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Cropping-system diversification drives long-term soil carbon gains more strongly than reduced tillage

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Abstract

Long-term measurements across the soil profile are essential for understanding how agricultural management affects soil organic carbon (SOC) storage, accumulation, and vertical distribution. We analyzed a 40-year record (1984–2023) from the Farming Systems Trial in Pennsylvania, USA, comparing conventional (CNV), legume-based organic (LEG), and manure-based organic (MNR) cropping systems. Seven sampling events were used to evaluate long-term surface SOC trajectories, three campaigns included the complete 0 – 100 cm soil profile, and full- and reduced-tillage treatments were compared from 2008 onward. Surface SOC increasingly diverged among cropping systems over time (system × year: $\chi^2 = 35.0$, $P < 0.001$). By 2023, SOC concentrations in the 0–20 cm layer were 2.46% in MNR, 2.30% in LEG, and 1.92% in CNV. Equivalent-soil-mass-corrected SOC stocks were 70.3, 65.7, and 54.7 Mg C ha^{-1}, respectively, corresponding to gains of 15.6 Mg C ha^{-1} in MNR and 11.0 Mg C ha^{-1} in LEG relative to CNV. Across the full 1 m profile, MNR and LEG stored 119.0 and 108.9 Mg C ha^{-1}, respectively, compared with 92.9 Mg C ha^{-1} under CNV. The effect of cropping system varied strongly with soil depth (system × depth: $\chi^2 = 77.9$, $P < 0.001$). In both 2021 and 2023, 91 – 94% of the additional SOC stored under the organic systems occurred within the upper 30 cm. Permanganate-oxidizable carbon followed the same vertical pattern, indicating that both total SOC and management-responsive carbon increased primarily within the surface and transition layers. Cropping-system diversification and organic inputs had a substantially greater influence on SOC than tillage intensity, which had no significant overall or system-dependent effect. These findings show that diversified organic cropping systems can produce substantial and persistent SOC gains over four decades. Full-profile sampling combined with equivalent-soil-mass accounting also clarifies where those gains occur, providing a stronger basis for evaluating agricultural soil-carbon storage.

Keywords: Soil Organic Matter, Deep Soil, Soil Carbon, Farming Systems Trial

1.0 Introduction

Soil organic carbon (SOC) represents the largest actively cycling terrestrial carbon reservoir, holding approximately three times more carbon (C) than the entire atmosphere (Das et al., 2025). Agricultural conversion and intensive crop production have been primary drivers of global SOC depletion; and since the dawn of agriculture, approximately 116 Petagrams (Pg) of carbon (C) have been lost from the world's soils (Sanderman et al., 2017). Conversion of natural ecosystems

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to cropland generally reduces SOC stocks in mineral soils, with reported losses commonly ranging from ~20–40% or more depending on climate, soil type, soil depth, original vegetation, and management history. These losses transfer soil C to the atmosphere primarily as CO_2 and degrade the physical, biological, and chemical functions supported by SOC, including water retention, aggregate stability, nutrient cycling, and biological activity (Don et al., 2011; Minasny et al., 2017). The imperative to rebuild depleted agricultural SOC stocks is now framed both as a climate mitigation strategy and as a prerequisite for long-term food and environmental security. Croplands worldwide are estimated to hold a sequestration potential of 0.90 – 1.85 Pg C yr^{-1} under improved management, representing 26 – 53% of the "4 per mile" global target established at COP21 for annual SOC stock increases (Minasny et al., 2017; Padarian et al., 2022; Zomer et al., 2017). Achieving even a fraction of this potential requires identifying which agricultural management systems accumulate SOC over decadal time scales, and whether the C that accumulates is distributed throughout the soil profile relevant to both permanence and climate accounting since surface C turns over more rapidly. Both questions can best be answered by long-term agricultural field experiments that have maintained consistent treatments for decades under replicated, side-by-side comparison (Das et al., 2023; Kimble et al., 2007; Lorenz and Lal, 2023a).

Organic farming has sustained scientific and policy interest as a management approach that rebuilds SOC. By excluding synthetic nitrogen (N) fertilizers and relying on biologically fixed N, organic amendments, and diverse crop rotations, organic systems redirect the quantity, quality, and distribution of organic inputs to the soil in ways that favor C accumulation (García-Palacios et al., 2018; Gattinger et al., 2012a; Littrell et al., 2021). A landmark meta-analysis by Gattinger et al., (2012) found that organic management increased higher topsoil SOC stocks than conventional management across 74 paired studies, with mean increase in SOC approximately 3.5 Mg C ha^{-1}. By 2023, approximately 98.9 million hectares were managed organically worldwide, 2.1 % of global agricultural land, representing a near-tripling of organic area over the past two decades (The world of Organic Agriculture 2025 : Latest Statistics About Organic Agriculture Worldwide, 2026). As this expansion continues, robust quantification of the SOC outcomes of organic systems, including their depth distribution and long-term trajectory, becomes increasingly important for science, policy, and carbon accounting.

Two descriptions of the existing literature limits the confidence with which these findings can be applied to management practices. First, most published comparisons include fewer than 20 years of management (Lorenz et al., 2025), and there is evidence that organic – conventional SOC differences compound over time in ways that shorter trials cannot reveal (Gattinger et al., 2012b; Lorenz and Lal, 2023b; Lori et al., 2024). Second, the majority of studies report SOC only to 0 – 20 or 0 – 30 cm (von Haden et al., 2020a; Rui et al., 2022; Woodings and Margenot, 2023), leaving open the critical question of whether organic management enriches the deeper profile with direct implications for the permanence and climate-relevance of C gains. Subsoils below 30 cm store approximately 55% of global SOC to 1 m depth, and deep soil C can persist for centuries owing to mineral associations and slow organic matter turnover (Rumpel and

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Kögel-Knabner, 2011). Current measurements, reporting, and verification (MRV) protocols for agricultural carbon typically require sampling to only 30 cm, and deep profile data from long-term organic farming trials remain sparse.

Tillage intensity adds a further layer of complexity. The introduction of reduced or no-till practices has been advocated as an additional lever for C sequestration within both organic and conventional systems, but meta-analyses that account for full-profile sampling have found that no-till often redistributes carbon toward the surface without increasing whole-profile stocks, with net effects approaching zero within approximately 14 years of adoption (Cai et al., 2022; Luo et al., 2010a). Whether tillage adds to, or is simply secondary to, the system-level SOC outcomes of organic management has rarely been tested within a single controlled, long-term experiment where both factors vary simultaneously.

The Farming Systems Trial (FST) at the Rodale Institute, established in 1981 in Kutztown, Pennsylvania, USA, is the longest continuously running side-by-side comparison of conventional and organic grain-based cropping systems in North America. With three systems: conventional agrochemical-based (CNV), low input legume-based organic (LEG), and manure-based organic (MNR), with tillage treatments -full tillage (FT) and reduced tillage (RT)- introduced in 2008, the FST offers a uniquely comprehensive platform for comparing the long-term, depth-resolved, and tillage-modified SOC outcomes of organic management. Prior work at the FST has documented higher SOM and biological activity under organic management (Hepperly et al., 2007; Littrell et al., 2021; Lorenz et al., 2025), but the SOC record has not previously been examined across the full 0 – 100 cm profile with equivalent soil mass (ESM) correction across multiple deep-core samples, nor has the depth distribution of the organic-system carbon advantage been resolved.

This study reports SOC dynamics from seven sampling events from 1984 to 2023 for a depth of 0 – 100 (and 0 – 80 cm for early year 1984 to 2008 & 0 -100 cm for 2018, 2021, 2023). The specific objectives were: (1) to characterize the long-term trajectory of surface SOC across the three systems from 1984 to 2023; (2) to determine whether the organic-system SOC advantage extends into the subsoil below 30 cm and to quantify the distribution of C across depth; (3) to evaluate the effect of reduced tillage and its interaction with cropping system on surface SOC stocks; and (4) to use permanganate-oxidizable carbon (POX – C) as independent indicators of the depth dependence of management effects on the labile carbon fraction.

2. Materials and Methods

2.1 Study site and experimental design

This study used historical soil C data from the Rodale Institute Farming Systems Trial (FST), a long-term field experiment established in 1981 near Kutztown, Pennsylvania, USA. The FST compares organic and conventional grain production systems under field-scale management. The site is located at the Rodale Institute main campus in southeastern Pennsylvania and has a humid, temperate climate. Soil is silt loam in the Oxyaquic Fragiudalf great group, with mapping units described as Clarksburg. The experiment was originally established as a randomized complete

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block design (RCBD) with eight replicated blocks. Prior to 2008, the trial consisted of three cropping systems: conventional (CNV), legume-based organic (LEG), and manure-based organic (MNR). Each system plot measured approximately 18 × 92 m and was sub-divided into three rotation-entry subplots making each plot size approximately 6 × 92 m. Each entry point allows different phases of each crop rotation to be analyzed in a single year. Grass buffer strips (5ft in width) separate plots to minimize cross-treatment movement of soil, residues, fertilizers, pesticides, and weed seeds.

From 1981 through 2007, all systems were managed under full tillage. In 2008, four of the eight replicate blocks were converted to reduced tillage (RT) management, while the remaining four blocks continued under full tillage (FT). Thus, the post-2008 design included two tillage treatments, FT and RT, crossed with the three cropping systems (CNG, LEG, and MNR).

2.2 Cropping systems

The three cropping systems differed in rotation length, nitrogen source, cover-crop use, crop diversity, and reliance on external inputs. The CNV system represented a chemically intensive grain production system, with fertility supplied primarily through inorganic N fertilizers and weed management based on synthetic herbicides. The LEG system represented a low-input organic cash-grain system, with nitrogen supplied primarily through leguminous cover crops and rotation-based nutrient cycling. The MNR system represented an organic grain–forage system, with N and C inputs supplied through leguminous cover crops, a perennial hay phase, and periodic composted dairy manure applications [twice in the 9-year rotation, year 1 and year 7 after the three years of hay phase at 18 tons/acre].

The LEG system followed a mid-length (4-years rotation) organic grain rotation including maize, oats, soybean, wheat, and leguminous cover crops. The MNR system followed a longer (9-years rotation) and more diversified rotation including maize, soybean, small grains, maize silage, and a multi-year hay phase (Table 1). Both organic systems were managed without synthetic fertilizers or pesticides. Where historical management records indicate limited non-N mineral amendments, such as potassium sulfate, these inputs were considered part of the system management history but not treated as primary nitrogen sources. Conventional system followed a typical intensive grain production system with 3-years rotation of maize and soybean.

Table 1. Farming Systems Trial (FST) rotation plan.

Systems	Year of Rotation	Rotation
Organic – Manure (MNR)	9	oats/rye–soybean/wheat–wheat/hay–hay–hay–hay–maize silage/wheat–wheat/vetch–maize/rye
Organic – Legume (LEG)	4	maize/rye–oats+clover/rye–soybean/wheat–wheat/vetch
Conventional (CNV)	3	maize–maize–soybean

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2.3 Tillage treatments

Before 2008, all plots were managed under FT. In the conventional system, FT generally involves chisel plowing followed by disk, harrow, and packing, for seedbed preparation. In the organic systems, full tillage involved moldboard plowing followed by disk, harrow, and packing, and secondary cultivation (tine weeding) as needed based on the weed density during early season. Beginning in 2008, reduced tillage (RT) was implemented differently across systems, reflecting realistic management constraints in conventional and organic production. In CNV, RT was implemented as herbicide-based no-till management. In LEG and MNR, RT was implemented as cover-crop-based rotational no-till, in which maize and soybean were direct-seeded into roller-crimped cover-crop residues using no-till seed drill, while small grains and cover crops still required occasional tillage for establishment. Therefore, the tillage treatment represents a functional system-specific tillage strategy rather than a mechanically identical operation across systems. The system × tillage interaction was interpreted with this management distinction in mind. Because tillage was not an experimental factor prior to 2008, tillage-effect analyses were restricted to post-2008 sampling campaigns (Pearsons et al., 2023).

2.4 Soil sampling and historical data compilation

Soil data were compiled from seven sampling events including, 1984, 2004, 2006, 2008, 2018, 2021, and 2023. Sampling depth increments differed among each sampling event because of changes in sampling objectives, equipment, and analytical priorities across the 40-year study period. The 1984 sampling included 0–10, 10–20, 20–30, 30–65, and 65–100 cm increments. The 2004 sampling included 0–20, 20–40, 40–60, and 60–80 cm increments. The 2006 and 2008 campaigns included 0–5, 5–10, 10–20, 20–30, 30–60, and 60–80 cm increments. The 2018, 2021, and 2023 sampling used a common five-layer deep-core profile: 0–10, 10–20, 20–30, 30–60, and 60–100 cm.

2.5 Laboratory measurements

The analytical variables available differed among sampling campaigns. Soil organic matter (SOM) was measured by loss-on-ignition (LOI) in 1984, 2006, 2008, 2018, 2021, and 2023. Total carbon (TC) was measured by dry combustion in 2004, 2006, 2008, 2018, 2021, and 2023. Combustion C measurement was not available for 1984, and LOI was not available for 2004. From 2006 onward, both LOI and combustion carbon were available, allowing cross-method comparison. Permanganate-oxidizable carbon (POXC) was measured for the 2021, and 2023 deep-core samples at 0–10, 10–20, 20–30, 30–60, and 60–100 cm. Dry-combustion total carbon was interpreted as SOC because the FST soils are non-calcareous or expected to contain negligible inorganic C.

2.6 Primary carbon metric and cross-campaign comparability

The primary response variable was dry-combustion SOC concentration, expressed as percent C. SOC concentration was used as the primary basis for cross-year comparison because it was less

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sensitive than LOI organic matter to methodological artifacts associated with furnace conditions, ignition duration, clay-bound water loss, and a laboratory- and year-specific OM:C conversion factor. In this dataset, the OM:C ratio at the surface varied from 1.72 to 2.01 across sampling years. LOI-based SOM was retained as a supporting variable for the 0 – 20 cm temporal series because it was the only measurement available at the 1984 baseline and remains the metric most familiar to the soil-health literature and interpretation. Measured LOI was used directly where available (1984, 2006, 2008, 2018, 2021, 2023); for 2004, where LOI was not measured, SOM was derived as SOC × 1.72. All other quantitative analyses, system contrasts, depth-profile analyses, SOC stocks, and ESM corrections used measured combustion C only. Below 30 cm, LOI was not used for inference, because OM:C ratios at depth were consistently unstable, consistent with known LOI overestimation from non-organic mass loss in deeper, clay-rich horizons.

2.7 Bulk density and SOC stock calculation

Bulk density (BD) was not measured in every sampling year. Rather than applying a single fixed-year reference across the 40-year record, BD was assigned from direct measurement in two representative years from the pre- and post-tillage-split periods. For samplings before the 2008 tillage split (1984, 2004, 2006, 2008), BD was taken from three-core composite samples collected in 2004, measured for all three systems across four depth increments (0–20, 20–40, 40–60, 60–80 cm). For samplings after the tillage split (2018, 2021, 2023), BD was taken from Giddings-probe cores collected in 2023, measured for all three systems across the full five-layer profile (0–10, 10–20, 20–30, 30–60, 60–100 cm). SOC stock (Mg C ha^{-1}) for each measured layer was calculated as:

$$SOC_{stock} = SOC\ (\%)\ x\ BD\ (g\ cm^{-3})\ x\ layer\ thikness\ (cm)\ x\ 100$$

Rotation-entry subplots within a block were averaged before zone summation to avoid pseudo-replication. Zone stocks were summed only from layers fully covering the target depth interval; no extrapolation across unsampled intervals was performed.

2.8 Equivalent soil mass correction

SOC stocks were corrected to an equivalent soil mass (ESM) basis to minimize bias caused by differences in bulk density among systems (Ellert and Bettany, 1995; von Haden et al., 2020b). At a fixed sampling depth, soil with lower bulk density contains less mineral soil mass than soil with higher bulk density; therefore, it can contain less carbon per unit area even when carbon concentration is identical. ESM correction accounts for this difference by expressing SOC stocks relative to common soil mass. For each depth zone, year, and system, ESM-corrected SOC stock was calculated as:

$$SOC_{ESM} = SOC_{fixed\ depth}\ x\ (\frac{M_{CNV}}{M_{system}})$$

Where $SOC_{fixed\text{-}depth}$ is the SOC stock calculated for the sampled fixed-depth interval, M_{CNV} is the mean soil mass of the conventional system for that depth zone and year, and M_{system} is the soil mass of the system being corrected. The conventional system was used as the reference because

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it consistently had the highest surface bulk density. The correction was applied independently within each depth zone.

2.9 Depth harmonization

For analysis requiring a common surface layer across all seven sampling events, depth increments within the upper 20 cm were combined into a single thickness-weighted mean per plot:

$$SOC_{zone} = \frac{\Sigma(SOC_i \, x \, thickness_i)}{\Sigma(thickness_i)}$$

Depth-distributed soil profile analyses were restricted to the three sampling events sharing an identical five-layer profile to 100 cm (2018, 2021, 2023); earlier sampling events used different depth increments that could not be harmonized to this same depth profiles without extrapolating across unsampled intervals and were therefore excluded from depth-resolved analysis. For profile summaries, the five layers were additionally grouped into a surface zone (0 – 20 cm), a transition zone (20 – 30 cm), and a subsoil zone (30 – 100 cm).

2.10 Quality assurance and quality control

The compiled dataset was screened with a rule-based procedure applied uniformly to all records. Records were removed when measured combustion C exceeded LOI-based organic matter (physically implausible under non-calcareous conditions, indicating instrument or data-entry error), or when C and N were jointly near zero despite appreciable LOI organic matter (indicating a failed or contaminated combustion run). Records were flagged but retained when deep-layer OM:C ratios fell outside plausible surface ranges, since this reflects expected LOI behavior at depth rather than sample failure, and was handled analytically by restricting deep inference to combustion carbon. Fifteen records from the 2006 campaign, representing whole-profile composite samples with organic matter far exceeding any mineral-soil increment, were identified as an incompatible sample type and excluded from all depth-resolved analyses. Bulk density values were likewise screened for physical plausibility given soil texture and cross-checked for depth-interval consistency with the paired SOC measurement.

2.11 Statistical analysis

All statistical analyses were performed in R (version 4.3) using the lme4 package for mixed-effects models and emmeans for estimated marginal means. Treatment effects were estimated with linear mixed-effects models fitted by maximum likelihood, with blocks as a random intercept throughout. The significance of fixed effects and interactions was assessed by likelihood-ratio tests comparing nested models. Rotation- entry subplots were averaged within each block × system (× tillage, where relevant) × year combination before analysis, to avoid pseudo-replication across entries. Statistical significance was evaluated at $\alpha = 0.05$. Two classes of pairwise comparison were used and are labeled accordingly wherever reported. Within-year contrasts among the three systems (section 3.1) used Tukey-adjusted comparisons of estimated

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marginal means from the corresponding mixed model. All other pairwise contrasts within-depth system contrasts (section 3.2), within-system tillage contrasts (section 3.3), and the depth-partitioned decomposition (section 3.2) used unadjusted Welch two-sample t-tests. The long-term surface trajectory (section 3.1) was modeled as SOC (& SOM) concentration and ESM-corrected stock, each as a function of system, year, and their interaction, with block as a random intercept. Depth analyses (section 3.2), restricted to 2018, 2021, and 2023, modeled SOC concentration and active carbon as functions of system, depth, year, and the system × depth interaction, with system contrasts estimated within each depth interval. Tillage analyses (section 3.3), restricted to the same three post-split samples (2018, 2021, 2023), modeled ESM-corrected surface stock as a function of system, tillage, year, and the system × tillage interaction, with block as the experimental unit for tillage inference since tillage was assigned at the block level; within-system FT-versus-RT contrasts were additionally tested at each depth to assess whether a tillage effect was localized within the profile. Treatment effects are reported throughout as both absolute differences (Mg C ha^{-1} for stocks) and relative differences (%) from the conventional system, alongside the associated test statistic and P-value.

3. Results

3.1 Long-term divergence of surface carbon among cropping systems

At the 1984 baseline, surface (0 – 20 cm) SOM did not differ among the three cropping systems, averaging 2.06 % under conventional management, 2.26 % under the legume system, and 2.22 % under the manure system. From this common starting point, the systems diverged markedly over the following four decades (Figure 1a). By 2023, surface SOC concentration averaged 2.46 ± 0.07 % under the MNR system and 2.30 ± 0.08 % under the LEG system, compared with 1.92 ± 0.11 % under CNV management (Figure 1b), corresponding to surface SOM values of 4.70%, 4.56%, and 4.02%, respectively (Figure 1a). Cropping system was the dominant control on surface SOC across the record (system effect: $\chi^2 = 38.1$, df = 2, $P < 0.001$), and the three systems did not accumulate carbon in parallel (system × year interaction: $\chi^2 = 35.0$, df = 10, $P < 0.001$). Both organic systems differed significantly from conventional in 2004, 2006, 2008, 2021, and 2023 (Tukey-adjusted $P < 0.05$), whereas the two organic systems never differed significantly from each other in any year. The only exception was 2018, when no system differed significantly from the others. Because this one data point interrupts an otherwise consistent ranking across six samplings and four decades, and because the same pattern appeared in both SOC concentration and SOM, we attribute it to interannual or rotation-phase variation at sampling rather than to a genuine convergence of the systems. SOC stocks (0 – 20 cm, ESM-corrected) followed the same trajectory as concentration. Cropping system drove stock differences significantly across the record ($\chi^2 = 36.5$, df = 2, $P < 0.001$; system × year: $\chi^2 = 35.3$, df = 10, $P < 0.001$). By 2023, the manure and legume systems held 70.3 ± 2.1 and 65.7 ± 2.2 Mg C ha^{-1} in the 0 – 20 cm layer, respectively, against 54.7 ± 3.2 Mg C ha^{-1} under conventional management, a surplus of +15.6 Mg C ha^{-1} ($P = 0.002$) and +11.0 Mg C ha^{-1} ($P = 0.015$).

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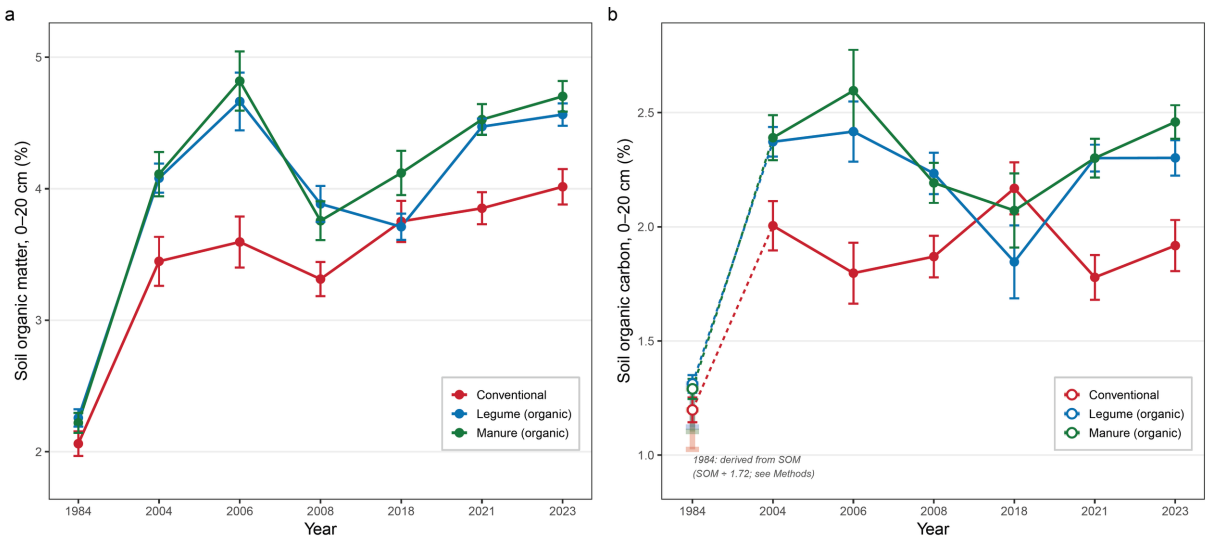

Figure 1. *Surface soil carbon trajectory, 1984–2023. (a) Soil organic matter (SOM, %; loss-on-ignition), 0–20 cm. (b) Soil organic carbon (SOC, %; dry-combustion), 0–20 cm. Points are system means (conventional, red; legume-organic, blue; manure-organic, green) ± SEM. In (b), the 1984 point (dashed line) is derived from SOM (÷1.72), not directly measured.*

3.2 Depth distribution of soil organic carbon

Depth advantage of the systems was tested using data from 2018, 2021, 2023, which were sampled to 100 cm. The effect of system on SOC concentration depended strongly on depth (system × depth interaction: $\chi^2 = 77.9$, df = 8, $P < 0.001$), results showed that management effects were pronounced near the surface and diminished sharply with depth (Figure 2). The organic-system advantage was largest at 10 – 20 cm, where the legume and manure systems held 32% (+0.53%) and 37% (+0.61%) more carbon than conventional, respectively (both $P < 0.001$). A significant advantage persisted into the 20 – 30 cm transition zone for both organic systems (legume: relative difference with CNV = +27 %, absolute difference with CNV = +0.22 %, P = 0.02; manure: relative difference with CNV = +50 %, absolute difference with CNV = +0.41 %, $P < 0.001$), but below 30 cm the three systems were statistically indistinguishable. All three converged on approximately 0.29 – 0.33 % SOC at 30 – 60 cm and 0.19 – 0.20 % at 60–100 cm, with no significant pairwise differences at either depth (Figure 2).

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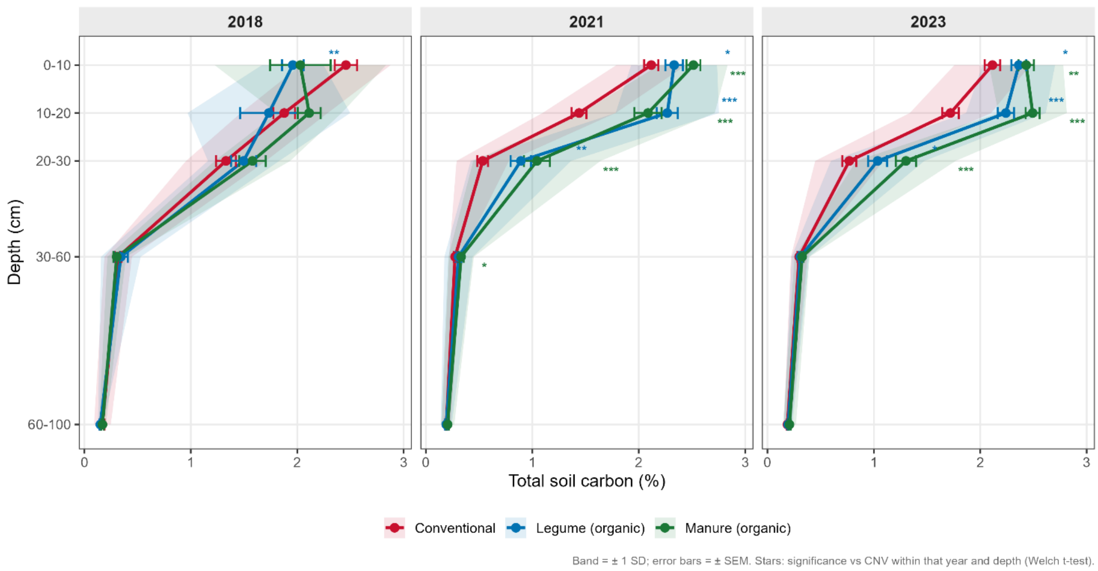

Figure 2. *Depth profiles of total soil carbon by cropping system, 2018, 2021, and 2023. Total soil carbon (%) by depth for conventional (red), legume-organic (blue), and manure-organic (green) systems (n = 8 blocks/system). Bands show ± 1 SD; error bars show ± SEM. Asterisks mark significant difference from conventional within that year and depth (Welch t-test: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).*

The same pattern emerged from zone-level stock comparisons (Table 2). In 2023, ESM-corrected SOC stocks under organic management exceeded conventional by +11.0 and +15.6 Mg C ha^{-1} in the 0 – 20 cm zone (legume P = 0.015 and manure P = 0.002) and by +4.0 and +8.0 Mg C ha^{-1} in the 20–30 cm zone (legume P = 0.08; manure P = 0.003). At 30–60 cm and 60–100 cm, no system differed significantly from conventional in either 2021 or 2023 (all P > 0.05) (Table 2).

Table 2. Soil organic carbon stock comparison across depth profiles.

Year	Zone (cm)	Conventional	Legume (organic)	Manure (organic)	Legume vs CNV	Manure vs CNV
2021	0-20	50.7 +/- 2.8	65.7 +/- 1.7	65.7 +/- 2.4	+15.0 (P=0.001, ***)	+15.0 (P=0.001, **)
2021	20-30	8.0 +/- 1.0	13.4 +/- 2.1	15.7 +/- 1.5	+5.4 (P=0.041, *)	+7.7 (P=0.001, ***)
2021	30-60	13.4 +/- 0.7	15.0 +/- 1.8	16.1 +/- 1.2	+1.6 (P=0.421)	+2.8 (P=0.070)
2021	60-100	12.2 +/- 0.8	12.2 +/- 0.8	13.0 +/- 1.2	-0.1 (P=0.946)	+0.8 (P=0.598)
2023	0-20	54.7 +/- 3.2	65.7 +/- 2.2	70.3 +/- 2.1	+11.0 (P=0.015, *)	+15.6 (P=0.002, **)
2023	20-30	11.6 +/- 1.2	15.6 +/- 1.7	19.6 +/- 1.8	+4.0 (P=0.079)	+8.0 (P=0.003, **)
2023	30-60	14.6 +/- 1.2	15.1 +/- 0.9	15.9 +/- 0.9	+0.5 (P=0.715)	+1.3 (P=0.383)
2023	60-100	12.0 +/- 0.7	12.4 +/- 0.7	13.2 +/- 1.3	+0.4 (P=0.666)	+1.2 (P=0.420)

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3.2.1 Partitioning the whole-profile surplus by depth zone

To test whether the organic-system carbon advantage extends below the plow layer or is confined to the upper profile, the whole-profile (0 – 100 cm) ESM-corrected stock surplus relative to conventional was partitioned into three depth components including surface (0 – 20 cm), transition (20 – 30 cm), and true subsoil (30 – 100 cm); such that the three components sum exactly to the whole-profile surplus. In 2023, the legume and manure systems held whole-profile surpluses of +16.0 and +26.2 Mg C ha^{-1}, respectively. Of these totals, 69% (legume) and 60% (manure) of the total stock originated in the 0 – 20 cm zone, and a further 25% and 31% in the 20–30 cm transition zone; together accounting for 94 % (legume) and 91% (manure) of the entire profile surplus from only the upper 30 cm of soil. The remaining true-subsoil component (30 – 100 cm, representing 70% of total profile thickness) contributed just +1.0 and +2.6 Mg C ha^{-1}, averaged 6% and 10% of the totals and neither differed significantly (legume: $P = 0.66$; manure: $P = 0.34$). This partition was closely replicated in 2021 (true-subsoil share: 7% for legume, $P = 0.55$; 14% for manure, $P = 0.19$) (Figure 3). Across the whole 0 – 100 cm profile, the legume and manure systems held 108.9 ± 3.8 and 119.0 ± 4.1 Mg C ha^{-1} in 2023, compared with 92.9 ± 5.0 Mg C ha^{-1} under conventional management, a surplus of + 16.0 Mg C ha^{-1} ($P = 0.001$) and + 26.2 Mg C ha^{-1} ($P = 0.02$), respectively. The ratio of surface (0 – 10 cm) to subsoil (30 – 60 cm) SOC did not differ among systems (7.7, 7.6, and 7.6 for conventional, legume, and manure; both $P > 0.6$), indicating that management altered the quantity of surface carbon without reshaping the vertical pattern of its distribution.

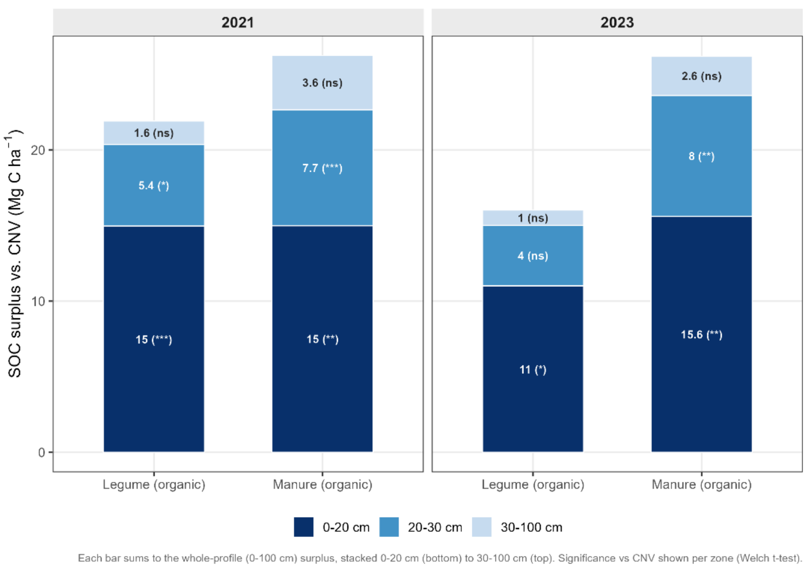

Figure 3. *Partition of the whole-profile SOC surplus by depth zone, 2021 and 2023. For the legume-organic and manure-organic systems, the total ESM-corrected SOC surplus relative to conventional management (0 – 100 cm; sum of all three segments) is decomposed into three*

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*depth zones: 0–20 cm (dark blue, bottom), 20–30 cm (medium blue), and 30–100 cm (pale blue, top), such that the three segments sum exactly to the whole-profile surplus. Values within each segment give the surplus (Mg C ha⁻¹) and its significance relative to conventional management within that zone (Welch two-sample t-test: * P < 0.05, ** P < 0.01, *** P < 0.001; ns = not significant).*

Active carbon (permanganate-oxidizable, POXC), measured in both 2021 and 2023, reinforced this picture. The effect of system on POXC depended strongly on depth (system × depth interaction: $\chi^2 = 132.7$, df = 8, $P < 0.001$). The manure system held significantly more active carbon than conventional from the surface through the 20–30 cm zone (0–10 cm: +119 ppm, $P < 0.001$; 10–20 cm: +201 ppm, $P < 0.001$; 20–30 cm: +156 ppm, $P < 0.001$), and the legume system showed the same gradient at 10–20 cm and 20–30 cm (+157 ppm and +89 ppm, both $P < 0.001$), though 0–10 cm difference did not show significance (+34 ppm, $P = 0.05$). Below 30 cm, active carbon did not differ significantly among systems at either depth (all $P > 0.10$); the same depth threshold observed for total SOC; suggesting that both the size and the lability of the organic-system carbon advantage are confined to the upper soil and transition zone. The exact magnitude of the surface advantage did vary between years (system × depth × year interaction: $\chi^2 = 76.1$, df = 8, $P < 0.001$). The manure system's advantage at 0 – 10 cm was larger in 2021 (+139 ppm) than in 2023 (+95 ppm), but the depth at which the management signal disappeared was identical in both sampling events, indicating that the surface-confinement of the active carbon response with system.

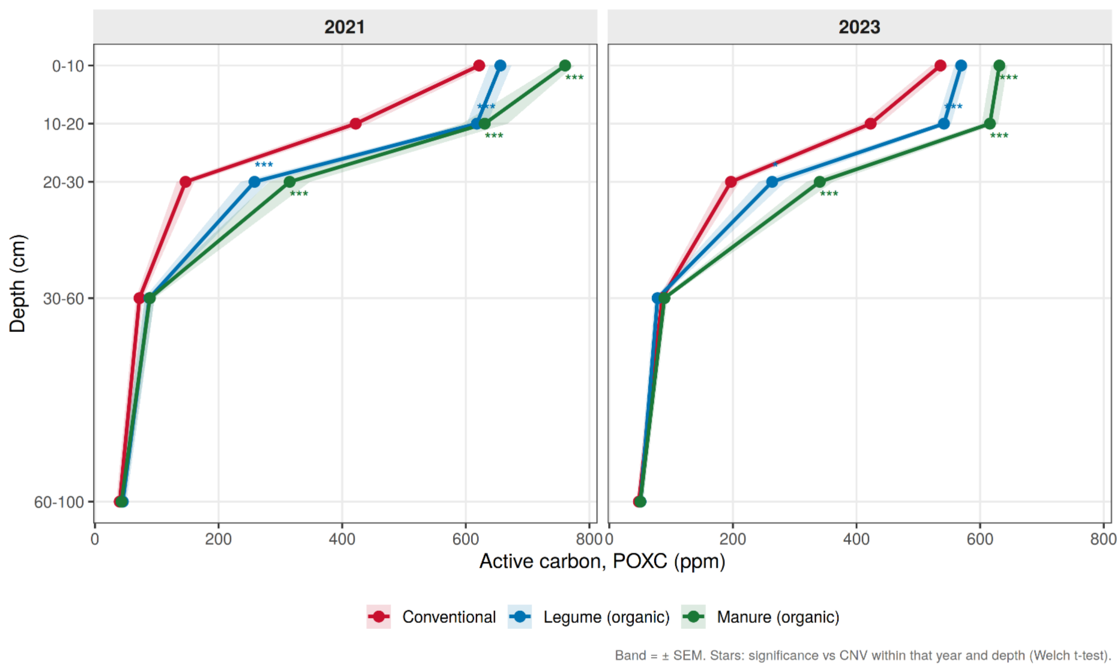

Figure 4. *Depth profiles of active carbon (POXC) by cropping system, 2021 and 2023. Permanganate-oxidizable carbon (POXC, ppm) plotted against depth for the conventional (red),*

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*legume-organic (blue), and manure-organic (green) systems in each of the two sampling years. Points show system means (n = 8 blocks per system); shaded bands show ± 1 SEM. Asterisks denote significant difference from the conventional system within that year and depth interval (Welch two-sample t-test: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$); absence of a symbol indicates a non-significant contrast.*

3.3 Tillage had little independent effect on surface carbon

Over the post-2008 period, when full-tillage (FT) and reduced-tillage (RT) plots were compared within each system, tillage did not alter surface (0–20 cm) SOC stocks overall (main effect: χ^2 = 0.09, df = 1, P = 0.76), nor was there a significant system-dependent response (system × tillage interaction: χ^2 = 3.32, df = 2, P = 0.19). No system showed a significant within-system contrast between tillage treatments when the three post-split sampling years were pooled: conventional management trended lower under reduced tillage (FT: 57.9, RT: 53.6 Mg C ha^{-1}; RT − FT = −4.3 Mg C ha^{-1}, P = 0.29), while the legume system trended higher (FT: 59.2, RT: 63.5 Mg C ha^{-1}; RT − FT = +4.3 Mg C ha^{-1}, P = 0.32), and the manure system showed a small, non-significant increase (RT − FT = +2.8 Mg C ha^{-1}, P = 0.50). The corresponding contrasts in surface SOC concentration and SOM (LOI) were directionally consistent but similarly non-significant (concentration: CNV P = 0.29, LEG P = 0.32, MNR P = 0.51; SOM: CNV P = 0.06, LEG P = 0.40, MNR P = 0.51).

Examined by individual sampling year, the legume system's response to reduced tillage was directionally consistent in two of three years (2021: RT − FT = +6.2 Mg C ha^{-1}, P = 0.065; 2023: +5.6 Mg C ha^{-1}, P = 0.26) but negligible in 2018 (+1.1 Mg C ha^{-1}, P = 0.91). Conventional management showed the reverse pattern, a negative but non-significant trend that strengthened over time (2018: +0.7; 2021: −5.2; 2023: −8.3 Mg C ha^{-1}) while the manure system showed no consistent direction across years. The continuously FT plots exhibited the same year-to-year fluctuation as the trial, confirming that the temporal variation observed after 2008 was not attributable to the introduction of reduced tillage.

Because the aggregate 0–20 cm zone could mask a tillage effect localized to a specific depth, tillage contrasts were additionally tested at each individual depth increment within each system, with rotation-entry subplots averaged within each block, consistent with block being the experimental unit for tillage inference. None of the fifteen system × depth combinations reached significance (all P > 0.12; Figure 5). A directional pattern was visible and mirrored the pooled 0–20 cm result: in the conventional system, reduced tillage trended lower at all three depths above 30 cm (0–10, 10–20, and 20–30 cm; largest at 10–20 cm, RT − FT = −0.23%, P = 0.13), while both organic systems trended higher across the same three depths (e.g., legume: +0.11, +0.19, and +0.16 percentage points at 0–10, 10–20, and 20–30 cm, respectively). Below 30 cm, this directional separation disappeared: all three systems converged to near-zero, non-significant tillage differences at both 30–60 cm and 60–100 cm (all |RT − FT| ≤ 0.04 percentage points). Taken together, these results indicate that reduced tillage produced, at most, a consistent but

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statistically unresolved directional tendency opposing in sign between conventional and organic management; confined to the upper 30 cm, and no detectable effect at any depth in the subsoil.

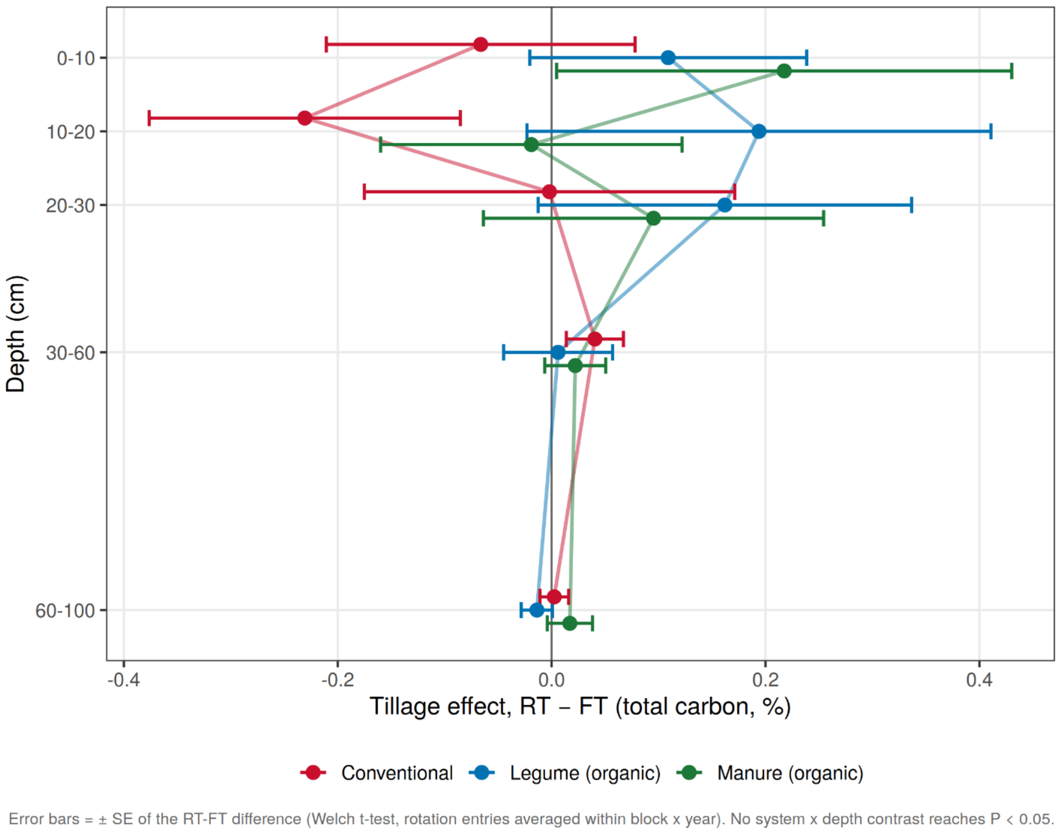

Figure 5. *Tillage effect (reduced minus full tillage) on total soil carbon by depth, within each cropping system. Points show the RT − FT difference in total carbon (%) at each depth increment for conventional (red), legume-organic (blue), and manure-organic (green) systems, pooled across 2018, 2021, and 2023; rotation-entry subplots were averaged within each block, year, and tillage combination before testing. Points are offset slightly within each depth for visual clarity. Error bars show ± 1 SE of the RT − FT difference (Welch two-sample t-test) and the vertical line marks zero effect. No system × depth contrast reached significance (all P > 0.12), consistent with the absence of a tillage effect on the aggregate 0–20 cm zone.*

4. Discussion

4.1 Organic management produced a persistent surface-soil carbon advantage

The principal finding of this study is that both organic cropping systems developed and maintained substantially greater surface-soil carbon than the conventional system. The three systems were statistically indistinguishable at the 1984 baseline, when soil organic matter (SOM) ranged from 2.06 to 2.26%, but diverged progressively thereafter. By 2023, SOM increased to

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4.70 % and 4.56% for organic manure and organic legume systems respectively compared to 4.02% for the conventional system. SOC concentration in the 0 – 20 cm layer was 28% greater in the manure-based organic system and 20% greater in the legume-based organic system than in the conventional system, corresponding to concentrations of 2.46, 2.30, and 1.92%, respectively. Equivalent-soil-mass-corrected stocks showed the same ranking, reaching 70.3 Mg C ha^{-1} in the manure system and 65.7 Mg C ha^{-1} in the legume system, compared with 54.7 Mg C ha^{-1} under conventional management. These values represent organic-system surpluses of 15.6 and 11.0 Mg C ha^{-1}, respectively. The magnitude of these differences exceeds the pooled organic–conventional topsoil stock difference of approximately 3 – 4 Mg C ha^{-1} reported by Gattinger et al., (2012b). The larger differences observed in the Farming Systems Trial (FST) likely reflect, the long duration of the experiment and the cumulative effects of repeated cover cropping, rotational diversification, perennial forage phases, and organic amendments. Earlier FST analyses similarly found that organic management increased SOC relative to conventional management after 34 years, particularly in surface soil (Lorenz et al., 2025).

No statistically detectable difference between the legume- and manure-based organic systems occurred in any of the seven sampling years. It indicates that both organic systems reached similar surface-SOC states within the uncertainty and spatial variability of the experiment, despite supplying carbon through different pathways. The manure system received direct carbon inputs from periodic compost applications and continuous root inputs during perennial hay phases. The legume system received no external organic amendment but supplied carbon through cover crops, crop residues, living roots, and biologically fixed nitrogen. Manure can increase SOC through direct organic-carbon additions and cover crops replace otherwise fallow periods with additional in situ photosynthetic carbon inputs (Das et al., 2023; Maillard and Angers, 2014; Poeplau et al., 2015). Greater rotational diversity can further increase belowground inputs; across 122 studies, increased crop diversity raised total soil C and N by approximately 3.6% and 5.3%, respectively (McDaniel et al., 2014). The similar long-term SOC stocks suggest that carbon accumulation depended on the integrated balance among input quantity, continuity, placement, biochemical quality, microbial processing, physical protection, and decomposition losses rather than manure addition alone. Although nitrogen-rich legume residues may decompose rapidly, readily decomposable inputs can be efficiently assimilated by microorganisms and subsequently stabilized as mineral-associated microbial carbon through microbial necromass (Camenzind et al., 2023). Recent studies show that legume cover crops can increase both particulate and mineral-associated organic carbon by stimulating microbial biomass and necromass formation (Hu et al., 2024), while cover cropping can further protect SOC through enhanced aggregation and mineral association (Zhu et al., 2024).

This interpretation agrees with earlier FST findings, Wander et al., (1994) reported that both organic systems accumulated biologically active carbon, but manure-amended soils contained more labile organic matter, whereas cover-cropped soils accumulated more total and particulate organic matter and showed indicators of greater stability. Littrell et al., (2021) similarly found that the manure system often supported greater SOC, aggregate stability, and

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aggregate-associated carbon than the legume system, although both exceeded conventional management. Thus, similar bulk SOC stocks do not imply identical carbon pools or turnover dynamics; manure and legume management appear to have followed different biogeochemical pathways toward a broadly similar total-SOC outcome.

The only departure from the persistent system ranking occurred in 2018, when the systems were not statistically separated for either SOC or SOM. This is best interpreted as a temporary loss of statistical resolution rather than biogeochemical convergence. The decline occurred in both dry-combustion SOC and loss-on-ignition SOM, making a method-specific laboratory error less likely, although variability from sampling, compositing, or sample preparation cannot be excluded. The same pattern also occurred in the continuously full-tilled plots, indicating that it was unrelated to the 2008 tillage split. SOC can vary substantially within and among years because of residue inputs, root growth and decomposition, particulate-organic-matter turnover, erosion and deposition, and sampling timing. Wuest, (2014) observed topsoil SOC variation equivalent to 14 – 16% of the temporal mean during repeated equivalent-mass sampling, demonstrating that short-term variability can temporarily obscure treatment differences. The reappearance of the organic-system advantage in subsequent years, its occurrence in both SOC and SOM, and the parallel fluctuation in continuously tilled plots indicate that the 2018 result was not a durable reversal of long-term management effects, and could be artificat of sampling timing (2018 sampling was done in January, compared to other years, where sampling was done in November).

4.2 Organic-system carbon gains were concentrated in the upper 30 cm

The organic-management effect was strongly depth dependent. Both organic systems contained more SOC than the conventional system through 30 cm, whereas no statistically detectable differences occurred below this depth. More than 90% of the ESM-corrected whole-profile carbon surplus in both organic systems was located within the upper 30 cm in 2023, and the same pattern was reproduced in 2021. Thus, four decades of organic management increased carbon primarily within the surface and transitional soil layers rather than uniformly throughout the 1m profile. This vertical pattern likely reflects the depth distribution of carbon inputs generated by the crop rotations. Although the manure system included a deep-rooted perennial alfalfa–orchardgrass phase, this occurred during only part of its nine-year rotation, while the legume system was dominated by annual crops and cover crops. Neither system therefore maintained sustained, high-density root inputs throughout the subsoil over the full rotation. Root abundance, rhizodeposition, and the availability of readily metabolizable substrates generally decline with depth, resulting in lower active microbial biomass and fewer opportunities for root-derived carbon to be transformed into microbial biomass, necromass, and ultimately mineral-associated organic matter (Herre et al., 2022; Sokol et al., 2024). Deep-rooted perennial crops can partly overcome this substrate limitation by delivering root residues and exudates directly into deeper horizons, thereby stimulating microbial growth and the stabilization of microbially processed carbon. However, this effect depends on crop species, rooting duration, nutrient

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availability, microbial physiology, and the capacity of subsoil minerals to retain newly processed carbon (Peixoto et al., 2022).

The approximately 30 cm boundary corresponds closely with the historical zone of direct management (plowing, residue incorporation, compost application). Compost, cover-crop biomass, and crop residues were therefore incorporated mainly within this soil volume of 30 cm. Littrell et al. (2021) similarly found that organic management increased total and active SOC throughout the 0–30 cm profile at the FST. The correspondence between the depth of management intervention and the depth of the SOC response suggests that residue placement and amendment incorporation were important controls on where additional carbon accumulated. This profile pattern is consistent with broader evidence that management-induced SOC gains are often concentrated near the surface. Prairie et al., (2023) reported that regenerative practices increased both POC and MAOC primarily in topsoil. Several interacting mechanisms may explain the weak response below 30 cm. Surface SOC receives direct inputs from manure, incorporated residues, cover crops, fine-root turnover, and rhizodeposition. Subsoil carbon inputs depend more strongly on deep-root production, dissolved organic carbon transport, bioturbation, and preferential flow. These inputs are generally smaller, more spatially heterogeneous, and distributed across a much larger mass of mineral soil, reducing their influence on measured SOC concentration and stock.

4.3 Surface SOC accumulation slowed after the initial decades

The seven-point surface-soil time series indicates that SOC accumulation was nonlinear over the 39-year observation period. Both organic systems increased rapidly relative to the 1984 baseline through approximately the mid-2000s, after which SOC fluctuated around a persistently elevated level. This trajectory is consistent with earlier observations from the FST (Hepperly et al., 2007) and with the general dynamics expected following a sustained change in management. When carbon inputs increase or decomposition losses decline, SOC stocks tend toward a new management-specific dynamic equilibrium; as the stock increases, annual losses also increase, progressively reducing the net rate of accumulation (Paustian et al., 2019; Poulton et al., 2018). The apparent slowing should not, however, be interpreted as direct evidence that the soil reached a fixed carbon-saturation limit. A temporal plateau can emerge under relatively constant carbon inputs when additions become increasingly balanced by decomposition and other losses. This is conceptually different from mineral saturation, which implies that additional carbon inputs no longer increase carbon stored within a particular stabilized soil fraction. Demonstrating saturation therefore requires comparisons across a gradient of carbon inputs and, ideally, measurements of particulate and mineral-associated carbon pools not simply an asymptotic pattern through time (Heinemann et al., 2025; Poeplau et al., 2024).

Recent evidence also challenges the assumption that mineral-associated carbon has a single, readily definable upper limit. Poeplau et al., (2024) concluded that fine-fraction carbon accumulation is primarily constrained by the supply of carbon inputs and is further regulated by soil texture, mineralogy, climate, and other site properties, which together define an ecosystem

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capacity for carbon stabilization rather than a universal saturation threshold. Similarly, Heinemann et al., (2025) found no consistent saturation response in long-term experiments receiving organic-carbon inputs up to approximately five times those typical of agricultural systems. Even under these exceptionally high inputs, SOC generally continued to increase, although much of the additional carbon accumulated in coarser particulate fractions rather than in the fine mineral-associated fraction.

The FST trajectory is therefore compatible with two interpretations. The organic systems may be approaching a quasi-equilibrium under their prevailing rotations, with average carbon additions increasingly balanced by decomposition, harvest removal, erosion, and other losses. Alternatively, SOC may still be accumulating slowly, but the rate is too small to distinguish confidently from rotation effects, interannual variability, and spatial heterogeneity using only seven sampling campaigns. The current record supports a deceleration in surface-SOC accumulation but does not establish either a fixed stabilization ceiling or a complete cessation of carbon gain. Resolving these alternatives would require more frequent SOC measurements and annual or rotation-level estimates of carbon inputs from crop residues, roots, cover crops, and manure. Nonlinear mixed-effects or process-based models could then be used to compare linear, asymptotic, and other dynamic trajectories while explicitly representing uncertainty (Olson and Al-Kaisi, 2015; Poulton et al., 2018).

4.4 Tillage effects were confined to the upper profile and depended on cropping system

Reducing tillage did not consistently increase SOC in any of the three cropping systems. Instead, the largest RT–FT differences occurred within the upper 30 cm and varied in direction among systems: SOC was generally higher under reduced tillage in the two organic systems but lower in the conventional system (Figure 5). This pattern is more consistent with redistribution of carbon within the historically tilled layer than with uniform net accumulation under reduced disturbance. None of the depth-specific contrasts was statistically significant (all $P > 0.12$). The largest difference occurred in the conventional system, where reduced tillage was associated with lower SOC at 10–20 cm (RT − FT = −0.23%, $P = 0.13$), although this effect remained statistically unresolved.

Under continuous herbicide-based no-till, crop residues remain concentrated near the soil surface, whereas full tillage periodically incorporates residues throughout the plow layer. In the comparatively simplified conventional rotation, which receives fewer cover-crop inputs and has lower rotational diversity, reduced residue incorporation may therefore decrease carbon delivery to the 10–20 cm layer without producing sufficient additional above- or belowground biomass to compensate. This interpretation is consistent with broader evidence that no-till frequently increases SOC concentration at the immediate surface while leaving deeper portions of the plow layer unchanged or slightly depleted (Angers and Eriksen-Hamel, 2008; Haddaway et al., 2017).

The legume system exhibited the opposite directional response. Reduced tillage was associated with numerically higher SOC throughout the upper 30 cm, with the largest difference at 10–20 cm (+0.19%), although none of these contrasts was statistically significant. This pattern

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may reflect an interaction between reduced disturbance and the continuous plant-derived carbon inputs characteristic of cover crop–based rotational no-till (Luo et al., 2010b). Roller-crimped residues remain at the soil surface, while living roots and rhizodeposition continue to supply carbon belowground. Under these conditions, reduced disturbance could promote aggregate formation and the physical protection of recently added particulate organic matter (Cotrufo and Lavallee, 2022; Lavallee et al., 2020). This interpretation is also consistent with global evidence that increases in aggregate-protected carbon are most likely when reduced disturbance is combined with diversified organic inputs rather than implemented in isolation (Feng et al., 2023). Nevertheless, the present dataset includes only three sampling years, and the directionally similar estimates observed in two of those years cannot distinguish an emerging treatment effect from sampling variability. The pattern should therefore be considered a hypothesis for future, more highly powered testing rather than an established response.

The manure system showed smaller and less directionally consistent tillage effects across depths. Its longer rotation, perennial forage phase, and periodic compost additions provide substantial and relatively continuous carbon inputs under both tillage regimes. These inputs may reduce the marginal influence of tillage intensity on bulk SOC compared with systems receiving smaller or less consistent organic inputs. Where carbon supply is already high, differences in disturbance may alter aggregate-size distribution or the vertical placement of carbon without producing a detectable change in total SOC over the period examined. Previous findings from the FST support this interpretation. Littrell et al., (2021) reported that reduced tillage altered aggregate-size distribution and increased carbon associated with large macroaggregates without increasing total SOC, indicating redistribution among physical carbon pools rather than net accumulation. Pearsons et al., (2023) similarly concluded that rotational diversity and organic inputs were stronger determinants of soil health than tillage reduction alone. Moreover, RT–FT differences converged toward zero below 30 cm in all three systems, indicating that the limited and system-dependent effects of tillage were confined to the historically tilled and residue-incorporation zone.

4.5 POXC revealed a parallel response in a management-sensitive carbon fraction

POXC showed a depth response similar to that of total SOC, with organic-management effects evident within the upper 30 cm but not in deeper layers. Because POXC represents an operationally defined, relatively management-sensitive carbon fraction, this agreement provides complementary evidence that the influence of the organic systems extended beyond changes in bulk SOC alone. The magnitude of the POXC response varied between 2021 and 2023, likely reflecting differences in recent residue inputs, rotation phase, environmental conditions, and microbial processing. Such temporal sensitivity is expected because POXC generally responds more rapidly to management than total SOC (Culman et al., 2012). It should not, however, be interpreted as a direct measure of a discrete “labile” or biologically available carbon pool. The permanganate assay oxidizes compounds with differing turnover rates and is particularly sensitive to lignin-derived and phenolic structures (Woodings and Margenot, 2023). POXC is

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therefore best interpreted here as an indicator of management-responsive carbon fraction rather than as a quantitative measure of carbon mineralizability or lability. The correspondence between POXC and total SOC strengthens the evidence that management effects were concentrated within the actively managed soil profile. However, it does not imply that both measurements reflect identical formation or stabilization processes. Determining whether the additional carbon occurred primarily as particulate, aggregate-protected, or mineral-associated material would require physical fractionation and complementary measurements of microbial transformation.

4.6 Implications for soil-carbon measurement and reporting

The principal measurement implication is that sampling depth must match the scale of the inference. Sampling only the upper 20 or 30 cm can adequately characterize topsoil responses but cannot establish whether a management practice increased carbon throughout the soil profile. Because management can redistribute SOC vertically, whole-profile sequestration claims require measurements extending below the primary zone of cultivation and residue incorporation (Raffeld et al., 2024). Stock comparisons must also account for management-induced differences in bulk density. Fixed-depth calculations may compare unequal masses of mineral soil, thereby attributing differences in soil mass to differences in carbon storage. Equivalent-soil-mass correction reduces this bias and is especially important where management affects aggregation, compaction, or porosity (von Haden et al., 2020b). Reporting both fixed-depth and ESM-corrected stocks, together with bulk density and coarse-fragment information, improves transparency and comparability among studies. The nonlinear temporal trajectory cautions against expressing soil carbon responses as a single constant annual sequestration rate. Rates estimated from early and late portions of the experiment would differ substantially because accumulation slowed as the systems reaches towards management specific equilibrium state (Caruso et al., 2018).

4.7 Limitations and priorities for future research

Several limitations constrain the temporal and mechanistic interpretation of the results. Bulk density was not measured during every historical sampling campaign, so the temporal resolution of ESM-corrected stocks was lower than that of SOC concentration. Repeated bulk-density measurements during future campaigns would allow changes in soil mass and carbon stock to be tracked more directly. Depth-resolved comparisons were also limited to the recent campaigns that shared a common sampling depth. Earlier sampling depths could not be harmonized without assuming uniform carbon distributions within relatively broad soil increments. Excluding those campaigns avoided introducing interpolation bias but shortened the period available for evaluating profile-level change. The study measured total SOC and POXC but did not separate particulate, aggregate-occluded, and mineral-associated carbon. Consequently, the data identify where carbon accumulated but cannot fully resolve the processes responsible for its persistence. Future measurements should combine full-profile carbon fractionation with root biomass, rhizodeposition, microbial necromass, dissolved organic carbon, and mineralogical indicators.

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These measurements would clarify whether the surface response was driven primarily by particulate inputs, microbial transformation, aggregate protection, or organo-mineral association.

5.0 Conclusion

Four decades of measurements from the Farming Systems Trial at Rodale Institute show that cropping-system design had a much stronger influence on SOC storage and accumulation than tillage intensity. By 2023, the two organic systems stored 11–16 Mg C ha^{-1} more than the conventional system in the upper 20 cm and 16–26 Mg C ha^{-1} more across the full 1 m profile. These gains were substantial and persistent, despite arising through different management pathways, including legume-derived inputs, diversified rotations, perennial cover, and manure amendments. The SOC response was strongly depth dependent. Across full-profile sampling campaigns, 91–94% of the organic-system carbon surplus occurred within the upper 30 cm. POXC showed the same vertical pattern, indicating that both total SOC and management-responsive carbon increased primarily within the surface and transition zones. Reduced tillage, by comparison, produced smaller and statistically unresolved effects, suggesting that reducing soil disturbance alone was less influential than maintaining sustained carbon inputs through cover crops, organic amendments, and diverse rotations. Together, these findings demonstrate the long-term potential of diversified organic cropping systems to rebuild SOC. Full-profile sampling and equivalent-soil-mass correction were essential for distinguishing whole-profile gains from their strongly surface-weighted distribution. Continued depth-resolved monitoring and carbon fractionation will help determine how these gains are distributed among particulate, aggregate-protected, and mineral-associated pools, and management derived equilibrium state of SOC accumulation.

Author Contribution

SD: Conceptualization, Formal Analysis, Data QA/QC, Writing, Reviewing, Editing
HS: Formal Analysis, Sampling, Software, Writing, Reviewing, Editing
AS: Analysis, Writing, Reviewing, Editing
CG: Data Collection, Writing, Reviewing, Editing

Competing Interest

Author declares no competing interests

Data Availability

Codes and data used in this paper could be found in : https://github.com/Saurav12das/Deep-Soil-Carbon---Farming-Systems-Trial---Rodale-Institute

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