doi:10.2489/jswc.2022.00056

Evaluating the impact of midwestern cropping systems on soil health and soil carbon dynamics

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Abstract: Crop producers are becoming more interested in improving the health of their soils. The effects of cropping practices on soil health have been studied extensively, but much uncertainty remains. This study investigated the impacts of standard midwestern US agronomic practices on soil health indicators. The Soil Management Assessment Framework was used to quantify soil quality index (SQI) scores for each system. Corn–soybean (*Zea mays* L.–*Glycine max* L.) rotations received 168 kg N ha^{-1} applied prior to corn. Treatments were the following: spring-applied urea ammonium nitrogen (SU168), fall-applied manure (FM) in no-till (NT) for 2 years (FM168NT2), FM with 10 years of NT and cereal rye (*Secale cereale*) cover crop (FM168NT10+R), and FM with 38 years of NT management (FM168NT38). Continuous corn (CC) treatments had FM applied annually at 224 kg N ha^{-1} with eight years of stover removal (FM224CC-S) and with no stover removal (FM224CC). Soil cores were taken to a depth of 15 cm in the spring of 2017 and analyzed for total carbon (TC), total nitrogen (TN), water-stable aggregates (WSA), bulk density (BD), and potentially mineralizable nitrogen (PMN). Results showed that FM168NT38 and FM224CC had significantly greater TC and TN than other treatments. There were minimal treatment differences in total WSA > 0.212 mm. No significant differences in PMN were found. Bulk density levels were significantly higher in NT treatments. The FM224CC and FM224CC-S treatments had the highest SQI scores, and FM168NT10+R had the lowest SQI score due to having higher BD and lower TC. Results suggest that the effect of cropping practices on some near-surface soil health indicators may be small and difficult to quantify. This study also demonstrated the need to adjust management to minimize compaction and maximize yield and soil health in cover-cropped systems.

The study also monitored soil TC levels to a depth of 120 cm from 2007 through 2017. The rate of change in TC over time at a given depth did not differ between treatments. Total C levels did not change significantly to a depth of 15 cm. Significant increases in TC were found in all treatments except FM224CC-S at 30 to 60 cm and 90 to 120 cm depths, and in all treatments at 60 to 90 cm depth. These results suggest that C accumulation deep in the soil profile may be typical in midwestern cropping systems. Deep sampling to ≥100 cm is needed to capture the complete picture of soil C dynamics to assess soil C accumulation potential.

Key words: bulk density—no-till—soil carbon—soil health—water-stable aggregates

The soil health benefits associated with various agricultural management practices have significant implications for soil and water quality. Soil health, also referred to as soil quality, has been defined as the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran and Zeiss 2000). Improving the health of agricultural soils has been linked to improvements in surface and groundwater quality, reduced sediment and pollutant transport, and more efficient use of agricultural inputs (National Research Council 1993). Healthy soils are typically more productive, less prone to erosion, and more resilient than degraded soils (Doran et al. 1994; Fageria 2002; Kibblewhite et al. 2008).

Switching to no-till (NT) cropping systems is one practice that has shown benefits to soil health (Schmidt et al. 2018; Nunes et al. 2018). It has been proposed that NT farming is a strategy that can increase soil organic carbon (SOC) levels and sequester carbon (C) in soils (West and Post 2002; Lal 2004). Tillage can cause compaction and disrupt aggregation, nutrient cycling, and soil microbial activity (Bronick and Lal 2005). It can also lead to substantial erosion by leaving the soil surface exposed to the actions of wind and water, in addition to in-field erosion due to tillage itself (Van Oost et al. 2006). Tilled soils generally have less microbial biomass (Wardle 1995) and altered mycorrhizal fungi populations (Jansa et al. 2003) compared to NT under similar crop rotations.

The presence of soil C affects aggregate stability and nutrient cycling and is associated with overall soil health. Aggregate stability has been identified as a critical factor in soil erosion and surface runoff dynamics (Barthès and Roose 2002) and an indicator of soil health (Amezketa 1999). Despite this, the effects of switching to NT on soil C levels and soil health remain unclear. Long-term research from Sanborn Field in Missouri indicates C sequestration can be achieved with conventional tillage as well as NT (Buyanovsky and Wagner 1998). Other research suggests that studies reporting greater accrual of SOC in NT may have been biased by shallow (≤30 cm) soil sampling depths (Baker et al. 2007). No-till soils have been found to have higher bulk density (BD) and greater penetration resistance in the upper soil profile (Vyn and Raimbault 1993; Fabrizzi et al. 2005). This could prevent deeper rooting in NT soils and lead to

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Received March 31, 2021; Revised June 10, 2021; Accepted June 30, 2021; Published online December 13, 2021.

more SOC accumulation near the surface. However, Boddey et al. (2010) reported the opposite in subtropical soils. Their results indicated that NT soils accumulated more C than conventionally tilled soils when assessed to 100 cm depth compared to 30 cm depth.

Research by Luo et al. (2010) suggests that rather than sequestering more C in soils, NT alters the distribution of SOC in the profile, with gains in the upper 10 cm and losses deeper in the profile. A meta-analysis by Angers and Eriksen-Hamel (2008) reported that full inversion tillage had significantly greater SOC than NT at depths of 21 to 35 cm, with no significant difference at depths >35 cm. However, NT still had an average of 4.9 Mg ha^{-1} more SOC than full inversion tillage over the entire sampling depth. A separate meta-analysis by Virto et al. (2012) reported an average of 3.4 Mg ha^{-1} more C in NT compared to inversion tillage systems. Their analysis found that greater crop C input was the only significant factor explaining increases in SOC at 0 to 30 cm depth, suggesting that increased C stocks were due to greater C inputs from NT residue more so than the elimination of tillage.

The use of cover crops is another practice that has been linked to improvements in soil health. A meta-analysis of 37 sites by Poeplau and Don (2015) showed that cover crop treatments led to a significant increase in soil SOC stocks over time compared to reference sites with no cover crop. Cover crops can also improve aggregate stability and increase soil porosity and soil water storage (Liu et al. 2005; Villamil et al. 2006; Basche et al. 2016). Returning cover crop residues to the soil can increase SOC and nitrogen (N) levels (Sainju and Singh 1997). The increased biological activity associated with cover crops can also enhance N cycling in the soil (Radke et al. 1988). Site-specific management that accounts for differing climate and cropping systems is needed to increase the likelihood of seeing soil health benefits with cover crops (Cates et al. 2018).

Corn (*Zea mays* L.) residue removal is a relatively common practice in the midwestern United States. However, it has the potential to impact soil health negatively due to lack of ground cover and reduced C inputs to soil. Wegner et al. (2018) found that residue removal can reduce aggregate stability and microbial enzyme activity, but the addition of a cover crop can offset these impacts. Lehman and Osborne (2016) showed that eight years of corn residue removal resulted in significantly lower SOC accumulation in the top 30 cm during the subsequent four-year study. Little data are available on the potential effects of residue removal on C deeper in the soil profile.

Using manure as a nutrient source has also been linked to soil health improvements, including increased SOC, more potentially mineralizable nitrogen (PMN), and reduced BD. A meta-analysis of studies on manure-C input effects by Maillard and Angers (2014) found that manuring increased SOC stocks relative to mineral fertilized plots. Iqbal et al. (2014) reported 92% more PMN and 28% higher organic matter levels in manured compared to nonmanured plots in India. Manuring can increase the porosity and aggregate stability of soil compared to mineral fertilization (Christensen and Johnston 1997) but has also been linked to reduced resistance to soil dispersion (Whalen and Chang 2002). However, research specific to liquid manures has shown inconsistent effects on soil properties. Long-term liquid swine manure application was found to increase nitrification and microbial activity of soils (Martí and Martí 2016). Antoneli et al. (2019) found improved porosity and organic matter with 10 years of liquid swine manure surface-applied to NT soybeans (*Glycine max* L.). Jokela et al. (2009) saw no improvement in aggregation or organic matter with four years of surface-applied liquid dairy manure on NT corn silage fields. The type of manure and length of time over which manure is applied are likely important when assessing manure effects on soil health.

Agricultural management practices such as using cover crops, livestock manure, and NT systems have been linked to soil health improvements. However, there is a lack of data from long-term studies to evaluate the rate and magnitude of change in soil health indicators due to these practices. Research on soil C at depths >30 cm is limited in the literature and is needed to provide more insight into the deep profile C dynamics in midwestern US cropland.

Researchers have been developing methods to quantify soil health indicators into a composite soil health score (Andrews et al. 2002; Wienhold et al. 2006; Karlen et al. 2008; Moebius-Clune et al. 2016). The Soil Management Assessment Framework (SMAF) is a program that provides a framework for combining ratings of soil health indicators affected by current management into an overall assessment of soil quality (Andrews et al. 2004; Karlen et al. 2008). Results from this study were assessed with the SMAF program to provide a comparison of soil health between different management systems using a soil quality index (SQI) score.

We hypothesize that NT, manure application, and inclusion of a cover crop will all show a positive impact on soil health and soil C levels. Our specific objectives are to evaluate soil health impacts of (1) tillage, (2) cereal rye (*Secale cereale*) cover crop, (3) residue removal, and (4) manure application on soil health indicators and overall SMAF SQI score, and (5) quantify changes in total C (TC) in soil profiles to a depth of 120 cm across multiple cropping systems.

Materials and Methods

Site Description. Experimental data were collected at the Iowa State University Northeast Research and Demonstration Farm near Nashua, Iowa. The soils at the site include Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls) (Kanwar et al. 1997). The Kenyon soil is classified as moderately well-drained, whereas the Floyd and Readlyn soils are moderately poorly drained. These soils, particularly Floyd and Readlyn, have a seasonal high water table. The plots are drained with a subsurface drainage system with a tile spacing of 28.5 m at a depth of 1.2 m.

The cropping system experiment at the site uses a randomized complete block design with six different treatments and three replications (blocks). Table 1 shows the management history at the research site. Continuous corn treatments had three plot replicates each. All other treatments were in a corn–soybean (CS) rotation with three replicates in corn and three in soybeans each year. For treatments managed with conservation tillage, the plots with corn residue were chisel plowed in the fall after corn harvest, and all corn and soybean plots were field cultivated in the spring before planting the crops. Plots managed with conventional tillage from 1978 to 1992 were moldboard plowed in the fall and field cultivated in the spring. The FM224CC-S treatment had approximately 30% of the stover removed after fall harvest from 2007 through 2014, and a single application of 2.3 Mg ha^{-1} application of gypsum

Table 1
Historical tillage and nitrogen (N) management for the experimental treatments at the Iowa State University Northeast Research Farm near Nashua, Iowa.

Treatment	N management (y)	N rate (kg ha^{-1})	Other management (y)	Crop rotation (y)	Tillage (y)
SU168	Spring UAN (1999 to 2017)	168	—	Corn–soybean (1978 to 2017)	No-till (1978 to 1999); conservation tillage (2000 to 2017)
FM168NT2	Fall manure (1999 to 2017)	168	—	Corn–soybean (1978 to 2017)	Ridge tillage (1978 to 1992); conservation tillage (1993 to 2015); no-till (2016 to 2017)
FM168NT10+R	Spring UAN (1999 to 2015); fall manure (2016 to 2017)	168	Cover crop (2007 to 2017)	Corn–soybean (1978 to 2017)	Conventional tillage (1978 to 1992); conservation tillage (1993 to 2006); no-till (2007 to 2017)
FM168NT38	Spring manure (1999 to 2006); fall manure (2007 to 2017)	168	—	Continuous corn (1978 to 1992); corn–soybean (1993 to 2017)	No-till (1978 to 2017)
FM224CC	Fall manure (1999 to 2017)	224	—	Continuous corn (1978 to 1999); corn–soybean (2000 to 2006); continuous corn (2007 to 2017)	Conservation tillage (1978 to 2017)
FM224CC-S	Fall manure (1999 to 2017)	224	Stover removal (2007 to 2014); gypsum (2015)	Continuous corn (1978 to 1999); corn–soybean (2000 to 2006); continuous corn (2007 to 2017)	Conventional tillage (1978 to 1992); conservation tillage (1993 to 2017)

Notes: FM = fall manure. SU = spring urea ammonium nitrate (UAN). NT = no-till. CC = continuous corn. +R = cereal rye cover crop. -S = stover removal.

Journal of Soil and Water Conservation 77(1):78-87 www.swcs.org

(23% calcium [Ca], 17% sulfur [S]) in the fall of 2015.

The fall-applied manure (FM) treatments received liquid swine manure from a growing-finishing swine facility. Manure was injected after crop harvest with a liquid manure tanker equipped with low disturbance injectors to a depth of approximately 15 cm. The SU168 treatment received spring applications of urea ammonium nitrate (UAN) injected to a depth of approximately 15 cm behind a fluted coulter blade approximately three weeks after corn was planted. In the cover crop treatment, Elbon cereal rye was drill seeded at a rate of 90 kg ha^{-1} after fall harvest and was terminated with glyphosate prior to spring planting. Table 2 shows agronomic management details and dates for the 2017 crop year.

Soil Sampling. Samples for soil health analyses were obtained on June 1 and 2 of 2017 from all corn plots. Samples were obtained from the quarter-row position approximately 20 cm from the row of corn. Wheel track rows were avoided whenever possible. Three locations in each plot were sampled to a depth of 15 cm with a 7.62 cm diameter manual core sampler. These 0 to 15 cm depth cores were used to determine BD and water-stable aggregates (WSA). Cores were wrapped in cellophane and stored at 4°C prior to analyses. Samples for PMN, TC, and TN analyses were obtained with a 1.75 cm diameter push probe to a depth of 15 cm. Twenty cores were taken from each sampling location within the BD sample's immediate vicinity and placed in Ziploc storage bags. Ten cores were stored at –2°C prior to PMN analysis. The remaining 10 cores were air-dried and stored at room temperature prior to TC and TN analyses.

Deep profile soil samples were collected after fall harvest beginning in 2007. Soil cores were taken from three locations in each plot to a depth of 120 cm with a Giddings truck-mounted hydraulic soil probe using zero contamination tubes and a 4 cm diameter probe. The cores were split into five depths: 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm. Three cores from each plot and depth were combined to a single sample and analyzed for TC using dry combustion (Brown 1998).

Soil Health Sample Analyses. The 7.62 cm diameter cores were weighed and a 20 g subsample was oven-dried for 48 h at 105°C to determine moisture content and BD of the core. The remaining core was prepared for the WSA test using procedures similar to

Table 2
Agronomic management for the 2017 crop year at the Iowa State University Northeast Research Farm near Nashua, Iowa.

Activity	Treatments	Date
Fall manure application	FM168NT2, FM168NT10+R	Oct. 6, 2016
Fall manure application	FM224CC, FM224CC-S, FM168NT38	Nov. 2, 2016
Fall chisel plow	FM224CC, FM224CC-S	Nov. 10, 2016
Cereal rye seeded	FM168NT10+R	Nov. 10, 2016
Cereal rye terminated	FM168NT10+R	Apr. 17, 2017
Spring field cultivate	FM224CC, FM224CC-S, SU168	May 4, 2017
Corn planted	All	May 6, 2017
UAN injection	SU168	May 31, 2017

Notes: FM = fall manure. SU = spring urea ammonium nitrate (UAN). NT = no-till. CC = continuous corn. +R = cereal rye cover crop. -S = stover removal.

those described in Cambardella and Elliott (1992) and Ontl et al. (2015). Field-moist cores were passed through an 8 mm sieve by breaking the soil along natural fractures. Roots greater than 1 cm in length were removed. Samples were then air-dried with a box fan for 48 h, after which a 10 g subsample was oven-dried at 105°C for 48 h to determine air-dried moisture content.

To prepare for wet-sieving, moisture content at field capacity was calculated for each sample based on particle size, organic matter, and BD (Saxton and Rawls 2006). In a plastic petri dish, a 100 g sample of air-dried soil was capillary wetted to field capacity plus 5% by applying deionized water to filter paper under the sample (Six et al. 1998). The petri dish was taped shut and stored overnight at 4°C. The next day the moist aggregates were spread on top of a set of sieves with 2.00 mm top sieve, 1.00 mm middle sieve, and 0.212 mm bottom sieve. The sieves were submerged in water for 5 minutes and then wet-sieved for 10 minutes with a 4 cm stroke length at 30 strokes min^{-1} (Mikha and Rice 2004). Water level in the wet-sieving apparatus was maintained such that samples remained submerged at the top of the stroke and water did not overflow the outer edge of the sieve at the bottom of the stroke (Nimmo and Perkins 2002). Material retained on each sieve was then backwashed into preweighed tins and oven-dried at 60°C for 48 h. After drying, the tins were weighed again to obtain dry mass of each fraction.

To determine the sand percentage of each fraction, 10 g of each dried fraction was added to 30 mL of 5 g L^{-1} sodium hexametaphosphate solution in a 125 mL bottle. The bottles were placed in a reciprocal shaker for 15 h to dissolve the aggregates (Cambardella and Elliott 1992). The undissolved material was assumed to be the sand portion of each aggregate fraction. The sand retained on each sieve was backwashed into preweighed tins and oven-dried at 60°C for 48 h. The mass of sand was subtracted from the total fraction mass to obtain each aggregate fraction's total mass. Sand particles are not considered aggregates, so this procedure gives a more accurate estimate of actual WSA. Figure 1 shows a schematic of the procedure for determining WSA.

The 1.75 cm diameter cores for TC and TN analyses were ground and passed through a 0.250 mm sieve. Subsamples (10 g) were oven-dried at 105°C for 48 h to determine air-dried moisture content. Sieved soil was submitted to the Iowa State University Soil and Plant Analysis Laboratory for dry combustion TC and TN tests. For the PMN test, approximately 150 g of field-moist soil was prepared for aerobic incubation (Drinkwater et al. 1996). Subsamples (10 g) were oven-dried at 105°C for 48 h to determine initial soil moisture content. Soil was placed in Thermo Scientific Nalgene Büchner cups (Thermo Fisher Scientific, Waltham, Massachusetts) with a vented bottom and polypropylene funnel to allow for drainage. Whatman 0.45 µm, 76 mm diameter filter paper (Whatman, Maidstone, United Kingdom) was placed over the vent holes prior to adding the soil. Samples were leached with 150 mL of deionized water on day 3, 7, 14, 28, and 42. Leachate was collected in glass jars via a funnel placed on the bottom of the plastic cup. The leachate was weighed and analyzed for nitrates (NO_3-N) with an Oakton ION 700 benchtop meter (Vernon Hills, Illinois). Samples were covered loosely with cellophane to prevent drying out during storage and stored in an incubator at 30°C between leaching events.

Soil Health Assessment. Seven soil quality indicators were used as input to the SMAF program. Soil chemical properties included pH, phosphorus (P), and potassium (K). These data were obtained from fall of 2016 plot sampling. Physical properties included WSA and BD, and biological properties were represented with TC and PMN (28-day aerobic test). In SMAF, WSA reflects macroaggregate stability (labeled "AGG" in SMAF), or the percentage of total soil mass in WSA >0.212 mm. It should be noted that other studies using SMAF have reported macroaggregate stability as all particles >0.250 mm (Andrews et al. 2004; Karlen et al. 2013). A 0.212 mm sieve was substituted for the 0.250 mm sieve reported in Andrews et al. (2004) due to sieve availability. Total organic C was replaced with TC (organic plus inorganic) in SMAF. Inorganic C is assumed to be negligible for samples with pH < 7.3 (Karlen et al. 2011), which was all samples in this case. The program uses scoring curves to assign a relative value from 0 to 1 for each indicator and provides an overall SQI. A score of 1 represents a soil that is functioning at 100% of its inherent potential. A detailed explanation of SMAF assessment is given in Andrews et al. (2004).

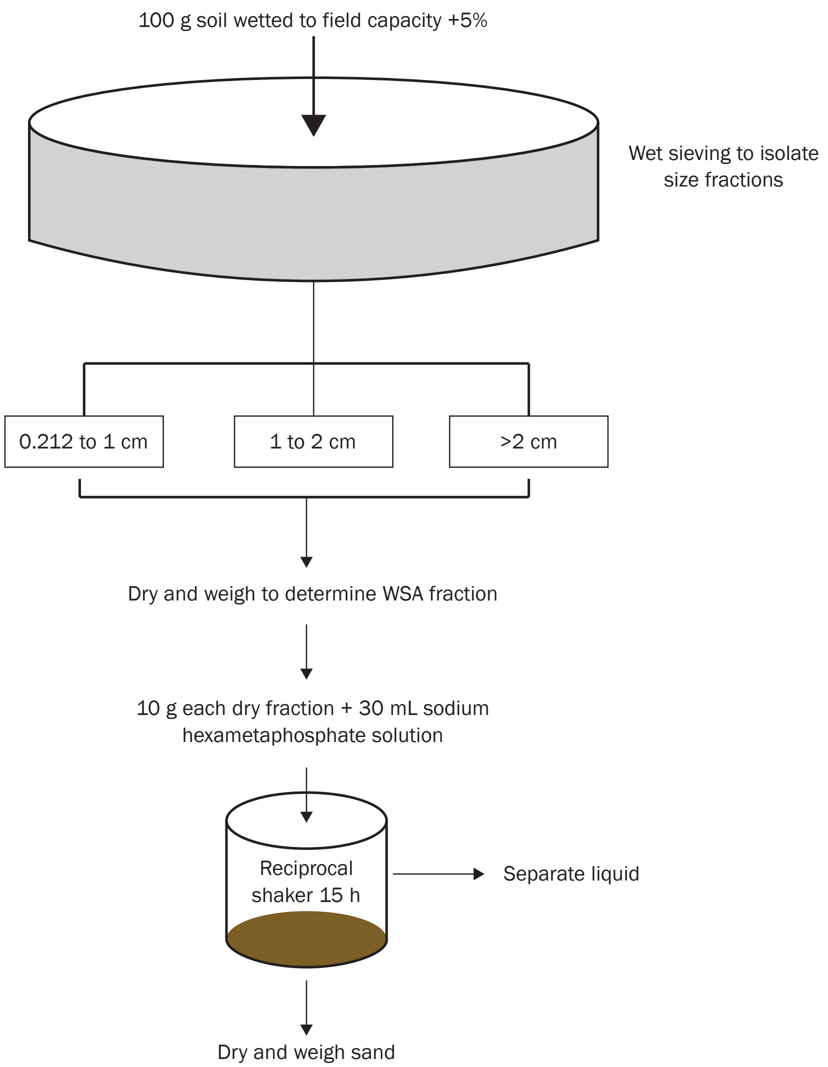
Statistical Analysis. Statistical analysis of soil health parameters was done with SAS software version 9.4 using PROC MIXED (SAS Institute 2015). Comparisons among treatments were tested at 5% significance level using the Kenward-Roger approximation. Treatment and block effects were modeled as fixed (Dixon 2016). Soil profile TC data were log-transformed and evaluated using PROC MIXED with significance set at $p \leq 0.05$ using repeated measures regression analysis with fixed block and treatment effects, a heterogeneous compound symmetry covariance structure, and Kenward-Roger approximation. We used the AIC goodness-of-fit test to select the best fitting model among a set of possible models.

Results and Discussion

Total Carbon and Total Nitrogen. Total C and TN from the 0 to 15 cm cores taken in the spring of 2017 are shown in table 3. The 15 cm sampling depth was used as this is the typical depth of tillage at the research location and is the depth where cropping management is most likely to affect soil properties. The FM224CC treatment had significantly more TC on a mass basis (g kg^{-1}) and stock basis (Mg C ha^{-1}) in the 0 to 15 cm layer than did FM224CC-S ($p = 0.031$). This possibly reflects the reduced residue input over

Figure 1

Schematic of the procedure for determining water-stable aggregation (WSA).



the eight-year period with stover removal. The FM168NT38 treatment had greater TC compared to FM168NT10+R (p = 0.034). Carbon stock in the FM168NT10+R treatment did not differ significantly relative to other NT treatments. The cover crop treatment had significantly lower corn and soybean yields from 2008 to 2015 (Dougherty et al. 2020). With lower yields, C inputs from corn and soybean residue may have been lower. Total N (g kg^{-1}) and N stocks were both significantly higher in FM168NT38 compared to all other CS rotation treatments. It should be noted that in addition to length of time in NT, the N management and crop rotation history also differed in the NT treatments. All of those factors could affect soil C and N levels.

Bulk Density. Table 3 also shows BD of the 0 to 15 cm cores taken in the spring of 2017. There was a trend toward higher BD in the NT treatments relative to treatments with tillage. The FM168NT2 and FM168NT10+R treatments had significantly higher BD than any of the tilled treatments. These results were not surprising given that tillage occurred one month before BD sampling in this study, and tillage generally reduces BD temporarily. The results agreed with research showing higher BD in NT compared to conventional tillage (Vyn and Raimbault 1993; Fabrizzi et al. 2005; Alvarez and Steinbach 2009). However, other research has found inconsistent results when comparing BD changes in NT compared to tilled soils. A review by Strudley et al. (2008) found that NT generally increases macropore connectivity and infiltration rates but has mixed effects on porosity and BD. No-till soils tend to have greater water holding capacity (Mahboubi et al. 1993) and more residue cover, potentially leading to wetter soils and greater compaction during field operations. It should be noted that the size of the core, sampling depth, soil moisture, and operator consistency can all affect BD sampling accuracy (Al-Shammary et al. 2018). We chose the core method for this research as it is the most commonly used method for BD estimation.

Water-Stable Aggregation. The percentage of total soil dry weight of each WSA fraction (after sand removal) is shown in figure 2. Sand accounted for between 30.5% and 31.8% of total dry soil weight and did not significantly differ between treatments. The total proportion of WSA > 0.212 mm was significantly greater in FM168NT38 compared to FM224CC-S (p = 0.049). There were no significant differences in total WSA > 0.212 mm between any of the other treatments. There were also no significant differences in WSA > 2 mm between any of the treatments. The FM168NT38 treatment had a significantly greater proportion of WSA in the 1 to 2 mm fraction relative to all other treatments except FM168NT2. In the continuous corn (CC) treatments, FM224CC and FM224CC-S did not differ, suggesting that eight years of stover removal and the single gypsum application in 2015 did not significantly affect WSA. Greater total aggregation was expected in the FM168NT10+R and FM168NT38 treatments given the cover crop and lack of tillage disturbance over a long period, but the geometric mean diameter of aggregates did not differ between any of the treatments (data not shown). Where significant differences did exist in the smaller fractions, they reflected minor shifts between aggregate size fractions within the 100 g samples of soil used for the WSA test. Possible effects on WSA due to interactions between N source, rate, and timing were not investigated, but may have impacted the results. There was a significant (p < 0.001) positive Pearson correlation coefficient (0.57) between TC and WSA > 0.212 mm (data not shown). This suggests two possibilities. One is that increasing soil C may lead to the formation of larger soil aggregates (Six et al. 2000). The other is that macroaggregates are able to hold and protect soil C from mineralization (Toosi et al. 2017).

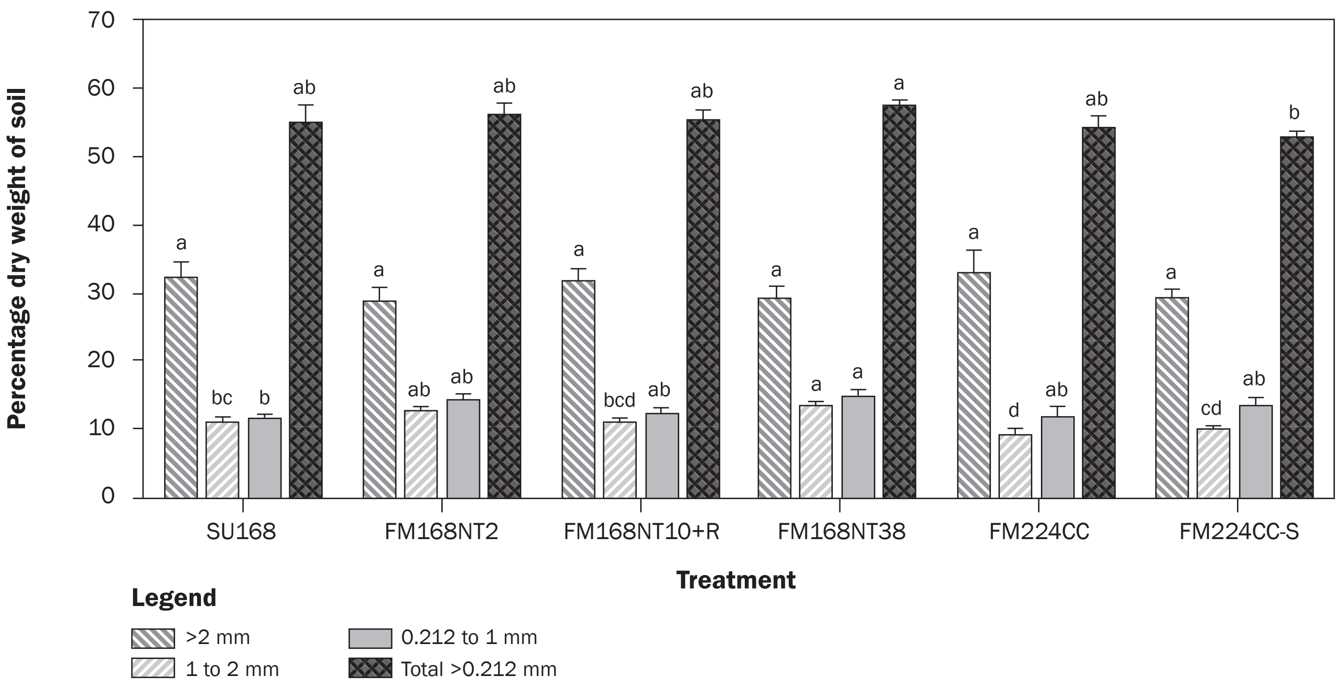
Detecting treatment effects on WSA proved difficult in this study. There was considerable plot-to-plot variation within a given treatment. The changing cropping

Table 3
Total carbon (TC), total nitrogen (TN), and bulk density (BD) from 0 to 15 cm depth cores sampled June 1 and 2, 2017.

Soil health indicator	SU168	FM168NT2	FM168NT10+R	FM168NT38	FM224CC	FM224CC-S
TC (g kg^{-1})	19.7bc	19.7bc	19.3c	21.7ab	23.0a	20.5bc
TC (Mg ha^{-1})	43.8b	45.8ab	45.6ab	49.5a	50.0a	43.0b
TN (g kg^{-1})	1.60bc	1.55c	1.58bc	1.87a	1.81ab	1.77abc
TN (kg ha^{-1})	70.7b	71.2b	72.5b	92.9a	93.4a	76.3ab
BD (g cm^3)	1.49bc	1.55a	1.58a	1.52ab	1.46cd	1.40d

Notes: FM = fall manure. SU = spring urea ammonium nitrate. NT = no-till. CC = continuous corn. +R = cereal rye cover crop. -S = stover removal. Means with the same letter within row are not significantly different at $p \leq 0.05$.

Figure 2
Water-stable aggregate fractions in each treatment at the Iowa State University Northeast Research and Demonstration Farm near Nashua, Iowa. Treatments with the same letter within size fraction are not significantly different at $p \leq 0.05$. FM = fall manure; SU = spring urea ammonium nitrate; NT = no-till; CC = continuous corn; +R = cereal rye cover crop; and -S = stover removal.



practices over time at the site make it difficult to draw conclusions regarding treatment effects on WSA. Management practices tend to have a greater effect on aggregation near the surface. Thus, this study's 15 cm sampling depth may have been too deep to capture surface aggregation dynamics. It is important to note that spring sampling was done approximately one month after tillage, which could affect soil aggregation and BD in plots with tillage. However, sampling after spring field operations represents the soil environment that cash crops are exposed to and has been done in similar research (Rorick and Kladivko 2017). The authors contend that growing-season measurements are suitable for soil health assessments for this reason.

Potentially Mineralizable Nitrogen. Cumulative NO_3-N mineralized over a 42 d PMN test is shown in table 4. Ammonium-N is generally a minor component of PMN and was not measured in this study. Total mineralization at day 42 ranged from 44.0 to 51.4 mg NO_3-N kg^{-1} soil. No significant differences in PMN were observed between treatments on any day.

Soil Management Assessment Framework Soil Quality Index Scores. Table 5 shows individual indicator scores and overall SQI scores for each treatment. SMAF scores for individual indicators suggest that the soils were functioning at or near full potential for PMN and WSA (0.99 to 1.00). Scores for soil pH (0.96 to 1.00) and P (0.93 to 1.00) were also near optimum levels. Corn–soybean rotation treatments were at suboptimum levels of K (0.78 to 0.80) relative to the CC treatments (1.00). There were significant differences in indicator scores for TC (0.59 to 0.74). The FM168NT38 treatment had a significantly higher TC score relative to FM168NT10+R (p = 0.010) and FM168NT2 (p = 0.031). The CC treatments did not have significantly different TC scores. Bulk density indicator scores (0.45 to 0.81) differed significantly, with FM224CC-S having the highest indicator score, reflecting the lowest BD. What was unexpected was that the

Table 4
Cumulative potentially mineralizable nitrogen (PMN) levels over time during aerobic incubation.

PMN level	mg NO_3-N kg^{-1} soil SU168	FM168NT2	FM168NT10+R	FM168NT38	FM224CC	FM224CC-S
PMN day 3	8.8a	9.8a	9.8a	9.3a	9.6a	10.5a
PMN day 7	16.3a	20.0a	19.8a	17.8a	20.3a	21.0a
PMN day 14	26.1a	30.2a	26.6a	23.9a	30.5a	29.1a
PMN day 28	35.6a	40.0a	37.0a	35.1a	37.7a	35.1a
PMN day 42	48.5a	51.4a	51.0a	47.4a	46.0a	44.0a

Notes: FM = fall manure. SU = spring urea ammonium nitrate. NT = no-till. CC = continuous corn. +R = cereal rye cover crop. -S = stover removal. Means with the same letter within day are not significantly different at $p \leq 0.05$.

Table 5
Individual indicator scores and overall Soil Quality Index (SQI) scores for each treatment from the Soil Management Assessment Framework analysis.

Treatment	Indicator scores* WSA	BD	TC	PMN	P	K	pH	SQI
SU168	0.99a	0.62bc	0.61b	1.00a	0.99a	0.79b	0.99a	0.85b
FM168NT2	1.00a	0.49d	0.61b	1.00a	1.00a	0.80b	1.00a	0.84bc
FM168NT10+R	0.99a	0.45d	0.59b	1.00a	0.99a	0.78b	0.99a	0.83c
FM168NT38	1.00a	0.55cd	0.71a	1.00a	1.00a	0.78b	0.99a	0.86b
FM224CC	0.99a	0.69b	0.74a	1.00a	1.00a	1.00a	0.96b	0.91a
FM224CC-S	1.00a	0.81a	0.65ab	0.99a	0.93b	1.00a	0.97b	0.91a

Notes: WSA = water-stable aggregates. BD = bulk density. TC = total carbon. PMN = potentially mineralizable nitrogen. P = phosphorus. K = potassium.

*A score of 1.00 indicates that the soil is functioning at 100% of its inherent potential for a given indicator. Indicator scores with the same letter within columns are not significantly different at $p \leq 0.05$.

FM224CC-S treatment would end up with a significantly higher indicator score for BD than all other treatments in the SMAF analysis. It is important to note that stover was last removed from this treatment in the fall of 2014, so there may be no correlation between BD and stover removal in this case. The NT plots all had significantly lower BD indicator scores than either of the tilled CC treatments. Overall SQI scores also differed. The CC treatments managed with conservation tillage had a significantly higher overall SQI than all other treatments, mostly due to the lower BD and higher TC observed in those plots. The lowest SQI score was observed in the FM168NT10+R treatment due to it also having the lowest BD and TC scores.

This study's SQI scores suggest a lower level of soil health in the FM168NT10+R cover crop treatment. This is primarily due to the weighting given to BD and TC in the SMAF program. On a stock basis, TC was not significantly different in the cover crop treatment compared to others. However, C is entered on a percentage basis in the SMAF program. It does not take into account C stocks, and therefore will assign a lower SQI score to a soil with higher BD and lower TC even if C stock is the same relative to another soil. Lower grain yields have been recorded in the cover crop treatment (Dougherty et al. 2020), thus C inputs from corn and soybean residue may have been lower. However, a considerable portion of SOC in agricultural land is derived from decomposed microbial necromass (Liang et al. 2019), and the cover crop would be expected to increase biological activity in the soil. The Mollisol soils at the research site are quite fertile with relatively high TC levels. Thus, improving soil health with cover crops in this type of soil may be a slow or difficult process. Further investigation is needed to determine why TC levels do not appear to be increasing with the cover crop treatment relative to the others.

The effect of stover removal was also of interest in this study. Karlen et al. (2011) found that stover harvest may have contributed to lower soil SQI scores over time but did not significantly affect total organic C levels. While it appears that stover removal may have factored into the significantly lower TC levels near the surface in FM224CC-S compared to FM224CC, it did not significantly affect the SQI scores for that treatment. Soil C levels can take decades to reach a new equilibrium in response to management changes (Sanderman and Baldock 2010). The lower TC in FM224CC-S relative to FM224CC could also be due in part to the effects from historical differences in plot management (table 1). The FM224CC-S treatment was moldboard plowed from 1978 to 1992, whereas FM224CC was managed with conservation tillage during that time.

Total Carbon in the Soil Profile. Results from repeated measures regression analysis of TC in the soil profile are shown in table 6. When comparing across treatments, the rate of change in TC over time was not significantly different between treatments at any depth. Given the confounding tillage, crop rotation, and N management history of these plots, we did not attempt to make any other comparisons across treatments. Rather, we focused on whether or not TC was changing within treatment over time for the 11-year period from 2007 to 2017. Table 6 shows initial TC from fall of 2007 deep core soil samples, and model estimates for change over time using repeated measures regression analysis. *P*-values reflect significance level for change over time within treatment at different depths. Model AIC values were –470, –278, –110, –19, and 357 for the 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm depths, respectively. There were no significant

Table 6
Soil profile initial total carbon (TC) (fall of 2007) and model estimate for change over time from repeated measures regression analysis of soil profile TC from 2007 to 2017. *P*-values reflect significance level for change over time within treatment at different depths.

Depth (cm)	Parameter	SU168	FM168NT2	FM168NT10+R	FM168NT38	FM224CC	FM224CC-S
0 to 15	Initial TC (g kg^{-1})	16.02	17.05	18.07	18.78	19.17	17.57
	Annual ± (g kg^{-1})	0.01	0.04	0.05	−0.01	0.10	−0.03
	p-value	0.903	0.552	0.513	0.952	0.397	0.788
15 to 30	Initial TC (g kg^{-1})	12.95	15.15	16.38	14.53	15.87	13.13
	Annual ± (g kg^{-1})	**0.14**	0.10	0.04	0.08	**0.25**	0.03
	p-value	0.038	0.107	0.529	0.193	0.003	0.739
30 to 60	Initial TC (g kg^{-1})	6.35	6.82	7.05	5.82	6.67	4.73
	Annual ± (g kg^{-1})	**0.17**	**0.15**	**0.14**	**0.13**	**0.16**	0.07
	p-value	<0.001	<0.001	<0.001	<0.001	0.002	0.054
60 to 90	Initial TC (g kg^{-1})	2.82	2.33	2.78	2.32	2.37	2.20
	Annual ± (g kg^{-1})	**0.11**	**0.10**	**0.14**	**0.13**	**0.11**	**0.09**
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
90 to 120	Initial TC (g kg^{-1})	1.65	1.92	2.18	1.82	2.07	1.87
	Annual ± (g kg^{-1})	**0.11**	**0.10**	**0.09**	**0.07**	**0.11**	0.08
	p-value	<0.001	<0.001	0.003	0.013	0.008	0.054

Notes: FM = fall manure. SU = spring urea ammonium nitrate. NT = no-till. CC = continuous corn. +R = cereal rye cover crop. -S = stover removal. Significant changes in TC over time within treatment at $p \leq 0.05$ are noted in bold.

changes in TC over time in any treatment in the top 15 cm of the profile. Two of the six treatments (SU168 and FM224CC) had a significant increase in TC over time at the 15 to 30 cm depth. Every treatment except FM224CC-S showed a significant increase in TC at the 30 to 60 cm depth. All treatments had a significant increase in TC from 60 to 90 cm, and all treatments except FM224CC-S had a significant increase at 90 to 120 cm.

The trend toward increasing TC below 30 cm in CC and CS cropping systems with different management practices is an important finding. The importance of deep sampling was illustrated in Tautges et al. (2019), where the authors concluded that ignoring C dynamics deep in the profile could lead to false conclusions about C sequestration under different management practices. However, much of the prior research looking at soil C levels has been focused near the surface. West and Post (2002) reviewed soil C studies from 67 long-term experiments, with only two reporting results below 30 cm in depth and none below 70 cm. In this study there was no apparent pattern of altered distribution of C in the soil profile with NT compared to tilled treatments as has been noted in other research (Luo et al. 2010). This could be due to TC being averaged over 15 cm increments near the surface and over 30 cm increments deeper in the profile, making it difficult to identify changes within each depth segment.

The rather complex and changing cropping history at the site and lack of long-term historical data makes it difficult to say with certainty where these systems are relative to historical C levels in the profile. As noted in Sanderman and Baldock (2010), it is difficult to predict C sequestration rates from stock change data when the state of the soil C system is not known. The varied cropping history at the research site also prevents assessment of specific management practices or cropping system effects on TC in the soil profile. Despite this and a lack of BD data for the deep core samples, a review of table 6 suggests substantial accumulation of C deep in the profile in all treatments. Assuming that TC is changing only where significant differences were found at $p \leq 0.05$ and using an average BD of 1.35 g cm^{-3} results in an average C accumulation of 1,300 kg C ha^{-1} y^{-1} in the soil profile to a depth of 120 cm. This method relies on estimating BD but suggests considerable accumulation of C in the profile. Literature reports of C sequestration rates for similar systems typically range from 100 up to 1,000 kg C ha^{-1} y^{-1} (Lal et al. 2007; Powlson et al. 2014; Paustian et al. 2016). The higher estimate obtained here is likely due to the greater soil depth assessed in this study relative to others.

Research by Sanford et al. (2012) showed a loss of SOC over 20 years to a depth of 90 cm in an Arlington, Wisconsin, cropping systems trial with similar management and climate relative to this study. The legacy effects from decades of prior soil management techniques create different baselines for comparison of soils (Sanderman and Baldock 2010). This could lead to differing results in systems with similar management in recent years. Differing drainage at the two sites could also be a factor. A complex set of factors could cause C to decrease or remain unchanged near the surface and accumulate deeper in the soil profile. A study of soil change in Iowa over 50 years by Veenstra and Burras (2015) found that SOC decreased in the top 30 cm and increased at the 50 to 150 cm depth, likely due to water movement, variations in pH, and microbial activity leading to dissolution of C at the surface and precipitation of C deeper in the profile. Carbon inputs from decomposed root systems and root exudation deep in the profile may also be playing a role. Corn and soybean roots are regularly found at depths >100 cm (Ordóñez et al. 2018), but studies rarely report soil C below 30 cm (Baker et al. 2007). Given the interest in compensating landowners for sequestering C, further research is needed to explore the complex set of factors leading to either C accumulation or loss in the soil profile.

Summary and Conclusions

Soils were sampled in June of 2017 to a depth of 15 cm and evaluated for TC, TN, WSA, BD, and PMN. Results indicated significant differences in TC, with a CC treatment having greater TC than a similar treatment with a history of stover removal. A long-term (38 y) NT treatment had significantly greater TN than the shorter term (<10 y) NT and tilled treatments in CS rotation ($p = 0.019$). Water-stable aggregation differed somewhat between treatments but there were few significant differences in the overall fraction of WSA > 0.212 mm. Bulk density levels were significantly higher in NT compared to treatments with tillage. Potentially mineralizable N levels did not differ significantly between treatments.

Evaluation with the SMAF revealed significant differences in SQI score between treatments, with a cover crop treatment managed with NT having the lowest SQI. Based on the SMAF analysis, the cereal rye cover crop did not improve SQI relative to similar treatments without a cover crop. This was due to a higher BD and lower TC on a percentage basis in plots with the cover crop. These results should not discourage cover crop use, as cover crops have multiple benefits, including improved water quality and helping with weed management and nutrient recycling. Higher BD is not uncommon in NT systems and does not necessarily reflect poor soil health. The SMAF program does not account for improved trafficability and water infiltration often observed with NT systems. Rather, the results illustrate the difficulty in identifying soil health differences with one-time sampling. Results also highlight and the importance of minimizing compaction and adjusting management to maximize yield and soil health in cover-cropped systems. Growing a cover crop successfully without impacting yield often requires changes in N application timing, planter settings, and herbicide programs relative to noncover-cropped systems. These changes were not made in this research trial to prevent additional confounding variables from affecting the results.

The study also evaluated TC levels incrementally to a depth of 120 cm over an 11-year period from 2007 through 2017. Results also showed significant increases in TC levels at various depths between 15 and 120 cm in several cropping systems typical to midwestern US agriculture. There was no significant difference between treatments in the rate of change in TC at a given depth. This research demonstrates the need to examine soils at depths greater than what has traditionally been reported in the literature when evaluating soil C levels and estimating C accumulation potential. This study's variable cropping history prevents attributing changes in TC to any specific management practice or cropping system. However, this research is valuable because it reflects practice changes that are common on commercial-scale farms. The consistent increase in TC deep in the soil profile suggests that C accumulation may be occurring across a range of standard midwestern cropping systems. The possibility that CS and CC systems may be experiencing significant increases in TC deep in the soil profile has important implications for C sequestration efforts and needs to be verified with research at other locations.

Acknowledgements

Funding for this research was provided in part by the Leopold Center for Sustainable Agriculture, the Iowa Nutrient Research Center, Iowa Pork Producers Association, and Calcium Products, Inc. This research was made possible by Ken Pecinovsky and other staff at the Northeast Research and Demonstration Farm in Nashua, Iowa.

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