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No-till and cropping system diversification improve soil health and crop yield

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ABSTRACT

The performance of no-till (NT) in temperate regions may be enhanced through the integration of additional conservation practices such as cover cropping and crop rotations. This study assessed the long-term impacts of continuous (20+ years) NT in comparison to plow-till (PT) management on soil properties and corn (*Zea mays* L.) yields in New York. The effects of tillage were assessed in combination with different cropping systems (24 years corn monoculture vs. 12 years corn monoculture; and with or without interseeded cover crops) on three soil textures: clay loam, loamy sand and silt loam. We measured four soil biological indicators - organic matter (OM), active carbon (ActC), respiration (Resp) and protein (Prot); four soil physical indicators - available water capacity (AWC), water stable aggregation (WSA), penetration resistance (PR) and water infiltration rate (InfRate); soil chemical indicators (plant available nutrients, pH and total N), and corn yield. Soil managed under long-term NT showed the most favorable soil biological, physical and chemical conditions for plant development, with higher levels of OM, Prot, Resp, WAS, total N, P and Zn, and InfRate. Benefits of introducing a grass-legume cover crop mixture into the cropping system were evident after 4 years for OM, Prot, Resp, AWC, Fe and Zn. Cover crop effects were greater under NT than PT, and additive to the NT benefits. On the clay loam soil, the effects of a 6-year interruption of continuous corn production with a perennial grass crop were still discernable with several soil health indicators 12 years after resuming corn production under NT. The better soil conditions under NT resulted in higher corn yields in both the loamy sand and silt loam soils, but not the clay loam. Our study shows that long-term NT can be viable in temperate regions, promoting significant improvement in soil health and crop yield and that these benefits are enhanced when NT is combined with crop rotation (perennial grass) and cover crops.

1. Introduction

Plow-till (PT) management under temperate conditions is normally practiced to accelerate soil warming and water evaporation in the spring, incorporate surface materials, and temporarily improve soil physical conditions for plant establishment and growth. However, soil changes by intensive tillage may actually do long-term harm by degrading soil for crop growth and increasing environmental degradation potential (Reicosky et al., 2011; Lal, 2015). The PT can decrease soil aggregate stability and soil macroporosity, increase soil compaction in the soil subsurface (Kinoshita et al., 2017), and promote soil surface crusting after tillage (Unger, 1992). Hence, PT might decrease the depth of root growth and soil water infiltration, and increase soil erosion (Baumhardt et al., 2015). In fact, soil erosion is one of the biggest challenges of PT systems, having on-farm and off-farm impacts: reduced soil depth, impairing the land productivity, and transporting sediments thereby degrading streams and lakes (Baumhardt et al., 2015).

Intensive tillage is also damaging to soil biological properties (Martínez et al., 2016a; Kumar et al., 2017; Alhameid et al., 2017). Past studies have shown that it accelerates biological decomposition of plant biomass due to higher availability of oxygen and by exposing older physically-protected soil organic carbon (OC); reduces organic matter

Abbreviations: NT, no-till; PT, plow-till; OM, organic matter; ActC, active carbon; Resp, respiration; Prot, protein; AWC, available water capacity; WSA, water stable aggregation; PR, penetration resistance; InfRate, water infiltration rate; N, nitrogen; OC, organic carbon; CC, cover crops; NC, no cover crops; TCM, time of corn monoculture; TN, total nitrogen; TC, total carbon

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(OM) content in the topsoil layer (Kumar et al., 2017), increases CO_2 emissions (Melland et al., 2017) and decreases both soil ability to retain nutrients and soil physical conditions (Martínez et al., 2016a; Alhameid et al., 2017).

In the 1930's reduced tillage began to be adopted in the United States of America (USA) as an option to reduce wind and water erosion, which was generating catastrophic erosion levels during the Dust Bowl (Kassam et al., 2015). In addition to reducing soil erosion, converting soil tillage management from PT to no-tillage (NT) may also improve soil health under temperate conditions and provide additional environmental and economic benefits (Soane et al., 2012; Kassam et al., 2015; Wittwer et al., 2017). We define soil health as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans" (Natrual Resources Conservation Services: Soil Health, 2012). When managed with other conservation practices like cropping system diversification through the inclusion of perennial crops and cover crops, NT may increase OM content, microbial biomass, and enzyme activity (Sharma et al., 2013; Kinoshita et al., 2017). These positive effects are promoted in part by an increase in biomass produced by cover crops. In addition, a decrease in OM mineralization may occur due to the effects of NT on soil processes and an absence of residue incorporation into the soil (Dabney et al., 2001; Lal, 2004; Alvarez and Steinbach, 2009). Conservation management practices can also stimulate formation and preservation of water stable aggregates (Bottinelli et al., 2017), which improves retention and movement of water in the soil system (Dairon et al., 2017). In the long-term, NT may also increase continuity and connectivity of soil pores, which impact diffusivity and permeability of air in the soil (Martínez et al., 2016a).

Currently, NT is practiced on > 150 million hectares worldwide (Kassam et al., 2015), with highest adoption levels in South America and Oceania. In this respect, the expanse under permanent NT relative to the total cropland area is approaching 100% in Argentina, Paraguay and southern Brazil, but still around 12% in the USA and 3% in Europe (year database 2013 - Kassam et al., 2015). The limited adoption of conservation agriculture systems in temperate conditions has been linked to lower soil temperatures and higher moisture content in the spring causing delayed drilling of spring-sown crops (Soane et al., 2012). Other factors that are limiting NT adoption in temperate regions include limited use of complementary conservation practices that enhance NT benefits, (Scopel et al., 2013) and the fact that available information on NT tends to be based on short-term and monocultural field experiments, which can produce results that are not typical for commercial production environments (Soane et al., 2012).

Increases in biological diversity by introducing cover and perennial rotation crops may enhance soil health and thereby increase the viability of NT systems. Polycultures lead to agroecosystems with greater multifunctionality (Finney and Kaye, 2017). The maximization of functional diversity promotes higher crop yield under NT with crop rotation compared to monoculture under temperate (DeFelice et al., 2006) and tropical climates (Pittelkow et al., 2015). In a global meta-analysis (5463 paired yield observations from 610 studies) comparing NT and PT with and without other conservation practices, (permanent soil cover by crop residues or cover crops, and crop rotation), Pittelkow et al. (2015) showed that NT under cropping system diversification can produce equivalent or greater yields than PT. Perennial and cover cropped rotations can exploit seasonal niches and thereby increase the perenniality of crop rotations (King and Blesh, 2018). Consequently, it may promote advances in functional ecology, making the NT system viable under temperate conditions.

The measurement of soil health over time through indicators that represent soil processes can be used to assess sustainable land management (Karlen et al., 1997). It expands on traditional soil testing, which has largely focused on the measurement of chemical soil properties (i.e., soil pH and nutrient contents) to evaluate soil fertility (Karlen et al., 2003; Moebius-Clune et al., 2016). The latter approach has proven useful for increasing agricultural production, but the narrow chemical focus has been a contributor to physical and biological soil degradation (Tilman et al., 2001; Andrews and Carroll, 2001; Karlen et al., 1997). This inadequacy spurred the development of more comprehensive assessment of soil health that evaluates multiple physical, biological, and chemical soil properties with an emphasis on those that are most sensitive to land management practices and correlated to ecosystem processes (Karlen et al., 2003).

The Comprehensive Assessment of Soil Health (CASH) approach was developed for the identification of specific soil constraints in agroecosystems as it relates to land productivity and potential environmental impacts. The CASH provides standardized, field-specific information on agronomically important constraints (Fine et al., 2017) and is an integral part of a broader soil health management planning framework. It offers measurement of physical indicators (wet aggregate stability, available water capacity, and penetration resistance), biological indicators (contents of organic matter, active carbon, extractable protein, soil respiration), and chemical properties (pH and available nutrients; Moebius-Clune et al., 2016).

There is a need to quantify long-term tillage and cover/rotation cropping effects on soil health in temperate regions (Soane et al., 2012). This kind of information may provide insight into the viability of these systems and perhaps help increase NT adoption and improve ecosystem services and global food security. We hypothesized that, under temperate conditions, (i) long-term continuous NT promotes better soil health than PT; (ii) the effects of NT are enhanced with the inclusion of cover or rotation crops; and (iii) these effects can enhance crop yields.

2. Materials and methods

2.1. Study sites

This study was carried out on three controlled field trials at the Cornell University Experimental Farms located in Willsboro and Aurora, New York, USA. In Willsboro, two long-term experiments were conducted, each on widely different soil types (Table 1): a Muskellunge clay loam [fine, mixed, active, frigid Aeric Epiaqualf (Gleyic Luvisol –

Table 1
Particle size distribution for the three soils studied.

Depth	Muskellunge clay loam			Stafford loamy fine sand			Honeoye-Lima silt loam		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
cm	------------------------%------------------------			------------------------%------------------------			------------------------%------------------------		
5	44.5	17.1	38.4	79.8	10.1	10.1	47.9	36.8	15.3
15	42.3	15.3	42.4	80.6	10.0	9.4	48.0	37.3	14.8
25	29.3	16.8	53.9	86.9	5.8	7.3	48.0	37.8	14.2
35	12.2	26.4	60.8	84.8	5.5	9.7	49.0	36.6	14.4
45	4.8	27.5	67.7	73.8	12.0	14.2	50.0	35.4	14.6
65	6.6	24.1	69.3	50.3	20.9	28.8	37.1	31.8	31.2
85	3.2	16.4	80.4	6.7	20.6	72.7	38.7	33.7	27.6

World Reference Base for Soil Resources, 2014); 44°22′37.92″ N, 73°22′43.68″ W] derived from glacio-lacustrine material; and a Stafford loamy fine sand [mixed, mesic Typic Psammaquent (Haplic Luvisol – World Reference Base for Soil Resources, 2014); 44°23′3.84″ N, 73°23′35.52″ W] formed in glacial outwash material. The clay loam soil has 400 g kg^{-1} clay material in the 0-to-30 cm depth and up to 800 g kg^{-1} in the subsoil. The loamy sand site has sand content > 800 g kg^{-1} in the top layer, but clay contents up to 700 g kg^{-1} in the bottom profile where the underlying glacio-lacustrine material resides.

At the Aurora site, one long-term experiment was located on a glacial till-derived Honeoye-Lima silt loam [fine-loamy, mixed, active, mesic Glossic Hapludalf and Oxyaquic Hapludalf (Calcic Luvisol – World Reference Base for Soil Resources, 2014); 42°44′00″ N, 76°39′38.2″ W].

In all trials, the PT plots were moldboard plowed (20 cm depth) annually in fall (Muskellunge soil) or spring (Stafford and Honeoye-Lima soils) and disked in the spring. Corn (CRM 85–90 days) was planted in the spring. The NT plots were untilled and planted with a NT planter. Fertilizer management of the fields consisted of banded application of 16.8 kg N ha^{-1}, 67.3 kg P ha^{-1}, and 67.3 kg K ha^{-1} at the time of planting. In addition, a side-dress application averaging 140 kg N ha^{-1} was added when the corn plants were approximately 40 cm tall. Two-pass herbicide was employed, utilizing 2,4-D and glyphosate at burndown and approximately one week prior to cover crop seeding (POST) to prevent potential herbicide impacts on cover crop establishment from soil-applied residual herbicides. Grain corn yields were determined for 3 growing seasons (2013 to 2015) by hand harvesting two 5-m corn rows at three locations in each plot.

2.1.1. Tillage and rotation experiment

On both trials at Willsboro, identical experiments were conducted in a crossed design with two tillage treatments (NT vs. PT) and two treatments involving different times of continuous corn monoculture (Table 2). One treatment involved 24 years of continuous corn, while another treatment involved 6 years of corn, 6 years of grass (primarily orchardgrass, *Dactylis glomerata*), and then 12 years of corn again, allowing for the evaluation of long-term rotational effects. Thus, the treatments were: NT with 12 years of corn monoculture (NT-12Corn), PT with 12 years of corn monoculture (PT-12Corn), NT with 24 years of corn monoculture (NT-24Corn) and PT with 24 years of corn monoculture (PT-24Corn). On the clay loam, plots were 18 m × 18 m in size, and on the loamy sand they were 14 m × 14 m. The crop production system on the NT-12Corn and PT-12Corn plots was corn after grass (from 1998 to 2004) and continuous corn (from 2004 to 2016). Silage yields were recorded from 2011 to 2016, six growing seasons.

2.1.2. Tillage and cover crop experiment

In Aurora, the experiment was established in 1992 with different tillage (NT vs. PT) and, beginning in 2013, the inclusion of cover crops in the subplot [cover crops (CC) vs. no cover crops (NC)]. Thus, the treatments were: NT with cover crops (NT-CC), PT with cover crops (PT-CC), NT without cover crops (NT-NC) and PT without cover crops (PT-NC). The plots were 6 m × 36 m in size. The crop production model in NT-NC and PT-NC were continuous corn annually from 1992 to 2016; and the crop production model on the NT-CC and PT-CC plots were continuous corn from 1992 to 2016, with the inclusion of a mix of cover crop from 2013 to 2016 (Table 2). The cover crops species used were: annual ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] seeded at 11.20 kg ha^{-1}, red clover (*Trifolium pratense* L.) seeded at 5.60 kg ha^{-1}, crimson clover (*Trifolium incarnatum* L.) seeded at 11.20 kg ha^{-1} and hairy vetch (*Vicia villosa* Roth) seeded at 8.40 kg ha^{-1}, which were established with a row interseeder (InterSeeder Technologies, Woodward, PA) immediately after N sidedress application.

2.2. Soil sampling and analysis

Soil samples were collected in May 2017 at approximately field capacity water content as a spade slab of 15 cm deep, 10 cm wide and 2.5 cm thick according to CASH guidelines (Moebius-Clune et al., 2016). Composite samples were derived by mixing six randomly collected inter-row subsamples of each plot in a bucket, and then placing a single subsample into a plastic bag, double bagged. Samples were kept in a cooler, transported to the laboratory and stored at 4 °C until analysis.

2.2.1. Physical properties

Wet aggregate stability (WAS) was determined using a rainfall simulator fitted with Teflon capillaries generating 0.6 mm water drops and an adjustable Mariotte-type tube to control hydraulic pressure (Ogden et al., 1997). Samples were air-dried to friable consistency, gently crumbled through an 8-mm sieve and oven-dried at 40 °C. Using stacked sieves of 2 and 0.25 mm soil samples were shaken for 10 s on a mechanical shaker. Aggregates of 0.25-to-2 mm size were returned to 40 °C to achieve consistent water potential. A single layer of aggregates was spread on a 0.25 mm mesh sieve, which was placed 0.5 m below the rainfall simulator to apply 2.5 J of energy over a 300-s period. WAS was determined as the fraction of soil remaining on the sieve, correcting for solid particles > 0.25 mm.

For Available Water Capacity (AWC) the difference between soil water content at field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) was assessed gravimetrically (g water g soil^{-1}). Saturated soil subsamples were equilibrated to pressures of −10 kPa (θ_{fc}) and −1500 kPa

Table 2
Treatment composition of each soil (locations) studied.

Soil/local	Treatment	Soil management	Cropping system/period			
			1992–1997	1998–2003	2004–2012	2013–2016
Muskellunge clay loam (Willsboro, NY, USA)	PT-24Corn	Plow-Till	Corn	Corn	Corn	Corn
	PT-12Corn	Plow-Till	Corn	Grass	Corn	Corn
	NT-24Corn	No-Till	Corn	Corn	Corn	Corn
	NT-12Corn	No-Till	Corn	Grass	Corn	Corn
Stafford loamy fine sand (Willsboro, NY, USA)	PT-24Corn	Plow-Till	Corn	Corn	Corn	Corn
	PT-12Corn	Plow-Till	Corn	Grass	Corn	Corn
	NT-24Corn	No-Till	Corn	Corn	Corn	Corn
	NT-12Corn	No-Till	Corn	Grass	Corn	Corn
Honeoye-Lima silt loam (Aurora, NY, USA)	PT-NC	Plow-Till	Corn	Corn	Corn	Corn
	PT-CC	Plow-Till	Corn	Corn	Corn	Corn + CC
	NT-NC	No-Till	Corn	Corn	Corn	Corn
	NT-CC	No-Till	Corn	Corn	Corn	Corn + CC

Corn + CC: Corn with cover crops mixture interseeded (annual ryegrass, red clover, crimson clover and hairy vetch).

Table 3
Analysis of variance for corn yield and soil physical, chemical, and biological properties for the Muskellunge clay loam.

Yield	DF	Yield							
Tillage	1	ns							
TCM	1	ns							
Tillage × TCM	1	ns							
Biological	DF	OM	ActC	Prot	Resp	Act/OM	Prot/OM	Resp/OM	
Tillage	1	*	ns	**	*	ns	*	ns	
TCM	1	*	ns	ns	*	ns	ns	ns	
Tillage × TCM	1	ns	ns	ns	ns	ns	ns	ns	
Physical	DF	AWC	WAS	PR15	PR45				
Tillage	1	ns	*	**	ns				
TCM	1	ns	ns	ns	ns				
Tillage × TCM	1	ns	ns	ns	ns				
Chemical	DF	TN	pH	P	K	Mg	Fe	Mn	Zn
Tillage	1	ns	***	*	ns	ns	ns	ns	*
TCM	1	ns	ns	*	ns	ns	ns	ns	ns
Tillage × TCM	1	ns	ns	ns	ns	ns	ns	ns	ns

TCM: Time with corn monoculture, OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR45: Penetration resistance into the 15-to-30 cm soil layer, InfRate: Infiltration rate, TC: Total carbon, TN: Total nitrogen.

* Significant at α = 0.05.

** Significant at α = 0.01.

*** Significant at α = 0.001.

(θ_{pwp}) on ceramic high-pressure plates in air pressure chambers (Soil Moisture Equipment Corp., Goleta, CA; Topp et al., 1993; Reynolds and Topp, 2008).

Penetration resistance (PR) measurements were collected in the field using a penetrometer (DICKEY-john Corp., Auburn, IL). Maximum PR was recorded for the depths of 0-to-15 cm (PR15) and 15-to-45 cm (PR45). The PR values were not adjusted for water content, but readings were taken near field capacity conditions (Duiker, 2002).

In July 2017, the water infiltration rate (InfRate) was measured in each plot at the Aurora Research Station only, on Honeoye-Lima silt loam using a rainfall-simulation technique based on Ogden et al. (1997). The portable rainfall simulator was placed onto a beveled edge infiltration ring (241-mm), which was inserted with minimal soil disturbance to a depth of 75 mm. A runoff tube was inserted down-slope at the lower edge of an overflow hole cut into the infiltration ring. The tube exited at the soil surface to guide runoff water out of the ring into an external vessel.

Runoff rates (*ro*) were determined by:

$$ro = \frac{V}{A*t}$$

where *A* was the area of the infiltrometer ring, and *t* was the time interval for collecting a determined volume of runoff water (*V*). Steady InfRate was determined by the difference between the rainfall rate and runoff rate when it reached steady-state conditions, whichever was longer (van Es and Schindelbeck, 2003).

2.2.2. Biological properties

Soil organic matter (OM) content was analyzed by mass loss on ignition in a muffle furnace at 500 °C for two hours. Active Carbon (ActC) was assessed as permanganate oxydizable carbon, measured in duplicate, by reacting a 2.5 g soil sample with 20 mL 0.02 M potassium permanganate ($KMnO_4$) solution (pH 7.2). Extracts were shaken (120 rpm, 2 min), then allowed to settle for exactly 8 min. An aliquot of solution was diluted 100 times before measurement for absorbance at 550 nm using a handheld spectrophotometer (Hach, Loveland, CO). Sample absorbance was calibrated with $KMnO_4$ standard curves and converted to mg ActC per kg soil using the equation of Weil et al. (2003). The ratio of ActC to soil OM (ActC/OM) was calculated which estimates OM quality.

Soil heterotrophic respiration (Resp) was measured in duplicate after four-day incubation using a method modified from Haney and Haney (2010). Soil sieved past 8 mm was weighed (20 g) in a perforated aluminum weighing boat and put inside a glass jar sitting atop two staggered Whatman qualitative filter papers. A preassembled CO_2 trap (10 mL glass beaker adhered to a plastic stand) was placed onto the weighing boat and the beaker was filled with 9 mL 0.5 M KOH. Distilled water (7.5 mL) was pipetted alongside the jar to facilitate rewetting of the sample via capillary rise. The amount of CO_2 respired and absorbed by the KOH trap over the course of incubation was determined by measuring the change in electrical conductivity of the solution with an OrionTM DuraProbeTM 4-Electrode Conductivity Cell (ThermoFisher Scientific, Inc., Waltham, MA). The necessary background correction for atmospheric CO_2 was quantified using blank (no soil) incubations.

Autoclaved-Citrate Extractable Protein (Prot) content was measured by first extracting the soil with 0.02 M sodium citrate at pH 7. The extract was then quantified by bicinchoninic acid assay against a bovine serum albumin standard curve for soil protein concentration after a sequence of centrifugation and autoclaving steps (Wright and Upadhyaya, 1996). The ratio of soil protein to soil OM (Protein/OM) was calculated, which is an indicator of soil OM quality.

2.2.3. Chemical properties

Soil pH was measured in a 1:1 soil:water slurry. Plant available soil nutrient concentrations (P, K, Mg, Fe, Mn and Zn) were measured after extracting using Modified Morgan (ammonium acetate solution plus acetic acid, pH 4.8) using inductively coupled plasma optical emission spectrometry (SPECTRO Analytical Instruments Inc., Mahwah, NJ). All nutrient contents were calculated per mass of soil (mg kg^{-1}).

2.3. Data analysis

Data were analyzed for significant effects of factors for each one of the three controlled trials based on a split plot design. For the Willsboro trials, tillage (NT and PT; factor 1), time with corn monoculture (24 years and 12 years; factor 2) and tillage by time with corn monoculture interaction were assumed fixed effects, and block, replicate and their interactions were random effects. For the Aurora trial, tillage (NT and PT; factor 1), cover crops (NC and CC; factor 2), and tillage vs. cover crops interaction were the fixed effects, and block, replicate and their interactions were random effects. Relevant means were compared for each indicator using Tukey's test. All test results were deemed

Table 4
Means for soil biological, physical and chemical properties by tillage and cover crop treatment for the Muskellunge clay loam.

Biological		OM		ActC		Prot		Resp		ActC/OM		Prot/OM		Resp/OM			
		------------------------mg g^{-1} ------------------------						mg CO_2 g^{-1}		------------------------ mg g^{-1}/mg g^{-1}------------------------				mg CO_2 g^{-1}/mg g^{-1}			
	24Corn Mean	30.8	B	0.590	A	5.18	A	0.472	B	0.019	A	0.168	A	0.015	A		
	12Corn Mean	37.0	A	0.664	A	5.37	A	0.565	A	0.018	A	0.145	A	0.015	A		
Plow till (PT)																	
	24Corn	31.5	b	0.626	a	4.04	b	0.438	b	0.020	a	0.128	a	0.013	a		
	12Corn	31.0	b	0.577	a	3.93	b	0.435	b	0.019	a	0.127	a	0.015	a		
	PT Mean	31.2	B	0.602	A	3.99	B	0.436	B	0.019	A	0.128	B	0.014	A		
No-till (NT)																	
	24Corn	33.0	ab	0.607	a	6.11	a	0.545	ab	0.018	a	0.185	a	0.018	a		
	12Corn	40.1	a	0.698	a	7.02	a	0.658	a	0.017	a	0.175	a	0.015	a		
	NT Mean	36.5	A	0.653	A	6.57	A	0.601	A	0.018	A	0.180	A	0.016	A		
Physical		AWC mm^3 mm^{-3}		WAS %		PR15 ------------------------------MPa-		PR45 -------------------------------									
	24Corn Mean	0.219	A	16.53	A	0.81	A	2.53	A								
	12Corn Mean	0.228	A	21.20	A	0.88	A	2.32	A								
Plow till (PT)																	
	24Corn	0.240	a	14.02	b	0.41	a	2.28	a								
	12Corn	0.233	a	13.34	b	0.37	a	2.40	a								
	PT Mean	0.236	A	13.68	B	0.39	B	2.31	A								
No-till (NT)																	
	24Corn	0,240	a	17.62	ab	1.49	b	2.26	a								
	12Corn	0.190	a	30.49	a	1.12	b	2.33	a								
	NT Mean	0.210	A	24.06	A	1.30	A	2.54	A								
Chemical		TN %		pH		P ------------------------		K ------------------------		Mg -------------------mg kg^{-1}-		Fe ------------------------		Mn ------------------------		Zn ------------	
	24Corn Mean	0.183	A	6.74	A	3.85	A	114.95	A	298.66	A	2.38	A	7.06	A	0.266	A
	12Corn Mean	0.210	A	7.02	A	2.57	B	123.84	A	334.51	A	1.81	A	7.23	A	0.270	A
Plow till (PT)																	
	24Corn	0.193	a	7.18	a	1.95	b	137.15	A	416.35	a	2.01	a	7.85	a	0.200	b
	12Corn	0.180	a	7.06	a	2.38	ab	116.48	A	330.07	ab	2.54	a	8.17	a	0.203	b
	PT Mean	0.186	A	7.11	A	2.17	B	126.81	A	373.21	A	2.27	A	8.01	A	0.201	B
No-till (NT)																	
	24Corn	0.176	a	6.72	a	4.62	a	108.64	a	213.75	b	2.14	a	5.99	b	0.320	ab
	12Corn	0.235	a	6.58	a	3.86	ab	115.32	a	306.18	ab	1.70	a	6.57	ab	0350	a
	NT Mean	0.206	A	6.65	B	4.24	A	111.98	A	260.00	A	1.92	A	6.28	A	0.335	A

24Corn: 24 years continuous corn, 12Corn: 12 years continuous corn after 6 years grass, OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR2: Penetration resistance into the 15-to-30 cm soil layer, TN: Total nitrogen. Means of each property followed by the same lowercase letter within a column are not significantly different at $\alpha = 0.05$ based on Tukey's test. Capital letters show significance of overall tillage and Cover Crop management treatment comparisons.

Table 5
Pearson correlation coefficients for SH indicators and total yield for the Muskellunge clay loam. NS is not statistically significant at α = 0.05.

	OM	ActC	Prot	Resp	AWC	WAS	PR15	TN	pH	P	K	Mg	Fe	Mn	Zn
ActC	0.850														
Prot	0.646	0.558													
Resp	0.762	0.727	0.714												
AWC	NS	0.491	NS	NS											
WAS	0.805	0.749	0.800	0.871	NS										
PR	NS	NS	NS	NS	−0.608	NS									
TN	0.778	0.883	0.550	0.762	0.546	0.854	NS								
pH	NS	NS	−0.593	NS	NS	NS	NS	NS							
P	NS	NS	0.562	NS	NS	NS	NS	NS	NS						
K	NS	0.630	NS	NS	0.689	NS	NS	0.547	0.666	NS					
Mg	NS	NS	NS	NS	0.862	NS	NS	NS	0.567	NS	0.749				
Fe	−0.548	−0.898	NS	−0.632	NS	NS	NS	−0.645	NS	NS	−0.604	NS			
Mn	NS	NS	0.589	NS	0.678	NS	NS	NS	NS	−0.544	NS	NS	NS		
Zn	0.605	0.474	0.881	0.557	NS	0.664	NS	NS	−0.609	0.525	NS	NS	NS	NS	
Yield	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, TN: Total nitrogen.

significant at α = 0.05. Pearson correlations analyses for soil and yield were performed for each trial. All statistical analyses were performed using R software version 3.1.1 (R Core Team, 2014).

3. Results

3.1. Tillage and rotation effects on clay loam

The interaction of tillage and time-of-corn-monoculture (TCM) were not significant for any of the soil health indicators on the Muskellunge clay loam (Table 3). As a single factor, tillage treatment significantly affected 8 of the 16 measured soil properties: biological: OM, Prot, Resp; physical: WAS and PR15; chemical: pH, P, and Zn. The TCM treatment, as a single factor, significantly affected 3 soil properties: OM, Resp and P. These significant factors showed that soils maintained under long-term NT have 17% more OM, 65% more Prot, 95% more P and 66% more Zn than soil managed long-term under PT (Table 4). The NT implementation also increased WAS by 76% and Resp by 17% (Table 4). Moreover, the soil under 24 years of corn monoculture showed significantly lower OM (17%) and Resp (17%) compared to the 12 years of corn monoculture after grass (Table 4). The content of Prot in the OM was significantly higher in the soil under long-term continuous NT than in the soil under long-term continuous PT (Tables 3 and 4).

An overall comparison of the means of each treatment (PT-24Corn, PT-12Corn, NT-24Corn and NT-12Corn) shows that soil under PT-24Corn, PT-12Corn and NT-24Corn are statistically similar, regarding OM, Zn, WAS and Resp. However, given the same soil properties, the NT-12Corn showed more favorable soil conditions than PT-24Corn and PT-12Corn (Table 4).

Pearson correlation coefficients (Table 5) showed that out of 120 pairs, 42 were significantly correlated to each other. Notable high positive correlations (≥0.8) were found for OM with ActC (r = 0.850), OM with WAS (r = 0.805), Prot with WAS (r = 0.800) and Resp with WAS (r = 0.871), ActC and TN (r = 0.883), and Prot with Zn (r = 0.881), TN with WAS (r = 0.854); and Mg with AWC (r = 0.862). High negative correlations were observed for ActC with Fe (r = −0.898).

Corn silage yields for NT for 6 years (2011-to-2016) in the Muskellunge clay loam were significantly higher than those for PT in 2014 and lower in 2015 and 2016. The effects of tillage, time of corn monoculture, and tillage vs. time of corn monoculture interaction were not significant for 6 years cumulative corn silage yield (Table 3). The means comparison, considering each tillage and time of corn monoculture as one treatment, also showed that there was no difference among treatments under the same soil type and weather conditions (Fig. 1B.)

3.2. Tillage and rotation effects on loamy fine sand

The interaction of tillage and (TCM) were not significant for any of the soil health indicators in the Stafford loamy fine sand (Table 6). Tillage treatment, as a single factor, significantly affected 9 of the 16 measured soil health properties: biological: OM, ActC, Prot, Resp; physical: WAS, PR, and chemical: TN, K, and Zn. The TCM treatment was not significant for any indicator (Table 6). Analyzing the simple effects to the significant factors described above, tillage means showed that the soil under long-term NT has approximately 67% more OM, 51% more ActC, 49% more Prot, 69% more TN, 45% more K and 92% more Zn than soil under the long-term PT treatment (Table 7). No-till adoption also increased the WAS by 92% and soil Resp by 82% (Table 7). The overall means comparison of tillage and TCM showed that the OM content and TN in the soil under PT-24Corn was not statistically different from PT-12Corn and NT-24Corn (Table 7). However, PT24Corn had significantly lower OM content and TN than the NT-12Corn treatment.

Pearson correlation coefficients (Table 8) computed for pairs of soil properties and corn yield in the Stafford loamy fine sand showed that out of 120 pairs, 42 were significantly correlated to each other. Notable high positive correlations (≥0.8) were found between biological properties for OM with ActC (r = 0.926), OM with Prot (r = 0.810), ActC with Prot (r = 0.870), and Prot with Resp (r = 0.800). For biological and physical properties Prot was highly correlated with WAS (r = 0.810), while high correlations with chemical properties included OM with TN (r = 0.873), ActC and TN (r = 0.912), Prot with TN (r = 0.901), and Resp with TN (r = 0.811). High correlations were also observed for K with Mg (r = 0.814). Total yield showed significant correlation with four soil biological/chemical attributes: OM (r = 0.501), ActC (r = 0.511), Prot (r = 0.532), TN (r = 0.642).

For the 6 years (2011-to-2016) in the Stafford loamy fine sand significantly lower corn yield was obtained for NT compared to PT in 2013, and higher corn yields were obtained in 2015 and 2016 (Fig. 1C). The interacting factors of tillage vs. TCM were not significant for the 6 years total yield (Table 6). However, the total yield mean was significantly higher (3.2%) in NT compared to PT (Table 6; Fig. 1D). The overall main effects from tillage and TCM showed no difference between treatments for corn silage yield under the same soil type and weather conditions (Fig. 1D).

3.3. Tillage and cover crop experiment on silt loam

Tillage significantly affected 10 of the 17 measured soil properties. Biological: OM, ActC, Prot, Resp; physical: WAS, InfRate; and chemical: TN, P, K and Fe (Table 9). Tillage means showed that the soil under

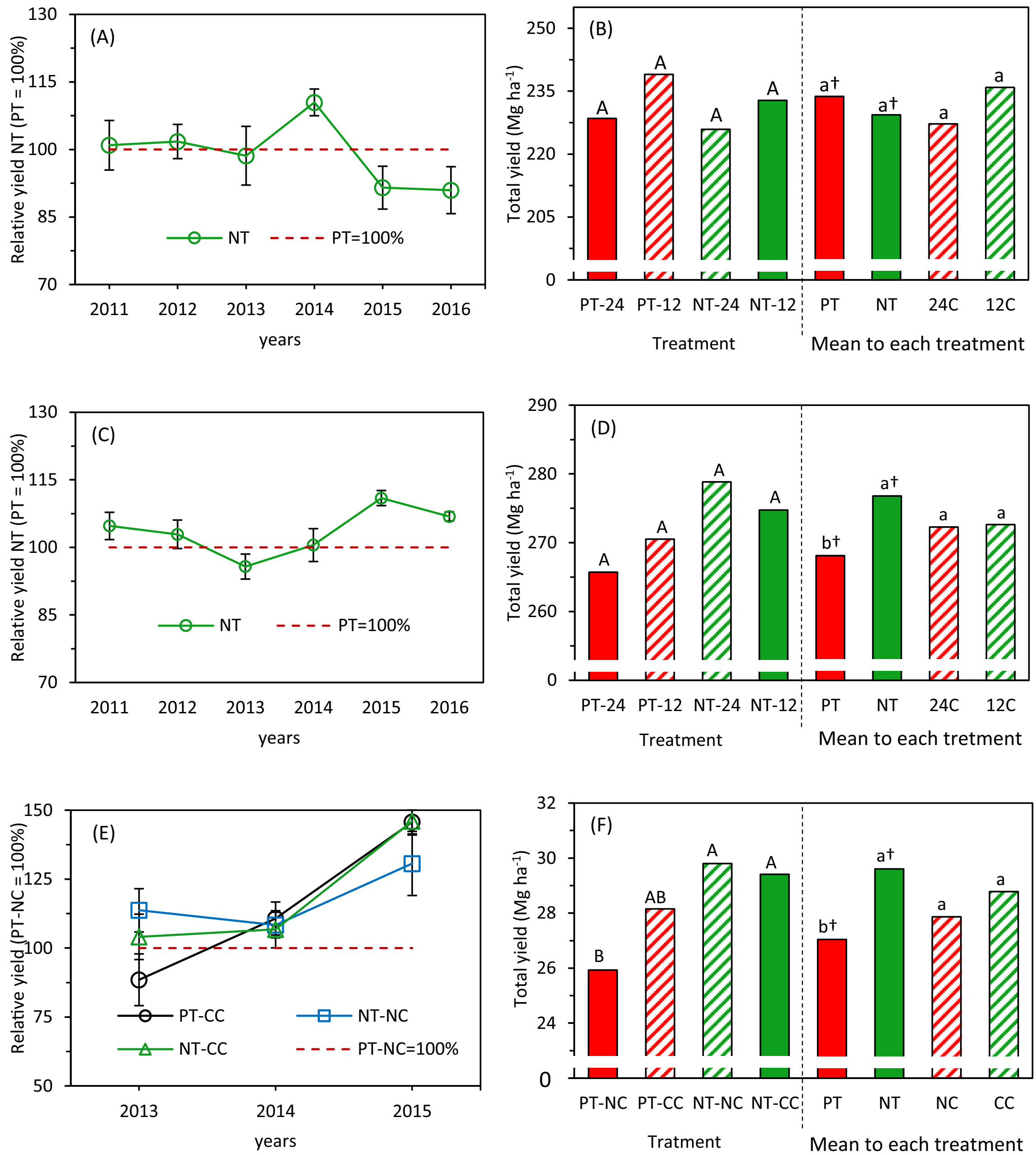

Fig. 1. Relative silage corn yield for no till (NT), where yield in plow till is set at 100% (PT = 100%), and 6 years total silage corn yield by tillage and time of corn monoculture factors for the Muskellunge clay loam (A, B) and the Stafford loamy fine sand (C, D); relative grain corn yield for plow till with cover crop (PT-CC), no till without cover crop (NT-NC) and no till with cover crop (NT-CC), where yield in plow till without cover crop is set at 100% (PT-NC = 100%) and 3 years total grain corn yield by tillage and cover crops factors in a Honeoye-Lima silt loam (E, F). 24C is 24 years with corn monoculture and 12C is 12 years with corn monoculture. Vertical bars indicate standard deviation. The means of each property followed by the same capital letter are not significantly different at the α = 0.05 level based on a Tukey's test. Lowercase letters show significance of tillage (letters with†) and time of corn monoculture or cover crop factors.

long-term NT has approximately 15% more OM, 29% more ActC, 26% more protein, 17% more TN, 112% more P and 12% more K than soil managed under long-term PT (Table 10). The NT implementation also increased the WAS by 155%, InfRate by 67% and Resp by 33% (Table 10). Moreover, the ratios between ActC and OM and Resp and OM were significantly higher in the soil under long-term NT than in the soil under continuous PT (Tables 9 and 10).

The impact of 4 years cover cropping, as a main effect, significantly affected 6 of the 17 measured soil properties. Biological: OM, Prot, Resp; physical: AWC; and chemical: Fe and Zn (Table 9). Soil with CC had 5% more OM, 8% more Prot, 30% more Resp, 3% more AWC, 14% more Fe and 74% more Zn than soil under NC (Table 10). Moreover, the ratio of Resp and OM was significantly higher in the soil with CC than in the soil with NC (Tables 9 and 10).

The tillage by cover crop interaction was significant for 2 measured soil health properties: Resp and AWC (Table 9). Nevertheless, soil Resp was higher in NT than in PT in both cropping systems (CC and NC) and was higher in soil under CC than in the soil under NC in both NT and PT (Table 10). Mean AWC was not different between NT and PT within CC and NC treatments; however, AWC was higher in soil under NT with CC than in NT under NC (Table 10).

The means for individual tillage and cover crop factorial combinations showed an increasing trend of improved soil health with PT-NC < PT-CC < NT-NC < NT-CC for the following soil properties:

Table 6
Analysis of variance of corn yield and soil physical, chemical, and biological properties for the Stafford loamy fine sand.

Yield	DF	Yield							
Tillage	1	*							
TCM	1	ns							
Tillage × TCM	1	ns							
Biological	DF	OM	ActC	Prot	Resp	Act/OM	Prot/OM	Resp/OM	
Tillage	1	**	***	***	**	ns	ns	ns	
TCM	1	ns	ns	ns	ns	ns	ns	ns	
Tillage × TCM	1	ns	ns	ns	ns	ns	ns	ns	
Physical	DF	AWC	WAS	PR15	PR45				
Tillage	1	ns	*	**	ns				
TCM	1	ns	ns	ns	ns				
Tillage × TCM	1	ns	ns	ns	ns				
Chemical	DF	TN	pH	P	K	Mg	Fe	Mn	Zn
Tillage	1	**	ns	ns	*	ns	ns	ns	*
TCM	1	ns	ns	ns	ns	ns	ns	ns	ns
Tillage × TCM	1	ns	ns	ns	ns	ns	ns	ns	ns

TCM: Time with corn monoculture, OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR45: Penetration resistance into the 15-to-30 cm soil layer, InfRate: Infiltration rate, TC: Total carbon, TN: Total nitrogen.

* Significant at α = 0.05.

** Significant at α = 0.01.

*** Significant at α = 0.001.

OM, Resp, AWC and InfRate (Table 10). Although the difference was not statistically different, this trend also was observed for ActC and Prot. In terms of OM quality, the highest ratio between ActC and OM was found for NT-CC followed by NT-NC and PT treatments; and the highest ratio between Resp and OM was found to NT-CC followed by NT-NC, PT-CC and PT-NC (Table 10).

Pearson correlation coefficients matrix (Table 11), computed for every pair of soil properties and corn yield in the Honeoye-Lima silt loam showed that, out of 135 pairs, 59 were significantly correlated to each other. Notable high positive correlations (≥0.8) were between biological properties for OM with ActC ($r = 0.886$), ActC with Prot ($r = 0.899$), and Prot with Resp ($r = 0.808$). For biological and physical properties high correlations were found for Prot with WAS ($r = 0.818$), and for biological and chemical properties OM with TN ($r = 0.814$). Total yield showed very high positive correlations with WAS ($r = 0.925$), TN ($r = 0.917$) and K (0.933), as well as with OM ($r = 0.794$), ActC ($r = 0.796$), Prot ($r = 0.806$), and negative correlations with pH ($r = -0.901$), Fe ($r = -0.734$) and Mn ($r = -0.830$).

In the first year of cover cropping (2013) PT-CC showed significantly lower yields than NT-CC, NT-NC and PT-NC, while higher yields were observed for NT-CC, NT-NC and PT-CC compared to the conventional PT-NC in 2014 and 2015 (Fig. 1E). Total 3-year yields for NT-NC and NT-CC were highest and increased continually from 2013 to 2015 after cover crop introduction. Cover crop and tillage by cover crop interaction were not significantly different; however, the total yield was significantly higher, by 9.5%, for NT than PT (Table 9; Fig. 1F). The means comparison for each factorial treatment effect showed that the corn yields under PT-CC, NT-NC and NT-CC were, 8.6%, 14.9% and 13.4% higher, respectively, than those under PT-NC (Fig. 1F).

4. Discussion

4.1. Long-term tillage effects

The three experiments in this study all involved > 20 years of continuous NT and PT and allowed us to assess long-term effects on soil health and crop yield. The results show that continuous NT improved soil health with benefits to biological, physical and chemical properties, but changes were most marked for biological indicators (Tables 4, 7 and 10). Major soil health benefits promoted by NT implementation can be linked to the maintenance of crop residues on the soil surface and to the lack of frequent soil disturbance by plowing and weeding (Soane et al., 2012). This system resulted in dramatic increases in OM content, independent of soil texture (Tables 4, 7 and 10), in line with Dolan et al. (2006) and Alhameid et al. (2017) in the Upper Midwest USA. Thus, the increase in the OM content, under both tropical (Miranda et al., 2016) and temperate conditions (Moebius-Clune et al., 2008; Martínez et al., 2016b; Kinoshita et al., 2017) is a widely observed benefit from long-term NT systems.

Long-term NT also increased OM quality indicators (ActC, Prot, Resp) and tended to increase the ratio relative to OM content for the fine and medium-textured sites (ActC/OM, Prot/OM, and Resp/OM; Tables 3, 4, 6, 7, 9 and 10). The ActC (OC not complexed with minerals and that rapidly responds to the changes in agriculture practices) is a readily available food and energy source for the soil microbial life (Weil et al., 2003). The improvement in ActC from NT adoption apparently also promotes an increase in soil biological activity (Resp) compared to PT, independent of soil texture (Tables 4, 7 and 10). Past studies conducted under temperate conditions also showed better soil biological conditions under NT (Moebius-Clune et al., 2008; Kinoshita et al., 2017) and enzymatic activities (urease, acid phosphatase, glucosidase and alkaline phosphatase activities; Sharma et al., 2013). With this, it is noted that the Resp measurement from the NT soils involves the collection of a disturbed soil sample and the Resp measurement, therefore, represents a condition where an undisturbed soil becomes mechanically agitated.

Enhanced soil biology promotes both formation and preservation of soil aggregates (Weil et al., 2003; Bottinelli et al., 2017), evidenced by higher WAS in NT than PT (Tables 4, 7 and 10). This may be linked to the presence of plant residue on the soil surface and increases in OM level and microorganism activity (Jacobs et al., 2009; Kinoshita et al., 2017; Celik et al., 2017; Alhameid et al., 2017), as well as the absence of mechanical disturbance (Kumar et al., 2012; Zuber et al., 2015) of soil under NT. In turn, soil structure can have a positive effect on soil biological properties (Kumar et al., 2017), and on retention and movement of soil nutrients. In the same way, soil biology can affect cycling and retention of nutrients (Gupta and Germida, 2015), being directly correlated with the soil nutrient concentration (Tables 5, 8 and 11). Improvement in soil physical and biological properties, under NT, resulted in a higher concentration of P (clay loam and silt loam), Zn (clay loam and loamy fine sand), TN and K (silt loam and loamy fine sand; Tables 4, 7 and 10). Increases in K may be related to residue retention on the soil surface (although minimal for the clay loam and loamy sand sites where corn was harvested for silage in the most recent

Table 7
Means for soil biological, physical and chemical properties by tillage and crop management treatment for the Stafford loamy fine sand.

Biological		OM		ActC		Prot		Resp		ActC/OM		Prot/OM		Resp/OM			
		----------mg g^{-1}----------						mg CO_2 g^{-1}		----------mg g^{-1}/mg g^{-1}----------				mg CO_2 g^{-1}/mg g^{-1}			
	24Corn Mean	15.9	A	0.308	A	4.61	A	0.337	A	0.020	A	0.286	A	0.021	A		
	12Corn Mean	17.7	A	0.347	A	4.69	A	0.334	A	0.021	A	0.288	A	0.021	A		
Plow till (PT)																	
	24Corn	13.3	bc	0.263	b	3.77	b	0.256	b	0.020	a	0.290	a	0.023	a		
	12Corn	11.8	c	0.260	b	3.71	b	0.219	b	0.023	a	0.318	a	0.018	a		
	PT Mean	12.6	B	0.261	B	3.74	B	0.238	B	0.021	A	0.304	A	0.020	A		
No-till (NT)																	
	24Corn	19.9	ab	0.396	a	5.57	a	0.412	a	0.020	a	0.282	a	0.020	a		
	12Corn	22.4	a	0.391	ab	5.54	a	0.456	a	0.020	a	0.258	a	0.025	a		
	NT Mean	21.1	A	0.393	A	5.56	A	0.434	A	0.020	A	0.270	A	0.023	A		
Physical		AWC		WAS		PR15		PR45									
		mm^3 mm^{-3}		%		----------MPa----------											
	24Corn Mean	0.136	A	25.38	A	1.67	A	3.12	A								
	12Corn Mean	0.136	A	27.46	A	1.51	A	3.09	A								
Plow till (PT)																	
	24Corn	0.136	a	17.05	b	1.40	a	3.00	a								
	12Corn	0.134	a	19.14	b	1.28	a	3.16	a								
	PT Mean	0.135	A	18.09	B	1.34	B	3.08	A								
No-till (NT)																	
	24Corn	0,135	a	35.24	a	1.99	b	3.00	a								
	12Corn	0.140	a	34.27	a	1.70	b	3.24	a								
	NT Mean	0.137	A	34.74	A	1.84	A	3.12	A								
Chemical		TN		pH		P		K		Mg		Fe		Mn		Zn	
		%				----------mg kg^{-1}----------											
	24Corn Mean	0.110	A	6.34	A	5.35	A	21.75	A	73.59	A	2.27	A	7.29	A	0.235	A
	12Corn Mean	0.113	A	6.40	A	7.71	A	24.75	A	79.32	A	1.26	A	6.22	A	0.221	A
Plow till (PT)																	
	24Corn	0.085	bc	6.46	a	3.37	a	19.68	a	68.67	a	1.13	a	6.66	a	0.151	b
	12Corn	0.080	c	6.79	a	7.77	a	18.26	a	64.51	a	0.79	a	5.76	a	0.160	b
	PT Mean	0.083	B	6.63	A	5.57	A	18.97	B	66.59	A	0.96	A	6.21	A	0.156	B
No-till (NT)																	
	24Corn	0.138	ab	6.15	a	7.45	a	28.89	a	82.22	a	1.90	a	6.99	a	0.338	a
	12Corn	0.143	a	6.09	a	7.77	a	26.18	a	90.41	a	3.27	a	7.62	a	0263	ab
	NT Mean	0.140	A	6.12	A	7.49	A	27.54	A	86.32	A	2.58	A	7.31	A	0.300	A

24Corn: 24 years continuous corn, 12Corn: 12 years continuous corn after 6 years grass, OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR45: Penetration resistance into the 15-to-30 cm soil layer, TN: Total nitrogen. Means of each property followed by the same lowercase letter within a column are not significantly different at $\alpha = 0.05$ based on Tukey's test. Capital letters show significance of overall tillage and crop management treatment comparisons.

Table 8
Pearson correlation coefficients for SH indicators and total yield for the Stafford loamy fine sand. NS is not statistically significant at α = 0.05.

	OM	ActC	Prot	Resp	AWC	WAS	PR15	TN	pH	P	K	Mg	Fe	Mn	Zn
ActC	0.926														
Prot	0.810	0.870													
Resp	0.779	0.798	0.800												
AWC	0.505	NS	NS	NS											
WAS	0.699	0.668	0.810	0.566	NS										
PR	NS	NS	NS	NS	NS	NS									
TN	0.873	0.912	0.901	0.811	NS	0.665	NS								
pH	NS	NS	NS	NS	NS	NS	NS	NS							
P	NS	NS	NS	NS	NS	NS	NS	NS	NS						
K	0.658	0.693	0.548	0.612	NS	NS	NS	0.738	NS	0.516					
Mg	0.551	0.601	NS	0.511	0.601	NS	NS	0.611	0.628	0.539	0.814				
Fe	NS	NS	NS	NS	−0.514	0.518	NS	NS	−0.574	NS	NS	NS			
Mn	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		
Zn	0.533	0.515	0.676	NS	NS	0.769	NS	0.509	0.641	NS	NS	NS	NS	NS	
Yield	0.501	0.511	0.532	NS	NS	NS	NS	0.642	NS	NS	NS	NS	NS	NS	NS

OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, TN: Total nitrogen.

Table 9
Analysis of variance of corn yield and soil physical, chemical, and biological properties for the Honeoye-Lima silt loam.

Yield	DF	Yield						
Tillage	1	*						
Cover crop	1	ns						
Tillage × cover crop	1	ns						
Biological	DF	OM	ActC	Prot	Resp	Act/OM	Prot/OM	Resp/OM	
Tillage	1	**	**	**	***	**	ns	**	
Cover crop	1	*	ns	*	***	ns	ns	***	
Tillage × cover crop	1	ns	ns	ns	*	ns	ns	ns	
Physical	DF	AWC	WAS	PR15	PR45	InfRate			
Tillage	1	ns	***	ns	ns	*			
Cover crop	1	**	ns	ns	ns	ns			
Tillage × cover crop	1	*	ns	ns	ns	ns			
Chemical	DF	TN	pH	P	K	Mg	Fe	Mn	Zn
Tillage	1	***	ns	*	*	ns	**	ns	ns
Cover crop	1	ns	ns	ns	ns	ns	*	ns	*
Tillage × cover crop	1	ns	ns	ns	ns	ns	ns	ns	ns

OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR45: Penetration resistance into the 15-to-30 cm soil layer, InfRate: Infiltration rate, TC: Total carbon, TN: Total nitrogen.
* Significant at α = 0.05.
** Significant at α = 0.01.
*** Significant at α = 0.001.

6 years), which makes these nutrients more available in the 0-to-15 cm depth interval sampled in this study. pH in our experiments was generally lower under NT than PT (only significant for the clay loam soil; Tables 4, 7 and 10), possibly as a result of modest acidification from OM retention, as also reported by Martínez et al. (2016b). In the short-term, the higher level of these nutrients can decrease the need to add them as amendments in NT systems (Duiker and Beegle, 2006). In the long-term however, nutrient replacement remains necessary, due to continued crop removal at harvest.

We did not measure benefits from NT for AWC - even though OM levels were higher - and penetration resistance in the surface layer was generally higher for NT than PT. These results appear to contradict the common belief that NT soils are more drought resilient and suggest a possible weakness in the method of measurement. Root access to soil water is a complicated process affected by, among other things, the rooting structure of the plant, which can benefit from more continuous biopores under NT that are difficult to measure on a routine basis (Kinoshita et al., 2017).

Overall, the soil health effects from NT compared to PT were most pronounced for the biological indicators, with consistent benefits for OM, Prot, Resp, and ActC. Soil health improvement by NT adoption is reported for the topsoil layer (0-to-15 cm: sampled soil depth) in our trials. However, conventional plowing methods incorporate crop residues to the 0-to-20 cm depth. Therefore, the difference between sampled depth and residue incorporation depth might have impacted the soil health analysis results (e.g., soil biological indicators) of our study, making the difference between NT and PT even greater. The overall effects on soil carbon content may be overestimated due the soil health analysis being limited to the topsoil layer (Luo et al., 2010; Nunes et al., 2015). According to Baker et al. (2007), the cases where conservation tillage was found to sequester carbon, soils were sampled to a depth of 30 cm or less. In the few studies where sampling extended deeper than 30 cm, conservation tillage has shown no consistent accrual of OC. but mostly an effect on the distribution of OC. Thus, the effect of NT on OM content, a leading indicator of soil health, might be overestimated when only the topsoil layer is sampled.

Our results show that continuous NT showed modest improvements in corn yield for a loamy fine sand and silt loam, but not for a clay loam (Fig. 1). Past studies have reported lower (Ziadi et al., 2014; Arvidsson et al., 2014; Al-Kaisi et al., 2015), similar (Al-Kaisi et al., 2016) and higher (Rusinamhodzi et al., 2011; Grover et al., 2009) crop yields under NT in temperate regions. In general, NT tends to have lower crop yields in soil with poor drainage and high clay content, and higher yields in moderate to well-drained soils, under diversified cropping

Table 10
Means for soil biological, physical and chemical properties by tillage and cover crop treatment for the Honeoye-Lima silt loam.

Biological		OM		ActC		Prot		Resp		ActC/OM		Prot/OM		Resp/OM			
		------mg g^{-1}------						mg CO_2 g^{-1}		------mg g^{-1}/mg g^{-1}------				mg CO_2 g^{-1}/mg g^{-1}			
	NC Mean	27.4	B	0.462	A	4.06	B	0.480	B	0.017	A	0.149	A	0.018	B		
	CC Mean	28.8	A	0.491	A	4.37	A	0.625	A	0.017	A	0.151	A	0.022	A		
Plow till (PT)																	
	NC	25.7	b	0.414	b	3.65	b	0.422	Bb[a]	0.016	ab	0.142	a	0.016	c		
	CC	26.6	b	0.419	b	3.82	b	0.537	Ba[a]	0.015	b	0.143	a	0.020	b		
	PT Mean	26.2	B	0.416	B	3.73	B	0.475	B	0.016	B	0.143	A	0.018	B		
No-till (NT)																	
	NC	29.0	ab	0.511	a	4.48	a	0.540	Ab[a]	0.018	ab	0.155	a	0.019	b		
	CC	31.0	a	0.564	a	4.93	a	0.722	Aa[a]	0.018	a	0.159	a	0.023	a		
	NT Mean	30.0	A	0.538	A	4.70	A	0.630	A	0.018	A	0.157	A	0.021	A		
Physical		AWC		WAS		PR15		PR45		InfRate							
		mm^3 mm^{-3}		%		------MPa------				cm hr^{-1}							
	NC Mean	0.252	B	14.00	A	0.93	A	2.79	A	1.66	A						
	CC Mean	0.260	A	15.54	A	0.85	A	2.83	A	1.81	A						
Plow till (PT)																	
	NC	0.250	Aa[a]	7.25	b	0.89	a	2.55	a	1.54	ab						
	CC	0.252	Aa[a]	9.32	b	0.66	a	2.65	a	1.08	b						
	PT Mean	0.250	A	8.29	B	0.78	A	2.60	A	1.31	B						
No-till (NT)																	
	NC	0,253	Ab[a]	20.76	a	0.97	a	3.02	a	1.79	ab						
	CC	0.267	Aa[a]	21.76	a	1.04	a	3.03	a	2.54	a						
	NT Mean	0.261	A	21.26	A	1.01	A	3.02	A	2.17	A						
Chemical		TN		pH		P		K		Mg		Fe		Mn		Zn	
		%				------mg kg^{-1}------											
	NC Mean	0.160	A	7.88	A	13.06	A	85.32	A	366.53	A	0.528	B	7.59	A	0.88	B
	CC Mean	0165	A	7.85	A	17.26	A	87.78	A	375.39	A	0.602	A	8.65	A	1.53	A
Plow till (PT)																	
	NC	0.147	a	7.96	a	9.01	b	79.66	a	372.17	a	0.590	ab	8.56	a	0.84	a
	CC	0.152	a	7.93	a	10.42	b	83.49	a	369.05	a	0.703	a	9.19	a	2.06	a
	PT Mean	0.150	B	7.94	A	9.71	B	81.56	B	370.61	A	0.646	A	8.87	A	1.11	A
No-till (NT)																	
	NC	0.172	a	7.79	a	17.11	a	90.98	a	360.89	a	0.465	b	6.61	a	1.22	a
	CC	0.177	a	7.76	a	24.12	a	92.06	a	381.73	a	0.500	b	8.11	a	1.20	a
	NT Mean	0.175	A	7.76	A	20.61	A	91.52	A	371.31	A	0.484	B	7.36	A	1.30	A

NC: No cover crop, CC: Cover crop, OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR15: Penetration resistance into the 0-to-15 cm soil layer, PR45: Penetration resistance into the 15-to-30 cm soil layer, InfRate: Infiltration rate, TN: Total nitrogen. Means of each property followed by the same lowercase letter within a column are not significantly different at $\alpha = 0.05$ based on Tukey's test. Capital letters show significance of overall tillage and Cover Crop management treatment comparisons.

[a] Means comparison is included despite significant tillage × cover crop interaction.

Table 11
Pearson correlation coefficients for SH indicators and total yield for the Honeoye-Lima silt loam. NS is not statistically significant at α = 0.05.

	OM	ActC	Prot	Resp	AWC	WAS	PR15	IRate	TN	pH	P	K	Mg	Fe	Mn	Zn
ActC	0.886															
Prot	0.798	0.899														
Resp	0.774	0.792	0.808													
AWC	0.520	0.470	NS	0.573												
WAS	0.688	0.778	0.818	0.670	NS											
PR	NS	NS	NS	NS	NS	NS										
IRate	NS	NS	0.469	0.453	0.463	NS	NS									
TN	0.814	0.771	0.659	0.527	NS	0.643	NS	NS								
pH	−0.514	−0.624	−0.594	−0.525	NS	−0.678	NS	NS	−0.551							
P	0.441	0.574	0.573	0.537	0.465	0.501	NS	NS	NS	NS						
K	0.655	0.552	0.550	0.541	NS	0.506	NS	NS	0.488	NS	NS					
Mg	0.468	NS	NS	NS	NS	NS	NS	NS	0.407	NS	NS	NS				
Fe	−0.484	−0.789	−0.554	NS	NS	−0.628	NS	NS	−0.561	0.545	NS	NS	NS			
Mn	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.724		
Zn	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.524	0.654	
Yield	0.794	0.796	0.806	0.588	NS	0.925	NS	NS	0.917	−0.901	0.735	0.933	NS	−0.734	−0.830	NS

OM: Organic matter, ActC: Active carbon, Prot: Autoclaved citrate extractable protein index, Resp: Respiration, AWC: Available water capacity, WAS: Wet aggregate stability, PR14: Penetration resistance, IRate: Water infiltration rate, TN: Total nitrogen.

systems with cover and rotation crops (DeFelice et al., 2006; Al-Kaisi et al., 2016).

4.2. Cropping systems effects

Long-term monoculture cropping systems decrease soil health under temperate conditions, independent of soil tillage, when compared to more complex extended crop rotations (Karlen et al., 2006; Zuber et al., 2015). In our study, we measured less OM and less Prot for the clay loam soil under 24 years of continuous corn monoculture than under 12 years corn monoculture (Table 4), i.e., the positive effects from a 6-year interruption of continuous silage corn cropping by a rotation with grass was still discernable 12 years after re-conversion to continuous silage corn. This was not measured for the loamy sand soil where better aeration presumably results in higher OM decomposition rates. This suggests that benefits from soil building practices (perennial grass) are partly preserved when shifting to row crop production if the soil is not plowed.

We also determined that the interseeded cover crops mixture resulted in discernably improved soil health after 4 years in a continuous corn system soil independent of soil tillage practiced (Table 10), as also discussed by Alhameid et al. (2017) and Melkonian et al. (2017).

Several other studies showed that cropping system diversification, depending on the species used (i.e. through the introduction of cover crop mixtures and perennial crops), can result in positive effects on ecosystem functioning (Tilman et al., 2001; Finney and Kaye, 2017; King and Blesh, 2018). Introducing a cover crops mix into the continuous corn monocropping cropping system increased the time period with living plants and roots in the agroecosystem, increasing quantity, and quality of the OM (Tables 4, 7 and 10). The additional OM and continuously growing root system regulate C inputs and stimulate soil microbial activity due to the increased supply of root exudates, water, nutrients and oxygen to microorganisms (Kumar et al., 2017). Soil biological activity, consequently, affects catalytic reactions with soil OM, increases aggregate stabilization (Erktan et al., 2016) by enmeshment of aggregates and particles by fungal hyphae, produces extracellular polysaccharides which glue mineral particles, and produces hydrophobic substances (Six et al., 2004).

Introduction of interseeded mixed cover crops into the cropping system also increases the availability of some micronutrients, notably Zn (Table 10), presumably due to recycling of nutrients that may be leached to deeper soil horizons (Scopel et al., 2013).

Greater biology activity followed the trend NT-CC > NT-NC > PT-CC > PT-NC. The beneficial cover crop effect was greater for biological indicators under NT than PT, suggesting that greater benefits are derived from cover crops when the soil is not disturbed (Table 10). For wet aggregate stability, however, tillage effects are dominant. In general, these results demonstrate that crop rotation and cover crops have positive effects on soil health that are additive to those derived from NT alone, and if cover crops or crop rotation are not introduced, benefits from NT are lower. The species selection within the cropping systems was also important to soil health improvement under the most diversified cropping systems in this study, and increasing the diversity of cover crops species positively impacts agroecosystem services and promotes greater multifunctionality (Finney and Kaye, 2017; King and Blesh, 2018).

4.3. Yield and sustainability

Yield effects from tillage were observed for the loamy sand and silt loam sites. For these experiments, correlations between yield and soil health indicators were observed with soil biological indicators and WAS, especially for the silt loam site including tillage and cover cropping treatments. Yield was also strongly positively correlated with several chemical indicators, notable TN (related to Prot), and K and P (presumably related with residue retention at the soil surface under NT). Normally, farmer hesitation in adopting new management practices - such as NT, cover crops or crop rotation - stems from concerns about loss of yield, higher costs and lower profitability. However, our results show that long-term NT can keep or increase levels of crop yields in temperate regions (Fig. 1), mainly when the NT is implemented under a diversified cropping system (e.g. interseeded cover crops mixture and perennial grass).

In the first year of the experiment the introduction of the cover crop reduced yields (in part from some mechanical corn damage from the interseeding operation), but the cover crop treatments trended to higher yields in the subsequent years (Fig. 1E, F). This demonstrates a relatively rapid benefit from the use of cover crops mixture, which appears primarily related to enhanced biological properties (OM, Prot, and Resp; Table 10).

Previously, several studies also showed that increasing cropping system biodiversity (e.g. by the introduction of cover crops mixture, crop rotation, and perennial crops) can enhance the NT benefits (Scopel et al., 2013; Zuber et al., 2015; Mitchell et al., 2017; Alhameid et al., 2017). Comparing conservation agriculture systems from tropical regions of South America (Brazil) and from temperate regions of Europe, Scopel et al. (2013) showed that the success of continuous NT in Brazil results mostly from the permanent presence of an organic mulch on the soil surface and the incorporation of cover crops into the crop rotation. Some studies under temperate conditions also showed that the soil health benefits of NT are mostly associated with the level of crop residues retained on the soil surface (Moebius-Clune et al., 2008; Kinoshita et al., 2017) and introduction of cover crops or crop rotations (Alhameid et al., 2017).

Through benefits to soil health, the continuous NT systems, conducted under common conservation agriculture principles, can also mitigate the impacts of global climate change. The increases of OM content can help increase C sequestration, thus reducing net CO_2 emission and slowing global warming (Scopel et al., 2013; Melland et al., 2017). Considering all three of the major greenhouse gases together, Mangalassery et al. (2014) showed that tilled soil contributed 20% greater to net global warming than NT soil, indicating a potential for NT system to mitigate climate change.

5. Conclusions

This study focused on the effects of long-term tillage practices and diversified cropping (cover crops and rotation) on soil health and corn yields. We conclude that no-tillage has clear soil health benefits over plow till and contributed to a modest increase in corn yield for a silt loam and a loamy sand soil. On a clay loam soil, the soil health benefits were apparent, but no significant yield effects were observed. In addition, we observed an additive beneficial effect of cover crops on soil health 4 years after initiation, which was more strongly expressed under no-till than plow-till. Similarly, the effects of a perennial grass rotation on soil health were discernable after 12 years under no-till but not under plow-till. Therefore, our results indicate that, from a biophysical-agronomic perspective the NT system, especially when adopted with a more diversified cropping system, offers farmers opportunities for increased sustainability in intensive crop production.

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