late October-early November) and was not present for very long to produce many roots and above-ground biomass. It is possible that this additional organic matter breaking down slowly on the soil surface in the no cover crop control resulted in there being no significant differences at the 0-5 cm depth between the treatments.

Our hypothesis that corn preceded by continuous perennial root cover in comparison to corn that was preceded by continuous annual root cover would have more organic matter was supported. Soil organic matter at 0-5 cm depth was 20% higher in rotations with a history of perennials than those using annual cover crops. This supports the idea that perennials contribute more organic matter to the soil than annuals because they have a larger root mass that is present for a longer period of time than annual roots.

Water Stable Aggregates

Our hypothesis stating that water stable aggregates (WSA) would be higher in corn rotations with continuous plant cover as opposed to corn in a simple rotation without continuous cover was only partially supported. Corn in rotation with perennials had soil with 15% higher WSA than corn in rotation without a cover crop (Figure 4). Conversely, WSA of soil in corn in rotation with annual cover crops was not statistically different from corn that was in rotation without any cover crops (Figure 4). There are a few possible confounding factors that could explain why this occurred. First, even though the rotations were primarily no-till, which promotes the formation of aggregates, there was one tillage event in 2011 that occurred in the corn rotation with prior annual cover crops (Figure 1), which breaks up aggregates (Brady and Weil, 1996; Duiker 2011). This could explain why water stable aggregates were the same in the rotation with annual cover crops compared to the rotation without a cover crop. Between soil sampling in 2011 and 2013, adequate time may not have passed for plant roots and soil organisms to rebuild water stable aggregates and recover from the effects of the tillage event.

Another possible explanation for the lack of difference could be the fungi living in symbiosis with the crop roots. Corn roots host mycorrhizal fungi, which can help bind together soil aggregates (Miller and Jastrow, 1998). In the corn rotation with prior annual cover crops though, canola, rye, and soybean were present. Canola is not a host of mycorrhizal fungi, and rye may not have as much of a vibrant and extensive fungal community as corn does. In addition, the injected manure bands likely promote more soil microorganisms and binding of soil aggregates. However, the limits of the random sampling method described above may not have allowed us to accurately sample the manure band zones adding another possible confounding factor.

As we expected, soil in corn in rotations implementing prior perennials compared to those using annual cover crops had 18% higher water stable aggregates. This supports our rationale that perennials, which allocate more carbohydrates into the development of their dense and complex root systems that are also present for a longer period of time than in annuals, contribute to building more water stable aggregates than annual cover crops (Chatigny et al., 1997).

Conclusions

In this experiment, having more complex and developed live root systems in the ground for a longer period of time had a more pronounced effect on both soil organic matter in the top 0-5 cm and water stable aggregates in some cases, than smaller live roots that were not present in the ground for as long. Perennials before corn increased organic matter at 0-5 cm depth and water stable aggregates more than annual cover crops before corn. However, there was no difference in soil organic matter between no cover crop and the other two treatments (prior annual cover crops or perennials) and no difference in water stable aggregates in corn preceded by annual cover crops and corn with no cover crop. These results that we did not predict suggest that additional factors may have an effect on increasing soil organic matter and water stable aggregates, such as tillage, random sampling in fields that were injected with manure, and corn stover left on the surface of our no cover crop control. Thus, the only assumptions we can draw from the results are that perennials before cash crops have the potential to increase the two soil health indicators analyzed here, organic matter and water stable aggregates.

From here, recommendations can be provided to Northeastern dairy farmers on increasing their soil health by implementing perennials into their rotations in order to secure their productive soil's longevity. There may be limitations however that could cause farmers to not start perennials in their rotations, such as tying up land that could otherwise be used to grow cash crops or even just not having equipment, the market, or animals for forage, silage, and hay making. Further research may assess 1) if the increases in organic matter and water stable aggregates will continue to rise or change over time, 2) if sampling treatments with injected manure with a more spatially representative method will reveal treatment differences, 3) if the impact on soil organic matter and water stable aggregates can be isolated and quantified, and 4) if these soil health indicators significantly differ in one of our diverse rotations when comparing perennial legumes with taproots and perennial grasses with fibrous roots.

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