Received: 6 June 2024 | Accepted: 26 November 2024

DOI: 10.1002/saj2.70000

Soil Science Society of America Journal

ORIGINAL ARTICLE

Agricultural Soil and Food Systems

Soil organic carbon and total nitrogen after 34 years under conventional and organic management practices at the Rodale Institute Farming Systems Trial

Klaus Lorenz[1] | Emmanuel Omondi[2] | Rattan Lal[1] | Saurav Das[3] | Andrew Smith[3]

[1]School of Environment and Natural Resources, The Ohio State University, Columbus, Ohio, USA

[2]Department of Agricultural and Environmental Sciences, Tennessee State University, Nashville, Tennessee, USA

[3]Research Department, Rodale Institute, Kutztown, Pennsylvania, USA

Correspondence
Emmanuel C. Omondi, Department of Agricultural and Environmental Sciences, Tennessee State University, Nashville, TN 37209, USA.
Email: eomondi@tnstate.edu

Assigned to Associate Editor Alex Woodley.

Funding information
V. Kann Rasmussen Foundation, Grant/Award Number: 60047449

Abstract

Long-term agricultural experiments are uniquely positioned to capture the spatiotemporal dynamics of farming system effects on soil profile properties, which typically require decades for measurable changes to become apparent. Soil organic carbon (SOC) and total nitrogen (TN) concentrations and stocks were determined at a depth of 0–30 cm in the 34th year of the Rodale Institute Farming Systems Trial (FST), Kutztown, Pennsylvania, USA. Only the organic agriculture (OA) with manure (OA-MNR) system plots had higher SOC concentrations and stocks than the plots of the other systems but only at depths of 0–10 and 10–20 cm, and not on equivalent soil mass (ESM) basis to 30-cm depth. The ESM SOC stocks to 30-cm depth at the tilled plots were 53.3, 56.2, and 61.9 Mg C ha^{-1} for conventional (CONV), OA-legume (OA-LEG), and OA-MNR systems, respectively. The concentrations and stocks of TN, as well as ESM TN stocks to 30-cm depth at the tilled plots, were higher for both OA systems compared to CONV. However, observations at the recently established reduced tillage (RT) subplots were inconsistent, as at least 10 years may be needed to ensure that differences in tillage treatment effects on SOC can be detected. The results are consistent with many other long-term field experiments that have reported differences in SOC and TN concentrations and stocks only in the topsoil. Overall, the OA-MNR system was advantageous in 2015 in increasing SOC and TN compared to the CONV and OA-LEG systems. Thus, OA practices when combined with composted manure addition can result in increases in the SOC stock in the long term. However, subsequent studies should assess the implications for input of manure sourced from outside the OA-MNR system. Further, soil samples should be taken several times over multiple years to more comprehensively assess management-induced changes in soil properties.

Abbreviations: FST, Farming Systems Trial; OA, organic agriculture; RT, reduced tillage; SOC, soil organic carbon; SOM, soil organic matter; TC, total carbon; TN, total nitrogen.

Plain Language Summary

Long-term agricultural studies are important to capture changes in soil physical and chemical properties arising from different land-use practices. The objective of this study was to assess changes in soil organic carbon (SOC) and total nitrogen (TN) up to a 30-cm soil depth in a 34-year research field at Rodale Institute, Pennsylvania. The organic agriculture system that included the use of composted manure as fertilizer had higher SOC and TN compared to conventional and legume-based organic systems. The study also found higher TN in organic systems managed by tillage compared to the synthetic agrochemical-based conventional systems. These results were consistent with many similar long-term field experiments. However, results from the study highlighted the need for additional soil sampling over multiple years to more comprehensively assess management-induced changes in soil properties.

1 | INTRODUCTION

The management of soils for agricultural production faces numerous challenges, with the growing global population driving increased demand for food, fuel, and shelter. As global affluence rises, shifts in food consumption patterns toward land-intensive products, such as animal-based commodities, further complicate these challenges (Foley et al., 2011). A key distinction has been made in agricultural practices based on management approaches. Intensive agriculture, which relies heavily on inorganic fertilizers, is typically classified as conventional agriculture, while systems that depend more on natural sources of fertility are categorized as organic agriculture (OA; Lorenz & Lal, 2023). Studies have estimated an average of 20%–30% yield gap between conventional agriculture and OA, and there is a debate about global food security in terms of OA expansion (Borghino et al., 2024; Kniss et al., 2016; Seufert, 2019).

Despite the yield discrepancies, OA practices provide environmental and soil health benefits, which are often negated or minimized due to the reported tendency of OA systems to yield less per unit area (Reganold & Wachter, 2016). Studies have shown that OA can produce greater crop yields especially for some hay crops and under water stress conditions compared to conventional systems (Kniss et al., 2016; Pimentel et al., 2005), due to improvement in soil organic matter (SOM) and aggregate stability and resultant water holding capacity (Hepperly et al., 2007; Reganold, 2009).

However, the relationship between yield and soil organic carbon (SOC) is complex. Increased yields can result in the reduction of soil carbon (C) inputs as more C accumulates in harvestable parts, potentially depleting SOC stocks over time. This is concerning as SOC is crucial for soil health and long-term C storage, mitigating climate change by capturing atmospheric carbon dioxide (CO_2; Janzen, 2006; Lorenz & Lal, 2018). Agricultural practices over the last 12,000 years have led to substantial losses of SOC, with an estimated total debt of 116 Pg C (1 Pg = 1 Gt = 10^{15} g) for the top 2 m of soil (Sanderman et al., 2017). Restoring SOC stocks can improve soil health and resilience, contributing to broader re-carbonization efforts (DeCicco & Schlesinger, 2018; Lal et al., 2012, 2013).

Long-term field experiments show that higher crop yields are attainable with increased SOC levels, with yield benefits leveling off at about 2% SOC (Oldfield et al., 2019). In conventional systems, beneficial effects of SOC are often masked by external inputs like fertilizers, but in OA systems, SOC stocks are more critical due to the reliance on nutrient supply from SOM mineralization. However, there is no consensus on effects of OA practices such as application of organic fertilizer, exclusion of synthetic pesticides and genetically modified organisms (Kirchmann et al., 2016), and use of diverse crop rotations for weed control and crop protection on SOC stock changes (Lorenz & Lal, 2023). Organic amendments such as animal manure may have positive long-term effects on SOC stocks, soil fertility, soil water retention, and plant-available water (Das et al., 2023; Diacono & Montemurro, 2010; Eden et al., 2017; Maillard & Angers, 2014). Gattinger et al. (2012) reported that SOC stocks in 0–15 cm depth under OA were on average 1.98 Mg C ha^{-1} higher than those under conventional management. However, there is debate on the depth of the soil profile that needs to be sampled for assessment of SOC improvement. While Ghabbour et al. (2017) suggested that OA practices build and/or maintain SOC more effectively than conventional farming practices within the top 30-cm soil depth, Blanco-Canqui et al. (2017) reported that OA rotations with cattle and green manure only increased SOC stocks in the upper 15-cm depth. OA systems with lower yields and consequently lower primary soil C inputs from crop residues, together with tillage for weed control, may contribute to lower SOC stocks than under conventional management (Lorenz & Lal, 2023). Practices such as crop rotation with legumes/cover crops and application of manure have been reported to increase profile SOC stocks compared to those under conventional practices (Lorenz & Lal, 2023). Long-term field experiments are essential as conclusions based on 10–20 years of data can be very different than those based on 50 or more years of data (Johnston, 1997). For example, while SOC contents at 0–20 cm depth were not different between biodynamic and conventional systems at a long-term experiment in India 7 years after establishment, SOC contents were higher for the biodynamic farming system after 12 years (Lori et al., 2024).

Long-term field experiments provide unique opportunities to study the interannual variability, gradual change, and the development of agronomic and nutrient management practices on soil health and SOC, which otherwise take decades to determine measurable changes. Therefore, the objective of this study was to assess the SOC and total nitrogen (TN) stocks to 30-cm depth in the 34th year of the Rodale Institute's Farming Systems Trial (FST) near Kutztown, Pennsylvania, USA. The FST is the longest-running side-by-side comparison of conventional and OA corn and soybean (*Glycine max* L.) cropping systems in North America (Hepperly et al., 2007). Apart from transport of dissolved organic carbon, SOC, SOM, microbial biomass C, water extractable C, permanganate oxidizable C, potentially mineralizable C, wet aggregate stability, autoclaved-citrate extractable protein, TN, soil biology, aggregate size distribution, soil hydraulic properties, yields, nutrient density, grain quality, economics, herbicide leaching, and energy inputs have also been assessed at FST (Liptzin et al., 2022, 2023; Littrell et al., 2021; Pearsons et al., 2022, 2023). This study aimed to address the following questions: (i) How have more than three decades of OA management influenced SOC and TN concentrations and stocks compared to conventional practices under conventional tillage? (ii) How have 7 years of reduced tillage (RT) affected SOC and TN concentrations and stocks across different farming systems? (iii) Do organic matter (OM) inputs from cover crops, legume biomass, and manure have beneficial effects on SOC and TN concentrations and stocks? The results of this study are crucial for reevaluating and redefining the value of OA. They emphasize the need to expand the concept of return on investment (ROI) beyond just yield, advocating for a more comprehensive approach that includes both productivity and other ecosystem services.

Core Ideas

- More than three decades after implementing organic agriculture (OA) practices, soil organic carbon (SOC) concentrations and stocks were affected only up to 20-cm soil depth.
- Higher SOC stocks under OA compared to those under conventional practices were only observed under reduced tillage (RT) practices established less than a decade ago.
- A new steady-state equilibrium between soil carbon (C) inputs and outputs after implementing OA and RT practices may have not yet been reached.
- Farming systems should be assessed for management-associated changes in less responsive soil properties such as SOC after 50–100 years.

2 | MATERIALS AND METHODS

2.1 | Experimental design and site properties

The FST experiment covers 6 ha on a moderately well-drained Comly shaly silt loam and includes two USDA soil series (Hepperly et al., 2007). Soil texture of the soil series does not vary substantially and was not, thus, considered a confounding factor across experimental treatment plots (Alfahham et al., 2021). The climate is subhumid temperate with a mean annual temperature of 12.4°C and mean annual precipitation of 1105 mm. Temperate forests preceded agriculture in this region, and the site was used continuously to provide pasture and produce hay, corn, and small grains after the original forest was cleared about 250 years ago (Drinkwater et al., 1998; Peters et al., 1997). Before plot establishment, the FST field was managed for 25 years according to a conventional corn rotation (Alfahham et al., 2021).

The experiment was initiated in 1981 with three management systems (main plots), including: (i) conventional (CONV), (ii) OA legume (OA-LEG), and (iii) OA manure (OA-MNR) rotations. Representing most grain farms in the United States, the CONV system relies on synthetic fertilizers for crop production and synthetic herbicides for weed control, applied at rates recommended by Pennsylvania State University Extension (Moyer, 2013; Ryan et al., 2009). The OA-LEG rotation represents an organic cash grain system and features a mid-length rotation of annual grain and cover crops. The system's sources of N fertility include biological N fixation from the leguminous crops in rotation, including soybeans, hairy vetch (*Vicia villosa* L.), and clovers (*Trifolium* L.). The OA-MNR rotation represents an OA dairy or beef (*Bos taurus* Linnaeus, 1758) operation and features longer rotations of both annual feed grain crops and perennial forage crops. The system's fertility is primarily provided by leguminous crops and periodic applications of composted manure. Weeds at OA-LEG and OA-MNR are controlled by mechanical cultivation strategies, including two passes with a tine cultivator prior to crop and weed emergence (blind cultivation), one to two passes with a rotary hoe or tine cultivator after crop emergence, and up to three passes with interrow cultivators.

Major cash crops in the rotation include corn, wheat, soybean [*Glycine max* (L.) Merr.], and oat (*Avena sativa* L.). In the OA-MNR system, mixed perennial orchardgrass (*Dactylis glomerata* L.) and alfalfa (*Medicago sativa* L.) were included as hay in the rotation. Winter cover crops included red clover (*Trifolium pratense* L.), hairy vetch (*Vicia villosa* L.), and cereal rye (*Secale cereale* L.). The CONV system followed a 3-year rotation (corn–corn–soybean), OA-LEG followed a 4-year rotation (corn/rye–oats/clover and rye–soybean/wheat–wheat/vetch), and OA-MNR an 8-year rotation (soybean/wheat–wheat/hay–hay–hay–corn silage/wheat–wheat/vetch–corn/rye–oat/rye). The OA-LEG and OA-MNR systems have been receiving annual C inputs from 8.2 to 10.8 Mg ha^{-1} of cover crop residues, respectively. In addition, OA-MNR has been receiving C from 26.2 to 37.8 Mg ha^{-1} of composted manure once every 2–3 years of rotation (Mirsky et al., 2012; Pearsons et al., 2022).

The experiment was originally established as a randomized complete block design with eight replicates of each of the three management systems as the main plots. Main plots were 18 × 92 m in size, split into three 6 × 92 m subplots, which allowed for multiple crops to be represented each year given the different rotation sequences and lengths in the three management systems. These subplots also provide opportunities to compare one crop across all systems in any given year. The plots were separated with a 1.5-m grass strip to minimize cross-movement of soil, fertilizers, and pesticides.

Prior to 2008, CONV, OA-LEG, and OA-MNR were managed by intensive tillage. OA plots were tilled annually with primary inversion moldboard plowing to a depth of 15–20 cm and several secondary cultivation passes for weed control. Moldboard plowing was followed by disking and packing the seedbed to break large clods prior to planting. Secondary tillage cultivation strategies included two passes with a tine cultivator prior to crop and weed emergence (blind cultivation), one to two passes with a rotary hoe or tine cultivator after crop emergence, and up to three passes with interrow cultivators. Intensive tillage in CONV was limited to seedbed preparation (vertical chisel plowing to a depth of 20 cm, followed by disking and packing prior to planting crops). Subsequently, weed control in conventional cropping systems was achieved by herbicides.

Major modifications of the rotations were implemented in 2008 and 2014. Since 2008, four of the eight replicates were managed by RT, and the remaining four continue to be managed by conventional tillage. While weed management in CONV RT is accomplished by synthetic herbicides combined with herbicide-tolerant corn and soybean varieties (Pearsons et al., 2022), weed control in OA-LEG RT and OA-MNR RT is accomplished by rolling down established cover crops, mainly winter rye and hairy vetch, using a roller-crimper, to create a mulch and weed barrier. Given that the cover crops are established by tillage, this method is accurately referred to as RT, that is, cover-crop-based rotational no-tillage. Winter rye and hairy vetch cover crops were initially added to the conventional RT system, but this was changed in 2014 to retain only winter rye in one rotational sequence subplot in both CONV RT and tilled systems (Pearsons et al., 2022). This was to ensure uniformity of RT and tillage treatments in each cropping system. Other management practices also changed over time, that is, while previously the same varieties were grown on conventional and OA plots, genetically modified varieties were introduced in the conventional system in 2008 to replicate the common practices among grain growers instituting no-till practices in the United States and to ensure the success of weed management. A major modification occurred also in 2014, the year before soil sampling, as all plots were planted to oats before establishing new crop rotations. Apart from retaining only winter rye cover in the RT and tillage treatments of one CONV rotation sequence subplot mentioned above, all OA and CONV systems were harmonized to ensure uniform crops in RT and tillage treatments of each rotational sequence subplot. In each system, N inputs were added for the corn crop at equivalent available rates for corn. These inputs included composted cattle manure and legume plow-down (green manure) in the OA-MNR system; legume plow-down (red clover or hairy vetch) in the OA-LEG system; and ammoniated fertilizer in the CONV system (Hepperly et al., 2007).

About 168 kg N ha^{-1} was applied to corn in CONV to achieve a grain yield of 9.4 Mg ha^{-1}. Mineral fertilizer was applied as a split application with 33.6 kg ha^{-1} Urea N and phosphorus (P), and 11.2 kg potassium (K) ha^{-1} at planting (starter fertilization), followed by 134.5 kg N ha^{-1} as a sidetop-dress application in the form of urea ammonium nitrate (UAN) when corn plants were about 30-cm tall (second application). For starter fertilization, urea, monoammonium phosphate, and potash were mixed at a ratio of 50:60:16. Typically, no fertilizer was applied to soybeans in CONV. However, 67 kg N ha^{-1} sidetop dress was applied to wheat as UAN at the tillering to jointing stage (Feekes 4–6) to support vegetative growth and optimize nitrogen use efficiency. Composted manure was only applied every 2–3 years to the OA-MNR plots depending on crop rotation, and it was applied prior to planting oats or corn silage only (Pearsons et al., 2022). Prior to soil sampling for this study in 2015, composted manure was last applied to the OA-MNR plots in 2011 and 2013, depending on the crop rotation within each entry point of the OA-MNR system (Pearsons et al., 2022). The compost application rate in OA-MNR was determined based on a target input of 89.7 kg N ha^{-1} and the assumption that there was at least 40% residual N in the soil provided by legume plow-down or roll-down, along with N credit from SOM accumulated over the long duration of the experiment. Compost manure application rates over the years have ranged from 33.6 to 44.0 Mg ha^{-1}, with nutrient contents in the range of 8.4%–10.9% for C, 0.5%–0.7% for N, 0.12%–0.17% for P, 0.55%–0.98% for K, 0.61%–1.27% for calcium, 0.19%–0.35% for magnesium, and 0.09%–0.13% for sulfur.

2.2 | Soil sampling and processing

In October 2015, four soil cores, each 4.3 cm in diameter and 100-cm long, were taken from each of the four replicated subplots that had been managed as different cropping systems. Soil samples were taken from both tilled and RT subplots. For CONV, sampled plots were under corn or soybean in 2015, and for OA, tilled rotations included soybean–corn or corn–soybean; RT rotations included soybean/wheat–oat–corn or corn/rye–oat/rye–soybean/rye. Soil data were averaged over the three crop rotations to a combined 16 cores for each of the tilled CONV and CONV RT and similarly for the other treatments so that an equal number of observations could be tested for the six main treatments (CONV, CONV RT, OA-LEG, OA-LEG RT, OA-MNR, OA-MNR RT). The OA-LEG plots were under corn with rye as a cover crop (16 cores tilled rotations vetch–corn/rye–oat–red clover/rye; 16 cores RT rotations vetch–corn/rye–oat–red clover/rye). The 16 cores each from tilled and OA-MNR RT plots were under soybean/wheat rotation (rye–soybean/wheat–vetch/corn). Intact soil cores were collected along the middle of each plot into clear polyethylene terephthalate sleeves using a hydraulic soil probe (The Giddings Machine Co) with a 4-cm-diameter tip, then sealed and stored at 4˚C prior to processing.

Before each intact soil core was pushed out of the transparent sleeves and segmented into layers representing soil depths, its length was measured and inspected for evidence of compaction and soil loss. This study focused on the soil depth mostly affected by tillage, so the 30-cm intact soil cores were cut into 0–10, 10–20, and 20–30 cm layers, and the field-moist mass of each layer was recorded. The coarse fraction (>2 mm) and any root material were removed from the contents of each layer before passing it through a 2-mm sieve. Root material and coarse fraction were dried at 40˚C for mass determination. After processing, the mass of each soil layer was recorded, subsampled, and oven-dried at 105˚C for gravimetric water content determination. Gravimetric water content was used to calculate the mass of dry soil and bulk density (ρ_b) for each layer. Dold et al. (2018) reported that the difference between ρ_b determined by hydraulic deep-core sampling is not significantly different from that determined in soil pits, and hydraulic deep-core sampling also does not significantly affect SOC stock estimates.

2.3 | Soil analysis

The remaining soil sample was dried at 40˚C, and then a 10-g subsample was finely ground (<0.25 mm) for chemical analyses. Soil was analyzed for total carbon (TC) and TN via the dry combustion method (Thermo Fisher Scientific FLASH 2000 CN Soils). Since TC values before and after acid fumigation were not different, TC was assumed to represent SOC (Alfaham et al., 2021). The SOC stock [Mg C ha^{-1}] was calculated as

$$\text{SOCStock} = \sum_{i=1}^{n} \frac{\text{FSM}_i}{V_i} \times \text{SOC}_i \times D_i \times 10^2, \quad (1)$$

where n is the number of depth increments; FSM is the fine soil mass (g); V is the volume (cm^3); SOC is the soil organic carbon concentration (mass % C); D is the length of the depth increment (cm); and 10^2 is the unit conversion factor.

Because long-term land use influences ρ_b, SOC stocks were corrected for differences in soil mass by calculating SOC stocks on an equivalent soil mass (ESM) basis (Ellert & Bettany, 1995). The minimum ESM method was applied for the 0–30 cm depth increment. The reference soil mass was the lightest core out of all treatments (Poeplau & Don, 2013). The correction was performed as follows:

$$\text{SOCStock}_{\text{corr}} = \text{SOCStock}_i - \left(\frac{\text{CFSM}_i - \text{CFSM}_{\text{lightest}}}{\text{CV}_i} \times \text{SOC}_{\text{deepest}} \right), \quad (2)$$

where $\text{SOCStock}_{\text{corr}}$ is the corrected SOC stock (Mg C ha^{-1}); SOCStock_i is the uncorrected individual stock (Mg C ha^{-1}); CFSM_i is the cumulative fine soil mass (g) of the individual core to the desired depth; $\text{CFSM}_{\text{lightest}}$ is the cumulative fine soil mass of the lightest core of the site (g); CV_i is the cumulative volume (cm^3); and $\text{SOC}_{\text{deepest}}$ is the SOC concentration (% C) of the deepest sampled depth increment (Poeplau & Don, 2013). The mass-corrected SOC stock data were computed for 0–30 cm depth. Calculating SOC stocks on a mass basis can overcome biases in rock fragment content and ρ_b estimates introduced by sampling equipment (Beem-Miller et al., 2016). Similar calculations and mass corrections were applied to TN stocks. Mass-corrected stocks are used throughout the manuscript when reporting absolute losses or gains in SOC and TN, but not for concentration (g kg^{-1}) when discussing C and TN dynamics within the profile. Notably, mass-corrected stocks are less useful for examining SOC and TN dynamics within the soil profile, as the mass correction causes a shift in the effective soil depth (Poeplau & Don, 2013).

2.4 | Statistical analysis

The SOC and TN stocks for 0–10, 10–20, and 20–30 cm depths were calculated by the ESM method. These were then

TABLE 1 Mean concentrations (± SD; $N = 16$) of soil organic carbon (SOC) and total nitrogen (TN) and organic carbon to total nitrogen (OC:TN) ratios after 34 years under conventional and organic farming practices (pairwise comparison between treatments; Mann–Whitney U-test, $p < 0.05$).

	Conventional		Organic legume		Organic manure	
	Tillage	Reduced tillage	Tillage	Reduced tillage	Tillage	Reduced tillage
0–10 cm						
SOC (g C kg^{-1})	24.4 ± 2.2B	21.8 ± 2.5AB	24.9 ± 3.8C	25.3 ± 2.8A	28.5 ± 3.9BC	26.7 ± 4.8B
TN (g N kg^{-1})	3.0 ± 0.3AB	3.3 ± 0.3A	3.5 ± 0.4A	3.5 ± 0.3A	3.8 ± 0.3B	3.4 ± 0.7
OC:TN ratio	8.2 ± 0.7AB	6.7 ± 0.6AB	7.1 ± 0.7A	7.2 ± 0.6A	7.5 ± 0.9B	8.2 ± 1.9B
10–20 cm						
SOC (g C kg^{-1})	21.7 ± 2.7B	17.8 ± 2.2AB	23.6 ± 6.4	24.7 ± 3.5A	26.3 ± 4.8B	22.8 ± 6.8B
TN (g N kg^{-1})	2.7 ± 0.3AB	2.9 ± 0.2A	3.4 ± 0.4A	3.4 ± 0.3AC	3.6 ± 0.4B	2.9 ± 0.7C
OC:TN ratio	8.1 ± 1.0AB	6.2 ± 0.8AB	6.8 ± 1.3A	7.3 ± 0.8A	7.2 ± 1.0B	7.8 ± 1.8B
20–30 cm						
SOC (g C kg^{-1})	9.7 ± 4.8	8.8 ± 2.5A	12.0 ± 6.9	13.6 ± 7.2A	10.8 ± 7.6	8.9 ± 4.8
TN (g N kg^{-1})	1.9 ± 0.3AB	2.3 ± 0.2B	2.5 ± 0.4A	2.5 ± 0.5C	2.4 ± 0.5B	1.8 ± 0.6BC
OC:TN ratio	5.0 ± 2.0	3.8 ± 0.9A	4.5 ± 2.0	5.2 ± 1.9A	4.4 ± 2.3	5.1 ± 3.0

Note: Letter A indicates a significant difference between conventional and organic legume systems for the same tillage practice. Letter B indicates a significant difference between conventional and organic manure systems for the same tillage practice. Letter C indicates a significant difference between organic legume and organic manure systems for the same tillage practice.

Abbreviations: OC, organic carbon; SOC, soil organic carbon; TN, total nitrogen.

aggregated for the 0–30 cm depth. The results of the soil chemical analyses are based on arithmetic means (± SD) of 16 samples for each depth increment per cropping system. All variables failed the test for normality (Kolmogorov–Smirnov) even after the data transformation and parametric tests such as analysis of variance (ANOVA) could not be used. Therefore, the nonparametric Kruskal–Wallis H test was used, and the results indicated that the effects of treatment on each soil property per soil depth were significant (null hypothesis rejected). The nonparametric Mann–Whitney U-test was applied (significance level 95%) to perform pairwise comparisons between specific treatments for each depth. Statistical comparisons were done for the pairs under the same tillage practice: (i) CONV and OA-LEG, (ii) CONV and OA-MNR, and (iii) OA-LEG and OA-MNR. Statistical analyses were done using International Business Machine Statistical Package for the Social Sciences (IBM SPSS Statistics, Version 24).

3 | RESULTS

3.1 | SOC concentrations

The SOC concentrations in the studied plots ranged from 21.8 to 28.5 g C kg^{-1} at 0–10 cm depth, from 17.8 to 26.3 g C kg^{-1} at 10–20 cm depth, and from 8.8 to 13.6 g C kg^{-1} at 20–30 cm depth (Table 1). Significant differences between treatments were mainly found above 20-cm depth. For example, the SOC concentration at 0–10 cm depth for CONV tillage plots (24.4 g C kg^{-1}; B) was not significantly different from that for the OA-LEG tillage plots (24.9 g C kg^{-1}; C), whereas it was significantly lower compared to the SOC concentration for OA-MNR tillage plots (28.5 g C kg^{-1}; BC). Under RT practices, OA-LEG plots had higher SOC concentrations ($0.000 < p < 0.035$) compared to CONV plots at all depths. The SOC concentrations at 0–10 and 10–20 cm depths were also higher ($0.001 < p < 0.007$) in OA-MNR plots compared to those in CONV plots independent of tillage practice. The only significant difference between the two OA systems was higher SOC concentrations ($p = 0.015$) at 0–10 cm depth in tilled OA-MNR plots compared to tilled OA-LEG plots (Table 1).

3.2 | Soil TN concentrations

The TN concentrations ranged from 3.0 to 3.8 g N kg^{-1} at 0–10 cm depth, from 2.7 to 3.6 g N kg^{-1} at 10–20 cm depth, and from 1.5 to 2.5 g N kg^{-1} at 20–30 cm depth (Table 1). The TN concentrations at 0–10 and 10–20 cm depths in OA-LEG plots were higher ($0.000 < p < 0.007$) than those in CONV plots independent of tillage practice. At all depths, TN concentrations in tilled plots were higher ($0.000 < p < 0.003$) in OA-MNR than those in tilled CONV plots. Under RT, TN concentrations at 10–20 and 20–30 cm depths were higher ($p = 0.007$ and $p = 0.017$, respectively) in OA-LEG plots compared to OA-MNR plots (Table 1).

TABLE 2 Mean bulk density (g cm^{-3}; ± SD; $N = 16$) after 34 years under conventional and organic farming systems (pairwise comparison between treatments, Mann–Whitney U-test, $p < 0.05$).

	Conventional		Organic legume		Organic manure	
	Tillage	Reduced tillage	Tillage	Reduced tillage	Tillage	Reduced tillage
0–10 cm	0.98 ± 0.08	1.03 ± 0.07A	0.96 ± 0.12	0.91 ± 0.15AB	0.99 ± 0.14	1.05 ± 0.14B
10–20 cm	1.13 ± 0.05	1.16 ± 0.05A	1.11 ± 0.13	1.03 ± 0.11AB	1.10 ± 0.03	1.13 ± 0.13B
20–30 cm	1.30 ± 0.07A	1.24 ± 0.08	1.16 ± 0.20A	1.20 ± 0.12	1.23 ± 0.10	1.29 ± 0.17

Note: Letter A indicates a significant difference between conventional and organic legume systems for the same tillage practice. Letter B indicates a significant difference between organic legume and organic manure systems for the same tillage practice.

3.3 | SOC to TN ratios

The OC:TN ratios ranged from 6.7 to 8.2 at 0–10 cm depth, from 6.2 to 8.1 at 10–20 cm depth, and from 3.8 to 5.2 at 20–30 cm depth (Table 1). The OC:TN ratios at 0–10 and 10–20 cm depths under tillage were lower in OA-LEG compared to those in CONV plots but higher under RT ($p = 0.000$ and $p = 0.005$, and $p = 0.029$ and $p = 0.001$, respectively). This was also true for OA-MNR compared to CONV plots ($p = 0.043$ and $p = 0.047$, and $p = 0.003$ and $p = 0.005$, respectively). The OC:TN ratios did not differ between plots under different OA management practices (Table 1).

3.4 | Soil bulk density

The soil ρ_b ranged from 0.91 to 1.05 g cm^{-3} at 0–10 cm depth, from 1.03 to 1.16 g cm^{-3} at 10–20 cm depth, and from 1.16 to 1.30 g cm^{-3} at 20–30 cm depth (Table 2). There were some differences in ρ_b between treatments. Under RT, ρ_b at 0–10 and 10–20 cm depths was lower ($p = 0.014$ and $p = 0.001$, respectively) in OA-LEG compared to CONV plots. Among OA systems managed by RT practices, ρ_b was higher ($p = 0.032$ and $p = 0.035$, respectively) at 0–10 and 10–20 cm depths in OA-MNR plots compared to OA-LEG plots (Table 2).

3.5 | SOC and TN stocks per depth

The SOC stocks ranged from 20.0 to 25.2 Mg C ha^{-1} at 0–10 cm depth, from 17.7 to 25.5 Mg C ha^{-1} at 10–20 cm depth, and from 9.5 to 14.3 Mg C ha^{-1} at 20–30 cm depth (Table 3). Significant differences between treatments were only found above 20-cm depth. Independent of tillage practices, SOC stocks at 0–10 and 10–20 cm depths were higher ($0.001 < p < 0.014$) in OA-MNR than in CONV plots. Also independent of tillage practices, SOC stocks at 0–10 cm depth were higher ($p = 0.023$ and $p = 0.021$, respectively) in OA-MNR than in OA-LEG plots. The TN stocks ranged from 2.6 to 3.4 Mg N ha^{-1} at 0–10 cm depth, from 2.7 to 3.5 Mg N ha^{-1} at 10–20 cm depth, and from 2.0 to 2.6 Mg N ha^{-1} at 20–30 cm depth. In tilled plots, TN stocks were higher ($0.000 < p < 0.008$) in OA-LEG than those in CONV plots at all depths. At all depths, TN stocks in tilled OA-MNR plots were higher ($0.000 < p < 0.011$) than those in tilled CONV plots. The only difference between OA systems was found under RT practices with higher ($p = 0.010$) TN stocks in OA-LEG RT at 20–30 cm depth compared to those in OA-MNR RT plots (Table 3).

3.6 | SOC and TN stocks on ESM basis

The SOC and TN stocks to 30-cm depth on ESM basis ranged from 47.0 to 61.9 Mg C ha^{-1} and from 6.4 to 9.4 Mg N ha^{-1}, respectively. Under RT practices, SOC stocks were higher in both OA-LEG and OA-MNR plots compared to CONV plots ($p = 0.007$ and $p = 0.010$, respectively). For TN stocks, both OA-LEG and OA-MNR plots under tillage had higher values compared to CONV plots ($p = 0.012$ and $p = 0.039$, respectively; Table 4).

4 | DISCUSSION

The FST was launched in 1981 to uniquely address the challenge of scientifically testing the benefits of OA in comparison to conventional systems, a significant challenge at that time. By implementing a randomized, replicated trial design, FST became a pioneering study that helped drive the OA movement. Initially conceived to validate the benefits of OA on soil health properties, the scope of this long-term study has expanded significantly. FST now explores not only soil health but also water quality, human health (through grain nutrient density and bioactive compounds), economic viability, and even broader environmental concerns like energy use, greenhouse gas emissions, and carbon footprint with respect to management systems, tillage treatments, cover crops, and crop rotations.

In this study, focusing specifically on SOC and TN, results show that after 34 years, there is a significant difference in

TABLE 3 Mean soil organic carbon (SOC; Mg C ha^{-1}) and total nitrogen (TN; Mg N ha^{-1}) stocks (± SD; $N = 16$) per depth increment to 30-cm depth after 34 years under conventional and organic farming systems (pairwise comparison between treatments; Mann–Whitney U-test, $p < 0.05$).

	Conventional		Organic legume		Organic manure	
	Tillage	Reduced tillage	Tillage	Reduced tillage	Tillage	Reduced tillage
0–10 cm						
SOC	21.1 ± 3.0B	20.0 ± 2.9B	21.4 ± 3.3C	21.2 ± 4.6C	25.2 ± 5.2BC	24.9 ± 4.4BC
TN	2.6 ± 0.3AB	3.0 ± 0.3	3.0 ± 0.3A	3.0 ± 0.7	3.4 ± 0.6B	3.2 ± 0.8
10–20 cm						
SOC	21.5 ± 2.9B	17.7 ± 2.4AB	23.0 ± 5.8	22.8 ± 3.1A	25.5 ± 4.8B	22.0 ± 5.0B
TN	2.7 ± 0.3AB	2.9 ± 0.2AB	3.4 ± 0.4A	3.2 ± 0.5A	3.5 ± 0.5B	2.9 ± 0.6B
20–30 cm						
SOC	10.8 ± 5.3	9.5 ± 2.9	11.9 ± 6.7	14.3 ± 7.3	11.1 ± 6.2	9.6 ± 5.1
TN	2.2 ± 0.3AB	2.4 ± 0.3B	2.6 ± 0.6A	2.6 ± 0.6C	2.6 ± 0.4B	2.0 ± 0.7BC

Note: Letter A indicates a significant difference between conventional and organic legume systems for the same tillage practice. Letter B indicates a significant difference between conventional and organic manure systems for the same tillage practice. Letter C indicates a significant difference between organic legume and organic manure systems for the same tillage practice.

TABLE 4 Mean soil organic carbon (SOC; Mg C ha^{-1}) and total nitrogen (TN; Mg N ha^{-1}) stocks (± SD; $N = 16$) in 0–30 cm depth on equivalent soil mass (ESM) basis after 34 years under conventional and organic farming systems (pairwise comparison between treatments; Mann–Whitney U-test, $p < 0.05$).

	Conventional		Organic legume		Organic manure	
	Tillage	Reduced tillage	Tillage	Reduced tillage	Tillage	Reduced tillage
SOC	53.3 ± 9.4	47.0 ± 6.4AB	56.2 ± 14.1	57.8 ± 11.9A	61.9 ± 12.7	56.4 ± 10.7B
TN	7.7 ± 0.7AB	6.4 ± 0.5	8.9 ± 1.0A	8.8 ± 1.5	9.4 ± 1.3B	8.0 ± 1.8

Note: Letter A indicates a significant difference between conventional and organic legume systems for the same tillage practice. Letter B indicates a significant difference between conventional and organic manure systems for the same tillage practice.

SOC and TN concentrations and stocks between systems. The OA-MNR system demonstrated higher SOC concentrations and stocks at the 0–10 and 10–20 cm soil depths compared to conventional systems, although stock differences were not statistically significant on an ESM basis at the 30-cm depth. These findings align with Blanco-Canqui et al. (2017). However, the results are a reflection of a single time point sampling in 2015, which may not capture the dynamic interannual variability in SOC and TN caused by interactions of climate and management practices. Soil properties have to be studied several times during multiple years to more accurately compare farming system effects with respect to interannual variability (e.g., Pearsons et al., 2023).

4.1 | Tilled conventional compared with tilled organic plots

The topsoil SOC concentrations improved in a consistent manner over the last 34 years. In 1981, SOC concentrations at 0–10 cm depth were not different between the systems (Table 5; Wander et al., 1994), but topsoil SOC concentrations in 2002 were higher in both OA-LEG and OA-MNR plots compared to those in CONV plots (Pimentel et al., 2005). In 2004, SOC concentrations at 0–20 and 20–40 cm depth in both OA systems were also higher compared to those in CONV (Hepperly et al., 2007), while SOC concentrations at 0–20 cm depth did not differ between systems in 2007 (Pearsons et al., 2023). In 2015 (this study), SOC concentrations at 0–10 and 10–20 cm depth in OA-MNR were higher than those in CONV, while those were not different between OA-LEG and CONV plots. While no statistical comparison is possible, SOC concentrations at 0–10 cm depth or topsoil in OA-MNR were consistently higher over the last 34 years compared to other systems and also compared to the beginning of the experiment. Large addition of organic matter through manure, improvement in soil aggregate stability, and microbial activity could have driven this improvement (Das et al., 2023). However, comparisons to previously reported data are often challenging as details on soil sampling including soil depth are sometimes missing (e.g., Hepperly et al., 2007; Pimentel et al., 2005).

The SOC accumulation demands an increase in C inputs. The net primary productivity and aboveground biomass in

TABLE 5 Soil organic carbon (g C kg^{-1}) and total nitrogen (g N kg^{-1}) concentrations at 0–10 cm depth for the tilled plots from previous studies compared to this study.

Farming system	1981		1990		2015	
	C	N	C	N	C	N
	(g kg^{-1})					
Conventional	22.3a	3.41a	21.3a	3.25a	24.4A	30AB
Organic legume	23.6a	2.87b	24.5b	3.42a,b	24.9B	35A
Organic manure	22.7a	3.31a,b	23.4a,b	3.50b	28.5AB	38B

Note: Data for 1981 and 1990 were from Wander et al. (1994). Different lowercase letters indicate statistical differences between systems based on Fisher-protected LSDs ($p < 0.05$). Letter A indicates a significant difference between conventional and organic manure systems. Letter B indicates a significant difference between organic legume and organic manure systems (pairwise comparison between treatments, Mann–Whitney U-test, $p < 0.05$). Drinkwater et al. (1998), Pimentel et al. (2005), and Hepperly et al. (2007) data not considered as soil depths were not provided.

1981–1995 were higher in CONV compared to both OA plots, and the amount of residue C returned to the soil was higher for CONV and OA-MNR compared to OA-LEG (Drinkwater et al., 1998). In the 22nd year of FST existence, Pimentel et al. (2005) reported that the annual net aboveground C input was the same in OA-LEG and CONV plots. Further, corn and soybean yields were not different between the systems in the first 27 years (Ryan et al., 2009). Thus, not quantitative but rather qualitative differences in organic inputs may contribute to the differences in SOC concentrations between systems. Composted manure additions at OA-MNR provided greater aboveground inputs of partially decomposed biomass with a larger proportion of manure-derived C retained in the soil compared to plant residues (Drinkwater et al., 1998; Maillard & Angers, 2014; Mirsky et al., 2012).

The TN concentrations at 0–10 cm depth/topsoil improved over the last 34 years. In 1981, TN concentrations at 0–10 cm depth were lower in OA-LEG compared to CONV but not different between OA-MNR and CONV (Table 5). In contrast, in 1990, TN concentrations at 0–10 cm depth were higher in OA-MNR compared to CONV but not different between OA-LEG and CONV. In 2002, topsoil TN concentrations were higher in both OA systems compared to the CONV system (Hepperly et al., 2007), while OA-MNR had higher TN concentrations at 0–20 cm depth compared to the CONV system in 2007, with concentrations for both being not different from OA-LEG (Pearsons et al., 2023). In 2015, TN concentrations at 0–10, 10–20, and 20–30 cm depths were higher in both OA systems compared to those under conventional practices. Inorganic N fertilizer input can largely increase TN, which might have been a primary reason for the initial years of CONV plots having higher TN concentrations. Eventually, the mineralization of organic compounds from manure and plant residues contributed to higher TN concentrations in the OA systems. This is true for the OA-LEG plots, where residue N inputs and credits from legumes and their higher belowground biomass might have contributed to the higher TN concentration at OA-LEG compared to those at CONV. Legumes contributed to soil fertility by buildup of N content in the topsoil in accordance with Gattinger et al. (2012). Qualitative differences in the form of N inputs and subsequent effects on internal N cycling likely also had an impact on long-term TN retention. Legume-derived rather than fertilizer-derived N may be immobilized in microbial biomass and SOM (Drinkwater et al., 1998). Qualitative differences in N inputs despite similar cumulative N additions may have also contributed to higher retention of manure N and contributed to higher TN concentrations in OA-MNR compared to CONV plots (Drinkwater et al., 1998). Composted manure consisted of 0.6% total N. Repeated applications of composted manure can enhance soil organic nitrogen (SON) concentration by up to 90% (Diacono & Montemurro, 2010). However, soil N input and output processes at the FST are not monitored.

The SOC and TN concentrations at 0–10 cm depth did not differ between both OA systems in 1981 and 1990 (Table 5), and this was also the case for topsoil concentrations in 2002 (Hepperly et al., 2007; Pimentel et al., 2005). At 0–20 and 20–40 cm depths, SOC concentrations did also not differ between both OA systems in 2004 (Hepperly et al., 2007). In 2015, the only difference between both OA systems was higher SOC concentrations at 0–10 cm depth in OA-MNR compared to OA-LEG plots. Thus, the OA-MNR rotation may be more effective compared to the OA-LEG rotation in enhancing SOC concentration at 0–10 cm depth, opposite to the suggestions by Wander et al. (1994). However, monitoring of soil C inputs, carbon losses, and SOC for several years is needed for a more accurate comparison of system effects.

No comparisons of SOC stocks between systems based on measurements of organic C concentrations and soil bulk density have been published previously for the FST plots. In 2015, SOC stocks at 0–10 and 10–20 cm depths were higher in OA-MNR compared to CONV but not different at 20–30 cm depth, and also not different between OA-LEG and CONV plots at all depths. As soil bulk density did not differ between the systems, the higher SOC stocks in OA-MNR can be explained by the higher SOC concentrations compared to CONV. A meta-analysis of 42 research articles totaling 49 sites and 130 observations globally reported a positive linear relationship between cumulative manure C input and SOC stock increase (Maillard & Angers, 2014). Among the reasons for the relatively greater retention of C added as composted manure at FST may be a larger proportion of chemically recalcitrant organic compounds in the composted manure (He et al., 2016). Manure and other organic amendments have also been shown to increase plant-available water (Eden et al., 2017), and, thus, crop yields may be higher in drought years (Pimentel et al., 2005). Overall, the OA-MNR but not the OA-LEG rotation may be more efficient compared to the CONV rotation in accumulating SOC at 0–10, 10–20, and 0–20 cm depths (Drinkwater et al., 1998). However, both OA systems accumulated more TN than the CONV system at all depths. As TN stocks did not differ between OA-LEG and OA-MNR, N additions with either legumes or manure appear to be more effective compared to mineral fertilizer N in enhancing TN stocks (Drinkwater et al., 1998).

There were no differences in SOC stocks on ESM basis between the systems, but TN stocks on ESM basis were higher for both OA systems compared to the CONV system. Thus, while differences in TN concentrations and stocks between the systems were consistent, changes in soil properties should be monitored several times in multiple years to assess the efficiency of each system in accumulating, maintaining, or depleting SOC and TN.

4.2 | Conventional compared with organic plots under RT

Soil data for the plots under RT management are discussed only briefly, as 7 years of RT may not be sufficient to reach a new steady-state equilibrium (Drinkwater et al., 1998), which would allow a more accurate comparison of RT effects on soil properties for CONV, OA-LEG, and OA-MNR plots.

In contrast to the tilled plots, RT was associated with higher SOC concentrations at all depths in OA-LEG compared to CONV plots. Similar to Cooper et al. (2016), a reduction in crop yield, that is, corn and soybean yield, was observed after RT was implemented in the OA-LEG plots (Pearsons et al., 2022). Whether this yield reduction affected soil C inputs is unclear. In contrast, the incidence of weeds and associated soil C inputs may be higher following a reduction in tillage intensity in OA systems (Cooper et al., 2016), but no data are available for the FST plots. For example, the wider OC:TN ratios in OA-LEG compared to CONV indicate that more fresh and less decomposed OM was present after switching to RT, and this may have contributed to an accumulation of SOC (Wander et al., 1994). Qualitative differences in plant species composition may have also contributed to differential retention of SOC (Drinkwater et al., 1998).

Similar to the tilled plots, SOC concentrations at 0–10 and 10–20 cm depths in OA-MNR under RT were higher than those in CONV also managed by RT. In addition to the positive effects of the OA-MNR rotation on SOC described above, the reduction in tillage-associated decomposition and SOC loss may have also contributed to SOC increases. Thus, the tendency toward lower crop yields (Pearsons et al., 2022) and associated reduced soil C inputs was more than compensated. That SOM was less decomposed was also indicated by the wider OC:TN ratios in OA-MNR compared to CONV.

Reduction in tillage intensity may have contributed to an increase in TN concentrations at 0–10 and 10–20 cm depth in OA-LEG compared to CONV. Long-term RT duration can lead to improved plant–soil interactions and better N-use efficiency (Daryanto et al., 2017). The changes in RT OA-MNR may be explained by higher N availability and, thus, plant uptake at the better structured soils. The phytoavailability of manure N is an active field of research (He et al., 2016). Otherwise, TN losses in RT OA-MNR may have been lower as indicated by decreased N leaching, as observed in the year 2019, compared to the RT CONV system (Melinda et al., 2019, personal communication). Cover crops particularly influence soil N and reduce nitrate leaching (Thapa et al., 2018).

Among the organic rotations, the main differences at the RT plots were higher TN concentrations at 10–20 and 20–30 cm depths in OA-LEG compared to OA-MNR. Higher N inputs by legumes may have contributed to this TN increase (Gattinger et al., 2012), while a reduction in tillage-associated TN loss may also have occurred. The initial effects of a reduction in tillage intensity were inconsistent regarding SOC and TN stocks in both OA systems compared to CONV. As changes in bulk density were also inconsistent, the plots need to be resampled several times over multiple years and re-assessed regarding their effects on SOC and TN stocks.

5 | LIMITATIONS

Among the limitations of this study was the assumption that no differences existed in soil profile properties between the plots before the establishment of FST. Baseline soil profile assessment before plot establishment would have been helpful for the interpretation of differences in SOC dynamics between the systems, specifically during the initial years to separate soil from management effects. A standard protocol to measure the initial SOC stock and its temporal changes, that is, soil sampling every 5 years, would have been helpful similar to the protocols designed for calculating soil C credits (Zhang et al., 2024).

FST was not designed to monitor changes in SOC stocks but to track the impact of different practices on the farm's economic viability and energy usage, the nutritional quality of the food produced, the health of the soil, and the water that flows through the systems. The FST study was also intended to measure the impact of these practices on the environment. To get a deeper insight into what factors mainly contributed to changes in the SOC stock, another improvement in the study design would be collecting data on temporal changes in the most important components of the net ecosystem carbon balance (NECB) or net biome production (NBP) of the croplands (Ciais et al., 2010). Ultimately, the fraction of NBP entering the soil determines the amount of organic C accruing in the soil (Schulze et al., 2010). The bulk of cropland net primary production (NPP) is allocated to the production of biomass in foliage, shoots, and roots. However, the biomass removed needs to be corrected. This includes harvest and herbivory by insects and mammals. In addition, other components of NPP are rarely measured such as weed production, seed production, emission of volatile organic compounds (VOCs) to the atmosphere, exudation from roots, and C transfer to root symbionts. The sum of all these components is the total cropland NPP. Data on soil heterotrophic respiration, the C flux of photosynthetic origin loss to hydraulic conduits and rivers, the loss to the atmosphere by fire disturbance, the harvested component of NPP, VOC the NPP component emitted as biogenic volatile compounds emissions to the atmosphere, and the flux of C exported from cropland ecosystems by erosion need to be subtracted from NPP, and the input to the soil, for example, via manure applications added for the calculation of the cropland NBP (Ciais et al., 2010). While some of the component data are available for some years for FST systems, for example, C input (Pearsons et al., 2023), more data for the most important NECB or NEB components, for example, root-, weed-, and cover crop-derived C inputs and C removal by harvest over the entire experimental period, would be helpful for the interpretation of differences in temporal changes in SOC stocks between the FST farming systems.

While farmers and growers may benefit from the observations made at the FST experiments and adjust on-farm practices, accordingly, augmenting the data collection at the long-term field experiments with on-farm data from commercial producer fields in the region would strengthen the conclusions regarding FST effects on the environment. St. Luce et al. (2024) emphasized that on-farm monitoring studies are needed for a more comprehensive assessment of SOC changes and C sequestration potentials as actual on-farm changes will depend on site-specific factors and specific agronomic practices. Space-for-time substitution, paired studies, and long-term monitoring of SOC stocks on commercial farms using a variety of systems can validate findings from long-term agricultural experiments and provide data for process-based model improvements (Ellis & Paustian, 2024).

6 | CONCLUSIONS

Agricultural land is increasingly getting converted from conventional to OA practices driven by increasing consumer demand for organic products. However, long-term experiments and studies on working farms are needed to verify whether and how this land-use management change affects soil profile properties. While this study revealed positive effects of OA on SOC concentrations and stocks at the FST especially in OA-MNR systems, these were confined to the top 0–20 cm depth of the soil profile based on a one point in time soil sampling in 2015. Given that long-term average crop yields were similar between OA and conventional systems, higher SOC concentrations in OA-MNR system were likely due to direct effects of composted manure C addition. Thus, the need for input of manure from outside the OA-MNR system to increase SOC should be addressed in subsequent studies. Also, whether deeper soil depths will benefit from composted manure addition in the future if at all would require continued monitoring for several decades.

7 | SUMMARY OF OBSERVATIONS IN SUBSEQUENT YEARS

Several research groups have collected soil samples at FST since 2015 and published data on some soil properties, although these are often averaged for tillage treatments in cropping system comparisons, which will not be discussed here (e.g., Alfahham et al., 2021; Littrell et al., 2021). However, Pearsons et al. (2023) determined soil health properties for 0–20 cm depth multiple times in 2019–2020 without averaging cropping systems and tillage treatments.

The total soil C concentration at 0–20 cm depth was higher in the tilled plots in the CONV and OA-MNR systems compared to the OA-LEG system, while those were not different between the CONV and OA-MNR systems. Further, total soil N concentration was higher in the CONV system compared to the OA-LEG systems, while both were not different from OA-MNR. In 2015, however, SOC concentrations at 0–10 and 10–20 cm depths in OA-MNR were higher than those in CONV, while those were not different between OA-LEG and CONV systems (Table 1). In the same year, TN concentrations at 0–10 and 10–20 cm depths were higher in both OA systems compared to those under conventional practices and under tillage. Among the reasons for the differences between studies may be the fact that soils were sampled only at one point in time in 2015, while those were sampled several times in 2019–2020 and analytical results were averaged. Thus, the conclusions regarding treatment effects on soil properties at the tilled plots by Pearsons et al. (2023) may be more accurate.

The preliminary results of Pearsons et al. (2023) regarding the comparison of tilled with RT plots suggested that soil health in OA systems was determined more by diversified crop rotations and adequate organic inputs than by reducing tillage frequency, whereas in conventional systems, other co-adapting soil health practices might be necessary to alleviate surface compaction and realize the full benefits of

RT. Although data are not directly comparable, Pearson et al. (2023) confirmed the beneficial effect of OA-MNR on SOM accumulation already indicated in 2015, while the effects of RT on FST treatments appear to be weak initially (Littrell et al., 2021).

AUTHOR CONTRIBUTIONS

Klaus Lorenz: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft. **Emmanuel Omondi**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing—review and editing. **Rattan Lal**: Conceptualization; funding acquisition; investigation; methodology; resources; software; supervision; validation; visualization; writing—review and editing. **Saurav Das**: Writing—review and editing. **Andrew Smith**: Funding acquisition; resources; writing—review and editing.

ACKNOWLEDGMENTS

Financial support from the Villum Kann Rasmussen Foundation (60047449) to the Carbon Management and Sequestration Center is gratefully acknowledged. We extend our gratitude to Peter Renz and Basant Rimal of the Carbon Management and Sequestration Center for their assistance with soil processing and analyses. We are grateful to Dr. Kristine Nichols, former Chief Scientist at Rodale Institute, for helping develop soil sampling protocols and providing professional support during project implementation. We also acknowledge Rodale Institute Research Department staff for their invaluable assistance with deep core soil sampling and processing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Emmanuel Omondi https://orcid.org/0000-0002-3870-0809

REFERENCES

Alfahham, A., Amato, M. T., Omondi, E., Giménez, D., & Plante, A. F. (2021). Assessing the impact of organic versus conventional agricultural management on soil hydraulic properties in a long-term experiment. *Soil Science Society of America Journal*, *85*, 2135–2148. https://doi.org/10.1002/saj2.20314

Beem-Miller, J. P., Kong, A. Y. Y., Ogle, S., & Wolfe, D. (2016). Sampling for soil carbon stock assessment in rocky agricultural soils. *Soil Science Society of America Journal*, *80*, 1411–1423. https://doi.org/10.2136/sssaj2015.11.0405

Blanco-Canqui, H., Francis, C. A., & Galusha, T. D. (2017). Does organic farming accumulate carbon in deeper soil profiles in the long term? *Geoderma*, *288*, 213–221. https://doi.org/10.1016/j.geoderma.2016.10.031

Borghino, N., Wissinger, L., Erb, K. H., Le Mouël, C., & Nesme, T. (2024). Organic farming expansion and food security: A review of foresight modeling studies. *Global Food Security*, *41*, Article 100765. https://doi.org/10.1016/j.gfs.2024.100765

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S. L., Don, A., Luyssaert, S., Janssens, I. A., Bondeau, A., Dechow, R., Leip, A., Smith, P. C., Beer, C., Van Der Werf, G. R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E. D., & CARBOEUROPE Synthesis Team. (2010). The European carbon balance. Part 2: Croplands. *Global Change Biology*, *16*, 1409–1428. https://doi.org/10.1111/j.1365-2486.2009.02055.x

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Döring, T. F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., … Mäder, P. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: A meta-analysis. *Agronomy for Sustainable Development*, *36*, Article 22. https://doi.org/10.1007/s13593-016-0354-1

Daryanto, S., Wang, L., & Jacinthe, P. A. (2017). Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: A meta-analysis. *Scientific Reports*, *7*, Article 12117. https://doi.org/10.1038/s41598-017-12383-7

Das, S., Litptzin, D., & Maharjan, B. (2023). Long-term manure application improves soil health and stabilizes carbon in continuous maize production system. *Geoderma*, *430*, Article 116338. https://doi.org/10.1016/j.geoderma.2023.116338

DeCicco, J. M., & Schlesinger, W. H. (2018). Reconsidering bioenergy given the urgency of climate protection. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 9642–9645. https://doi.org/10.1073/pnas.1814120115

Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. *Agronomy for Sustainable Development*, *30*, 401–422. https://doi.org/10.1051/agro/2009040

Dold, C., Hatfield, J. L., Sauer, T. J., Cambardella, C., & Wacha, K. M. (2018). Hydraulic deep-core sampling affects bulk density and carbon stock measurements. *Agricultural & Environmental Letters*, *3*, Article 180007. https://doi.org/10.2134/ael2018.02.0007

Drinkwater, L. E., Wagoner, M. W., & Sarrantonio, M. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature*, *396*, 262–265. https://doi.org/10.1038/24376

Eden, M., Gerke, H. H., & Houot, S. (2017). Organic waste recycling in agriculture and related effects on soil water retention and plant available water: A review. *Agronomy for Sustainable Development*, *37*, Article 11. https://doi.org/10.1007/s13593-017-0419-9

Ellert, B. H., & Bettany, J. R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, *75*, 529–538. https://doi.org/10.4141/cjss95-075

Ellis, E., & Paustian, K. (2024). Importance of on-farm research for validating process-based models of climate-smart agriculture. *Carbon Balance and Management*, *19*, Article 16. https://doi.org/10.1186/s13021-024-00260-6

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337–342. https://doi.org/10.1038/nature10452

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N. E.-H., & Niggli, U. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 18226–18231. https://doi.org/10.1073/pnas.1209429109

Ghabbour, E. A., Davies, G., Misiewicz, T., Alami, R. A., Askounis, E. M., Cuozzo, N. P., Filice, A. J., Haskell, J. M., Moy, A. K., Roach, A. C., & Shade, J. (2017). National comparison of the total and sequestered organic matter contents of conventional and organic farm soils. *Advances in Agronomy*, *146*, 1–35. https://doi.org/10.1016/bs.agron.2017.07.003

He, Z., Pagliari, P. H., & Waldrip, H. M. (2016). Applied and environmental chemistry of animal manure: A review. *Pedosphere*, *26*, 779–816. https://doi.org/10.1016/S1002-0160(15)60087-X

Hepperly, P., Seidel, R., Pimentel, D., Hanson, J., & Douds, D. (2007). Organic farming enhances soil carbon and its benefits. In J. M. Kimble, C. W. Rice, D. Reed, S. Mooney, R. F. Follett, & R. Lal (Eds.), *Soil carbon management: Economic, environmental and societal benefits* (pp. 129–153). CRC Press.

Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? *Soil Biology & Biochemistry*, *38*, 419–425. https://doi.org/10.1016/j.soilbio.2005.10.008

Johnston, A. E. (1997). The value of long-term field experiments in agricultural, ecological, and environmental research. *Advances in Agronomy*, *59*, 291–333. https://doi.org/10.1016/S0065-2113(08)60057-7

Kirchmann, H., Kätterer, T., Bergström, L., Börjesson, G., & Bolinder, M. A. (2016). Flaws and criteria for design and evaluation of comparative organic and conventional cropping systems. *Field Crops Research*, *186*, 99–106. https://doi.org/10.1016/j.fcr.2015.11.006

Kniss, A. R., Savage, S. D., & Jabbour, R. (2016). Commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. *PLoS ONE*, *11*, Article e0161673. https://doi.org/10.1371/journal.pone.0161673

Lal, R., Lorenz, K., Hüttl, R., Schneider, B. U., & von Braun, J. (Eds.). (2012). *Recarbonization of the biosphere*. Springer.

Lal, R., Lorenz, K., Hüttl, R., Schneider, B. U., & von Braun, J. (Eds.). (2013). *Ecosystem services & carbon sequestration in the biosphere*. Springer.

Liptzin, D., Norris, C. E., Cappellazzi, S. B., Bean, G. M., Cope, M., Greub, K. L. H., Rieke, E. L., Tracy, P. W., Aberle, E., Ashworth, A., Tavarez, O. B., Bary, A. I., Baumhardt, R. L., Gracia, A. B., Brainard, D. C., Brennan, J. R., Reyes, D. B., Bruhjell, D., Carlyle, C. N., … Honeycutt, C. W. (2022). An evaluation of carbon indicators of soil health in long-term agricultural experiments. *Soil Biology and Biochemistry*, *172*, Article 108708. https://doi.org/10.1016/j.soilbio.2022.108708

Liptzin, D., Rieke, E. L., Cappellazzi, S. B., Bean, G. M., Cope, M., Greub, K. L. H., Norris, C. E., Tracy, P. W., Aberle, E., Ashworth, A., Tavarez, O. B., Bary, A. I., Baumhardt, R. L., Gracia, A. B., Brainard, D. C., Brennan, J. R., Reyes, D. B., Bruhjell, D., Carlyle, C. N., … Honeycutt, C. W. (2023). An evaluation of nitrogen indicators for soil health in long-term agricultural experiments. *Soil Science Society of America Journal*, *87*, 868–884. https://doi.org/10.1002/saj2.20558

Littrell, J., Xu, S., Omondi, E., Saha, D., Lee, J., & Jagadamma, S. (2021). Long-term organic management combined with conservation tillage enhanced soil organic carbon accumulation and aggregation. *Soil Science Society of America Journal*, *85*, 1741–1754. https://doi.org/10.1002/saj2.20259

Lorenz, K., & Lal, R. (2018). *Carbon sequestration in agricultural ecosystems*. Springer.

Lorenz, K., & Lal, R. (2023). *Organic agriculture and climate change*. Springer Nature Switzerland AG.

Lori, M., Kundel, D., Mäder, P., Singh, A., Patel, D., Sisodia, B. S., Riar, A., & Krause, H. M. (2024). Organic farming systems improve soil quality and shape microbial communities across a cotton-based crop rotation in an Indian Vertisol. *FEMS Microbiology Ecology*, *100*, Article fiae127. https://doi.org/10.1093/femsec/fiae127

Maillard, É., & Angers, D. A. (2014). Animal manure application and soil organic carbon stocks: A meta-analysis. *Global Change Biology*, *20*, 666–679. https://doi.org/10.1111/gcb.12438

Mirsky, S. B., Ryan, M. R., Curran, W. S., Teasdale, J. R., Maul, J., Spargo, J. T., Moyer, J., Grantham, A. M., Weber, D., Way, T. R., & Camargo, G. G. (2012). Conservation tillage issues: Cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. *Renewable Agriculture and Food Systems*, *27*, 31–34. https://doi.org/10.1017/S1742170511000457

Moyer, J. (2013). Perspective on Rodale Institute's Farming Systems Trial. *Crop Management*, *12*, 1–3. https://doi.org/10.1094/CM-2013-0429-03-PS

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil*, *5*, 15–32. https://doi.org/10.5194/soil-5-15-2019

Pearsons, K. A., Omondi, E. C., Heins, B. J., Zinati, G., Smith, A., & Rui, Y. (2022). Reducing tillage affects long-term yields but not grain quality of maize, soybeans, oats, and wheat produced in three contrasting farming systems. *Sustainability*, *14*, Article 631. https://doi.org/10.3390/su14020631

Pearsons, K. A., Omondi, E. C., Zinati, G., Smith, A., & &Rui, Y. (2023). A tale of two systems: Does reducing tillage affect soil health differently in long-term, side-by-side conventional and organic agricultural systems? *Soil & Tillage Research*, *226*, Article 105562. https://doi.org/10.1016/j.still.2022.105562

Peters, S., Wander, M., Saporito, L., Harris, G., & Friedman, D. (1997). Management impacts on SOM and related soil properties in a long-term farming systems trial in Pennsylvania: 1981–1991. In E. Paul, K. Paustian, E. Elliott, & C. Cole (Eds.), *Soil organic matter in temperate agroecosystems: Long-term experiments in North America* (pp. 183–204). CRC Press.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., & Seidel, R. (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience*, *55*, 573–582. https://doi.org/10.1641/0006-3568(2005)055[0573:EEAECO]2.0.CO;2

Poeplau, C., & Don, A. (2013). Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma*, *192*, 189–201. https://doi.org/10.1016/j.geoderma.2012.08.003

Reganold, J. P. (2009). Comparison of soil properties as influenced by organic and conventional farming systems. *American Journal of Alternative Agriculture*, *3*, 144–155. https://doi.org/10.1017/S0889189300002423

Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, *2*, Article 15221. https://doi.org/10.1038/NPlants.2015.221

Ryan, M. R., Smith, R. G., Mortensen, D. A., Teasdale, J. R., Curran, W. S., Seidel, R., & Shumway, D. L. (2009). Weed–crop competition relationships differ between organic and conventional cropping systems. *Weed Research*, *49*, 572–580. https://doi.org/10.1111/j.1365-3180.2009.00736.x

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 9575–9580. https://doi.org/10.1073/pnas.1706103114

Schulze, E. D., Ciais, P., Luyssaert, S., Schrumpf, M., Janssens, I. A., Thiruchittampalam, B., Theloke, J., Saurat, M., Bringezu, S., Lelieveld, J., Lohila, A., Rebmann, C., Jung, M., Bastviken, D., Abril, G., Grassi, G., Leip, A., Freibauer, A., Kutsch, W., … Dolman, A. J. (2010). The European carbon balance. Part 4: Integration of carbon and other trace-gas fluxes. *Global Change Biology*, *16*, 1451–1469. https://doi.org/10.1111/j.1365-2486.2010.02215.x

Seufert, C. (2019). Comparing yields: Organic versus conventional agriculture. In P. Ferranti, E. M. Berry, & J. R. Anderson (Eds.), *Encyclopedia of food security and sustainability* (Vol. 3, pp. 196–208). Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.22027-1

St Luce, M., McConkey, B., Schoenau, J., Brandt, K., Hangs, R., & Zhang, H. (2024). Impacts of conservation agriculture on soil C and N stocks and organic matter fractions: Comparing commercial producer fields with a long-term small-plot experiment in Brown Chernozems of Saskatchewan. *Canadian Journal of Soil Science*, *104*, 2083–301. https://doi.org/10.1139/cjss-2023-0118

Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. *Journal of Environmental Quality*, *47*, 1400–1411. https://doi.org/10.2134/jeq2018.03.0107

Wander, M., Traina, S., Stinner, B., & Peters, S. (1994). Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal*, *58*, 1130–1139. https://doi.org/10.2136/sssaj1994.03615995005800040018x

Zhang, K., Liu, Z., McCarl, B. A., & Fei, C. J. (2024). Enhancing agricultural soil carbon sequestration: A review with some research needs. *Climate*, *12*, Article 151. https://doi.org/10.3390/cli12100151

How to cite this article: Lorenz, K., Omondi, E., Lal, R., Das, S., & Smith, A. (2025). Soil organic carbon and total nitrogen after 34 years under conventional and organic management practices at the Rodale Institute Farming Systems Trial. *Soil Science Society of America Journal*, *89*, e70000. https://doi.org/10.1002/saj2.70000