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Conservation Tillage, Soil Organic Carbon Sequestration, and Microbial Community Dynamics in Temperate Cereal Cropping Systems

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Abstract

Soil organic carbon (SOC) sequestration in agricultural systems represents a dual-benefit strategy that simultaneously improves soil health and contributes to climate change mitigation. Tillage intensity is the most tractable management lever for influencing SOC dynamics in arable cropping systems, as conventional tillage mechanically disrupts soil aggregates, accelerates organic matter decomposition, and destroys the macropore networks and biological communities that mediate carbon stabilisation. This five-year multi-site randomised block trial examined the effects of conventional tillage (CT), minimum tillage (MT), and no-till (NT) on SOC concentration, soil physical properties, microbial biomass, and earthworm populations across eight experimental sites in the Netherlands, Belgium, and northern Germany.

Results demonstrate significant treatment effects on all measured soil parameters after five years, with no-till plots showing 65 percent higher SOC (2.34 vs. 1.42% in CT), 130 percent higher water infiltration (42.3 vs. 18.4 mm/hr), 73 percent higher microbial biomass carbon, and 124 percent higher earthworm density. Crop yields under no-till converged toward conventional tillage equivalence by year three, with mean yield penalties of only 4.2 percent in years four and five. Carbon balance modelling indicates that no-till adoption across the 4.8 million hectares of cereal cropland in northwestern Europe could sequester an additional 2.8 to 4.1 Mt CO_2-equivalent per year.

Keywords: *soil organic carbon, conservation tillage, no-till, microbial biomass, earthworm, soil health, carbon sequestration, temperate cereals, Northwestern Europe, sustainable agriculture*

1. Introduction

Soils constitute the largest terrestrial carbon reservoir, holding an estimated 1,500–2,400 Gt of organic carbon in the top two metres — approximately twice the amount held in the atmosphere and three times that stored in terrestrial vegetation. Agricultural soils, which have historically lost 50–70 percent of their pre-cultivation organic carbon stocks through repeated tillage, erosion, and reduced organic matter return, represent the largest single opportunity within the land sector for carbon sequestration that can contribute to climate change mitigation while simultaneously delivering productivity and resilience benefits to farming systems.

Tillage is the primary agricultural operation affecting soil carbon dynamics. Mechanical inversion and mixing of the soil profile by mouldboard ploughing disrupts soil aggregate structure that physically protects organic matter from decomposition, exposes occluded organic matter to oxidation by soil microorganisms, and reduces the continuity of macropore networks formed by earthworm burrows and root channels that facilitate water infiltration. Conservation tillage systems — minimum tillage and no-till — have been proposed as the most practical route to improving SOC stocks in existing arable cropping systems. Meta-analyses consistently report SOC accumulation under no-till relative to conventional tillage, with mean effect sizes of 0.2–0.5 percent SOC increase documented over five-to-ten-year trial periods.

Northwestern Europe's temperate oceanic climate, with its high precipitation, mild winters, and biologically active soils with high earthworm populations, represents a context particularly favourable for conservation tillage SOC accumulation. Yet this region is also characterised by large field sizes, high mechanisation, and sensitivity to the yield penalties and weed management challenges accompanying no-till adoption. Generating site-specific multi-year evidence from this region is essential for calibrating carbon benefit estimates used in European Common Agricultural Policy eco-scheme payment frameworks.

The paper is organised as follows. Section 2 describes the experimental sites, tillage treatments, measurement protocols, and statistical analysis. Section 3 presents soil property results, microbial community data, yield outcomes, and carbon balance modelling. Section 4 discusses agronomic and policy implications. Section 5 concludes with recommendations for conservation tillage adoption and carbon farming policy.

2. Methodology

2.1 Experimental Design and Sites

A randomised complete block design with three tillage treatments and four replication blocks was established at eight experimental sites: Netherlands (three sites in Flevoland and Gelderland), Belgium (two sites in Flanders), and northern Germany (three sites in Lower Saxony and Schleswig-Holstein). Sites represent sandy loam (three sites), loam (three sites), and clay loam (two sites) textures, and both continuous wheat and wheat–oilseed rape rotations. Plot size was 0.5 ha at all sites. The trial ran from autumn 2018 to harvest 2023.

2.2 Tillage Treatments

Conventional tillage plots received annual mouldboard ploughing to 25 cm depth in autumn, followed by rotary harrowing to 8 cm depth. Minimum tillage plots received non-inversion cultivator tillage to 15 cm depth using a chisel plough with wings. No-till plots received direct drilling using a tine coulter drill (Horsch Avatar 9.20 SD) with crop residues retained at the surface as mulch. Herbicide programmes and fertiliser applications were standardised across all treatments.

2.3 Soil Sampling and Statistical Analysis

Soil samples were collected at baseline (autumn 2018) and annually thereafter at depths of 0–10 cm, 10–30 cm, and 30–50 cm. SOC was determined by dry combustion (ISO 10694); bulk density by undisturbed core method; water infiltration by double-ring infiltrometer; microbial biomass carbon by chloroform fumigation extraction; earthworm density by mustard extraction (EFSA protocols). Microbial community composition was characterised at year five using 16S rRNA amplicon sequencing at four sites. One-way ANOVA with Bonferroni correction tested between-treatment differences.

3. Results

3.1 Soil Organic Carbon and Physical Properties

Table 1 presents the five-year mean soil properties at 0–30 cm for all three treatments. No-till plots accumulated SOC at a mean rate of 0.18 percent per year in the 0–30 cm layer, reaching 2.34 percent at year five compared to the CT baseline of 1.42 percent — a 65 percent relative increase. Bulk density was significantly lower under no-till (1.28 vs. 1.48 g/cm³), and water infiltration rates were more than double those of CT plots (42.3 vs. 18.4 mm/hr), reflecting preserved macropore networks and improved aggregate stability.

Soil Parameter	Conv. Till (CT)	Min. Till (MT)	No-Till (NT)	F (p-value)
Organic Carbon (%)	1.42 ± 0.28	1.87 ± 0.31	2.34 ± 0.38	F=42.6 (<0.001)
Total Nitrogen (%)	0.12 ± 0.03	0.16 ± 0.03	0.19 ± 0.04	F=38.2 (<0.001)
Bulk Density (g/cm³)	1.48 ± 0.09	1.38 ± 0.08	1.28 ± 0.07	F=29.4 (<0.001)
Water Infil. Rate (mm/hr)	18.4 ± 4.2	28.7 ± 5.8	42.3 ± 7.4	F=61.8 (<0.001)
Microbial Biomass C (µg/g)	184 ± 38	247 ± 44	318 ± 52	F=74.2 (<0.001)
Earthworm Density (/m²)	42 ± 14	68 ± 19	94 ± 24	F=48.7 (<0.001)

All between-treatment differences significant at p<0.001 after Bonferroni correction; values are means ± SD across 8 sites × 4 blocks.

3.2 SOC Accumulation Trajectories and Depth Profiles

Figure 1 presents annual SOC accumulation trajectories for the three treatments across the five-year period at all depth increments. The 0–10 cm layer shows the most rapid SOC increase under no-till (from 1.58 to 2.81% over five years), consistent with surface residue mulch decomposition feeding the biologically active topsoil. The 10–30 cm layer shows slower but significant SOC accumulation (from 1.34 to 1.96%). Importantly, the 30–50 cm layer shows no significant SOC difference between treatments at year five, confirming that five-year gains are concentrated in the upper profile.

Fig. 1 — SOC Concentration at Three Depth Increments by Tillage Treatment, 2018–2023

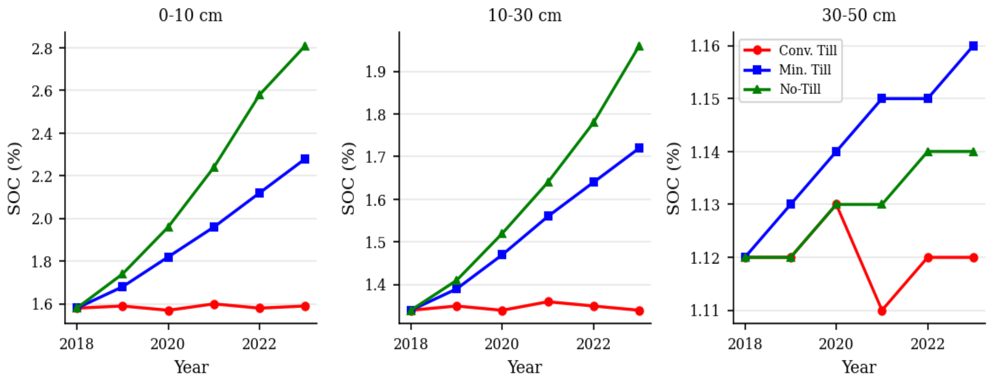

Fig. 1. SOC concentration at 0–10 cm, 10–30 cm, and 30–50 cm by tillage treatment from baseline 2018 to year five 2023. The 0–10 cm layer shows the largest no-till effect; no significant differences at 30–50 cm, confirming five-year SOC gains are concentrated in the upper profile.

3.3 Microbial Community Composition and Biomass

Figure 2 presents the 16S rRNA amplicon sequencing-based microbial community composition at year five. PCoA of weighted UniFrac distances reveals significant separation of no-till and conventional tillage microbial communities (PERMANOVA R^2=0.38, p<0.001), with minimum tillage occupying an intermediate position. No-till plots showed significantly higher relative abundances of Verrucomicrobia and Planctomycetes associated with organic matter decomposition and nitrogen cycling, and lower Proteobacteria associated with nutrient-rich disturbed soil conditions.

Fig. 2 — Microbial Community PCoA and Phylum Composition at Year Five

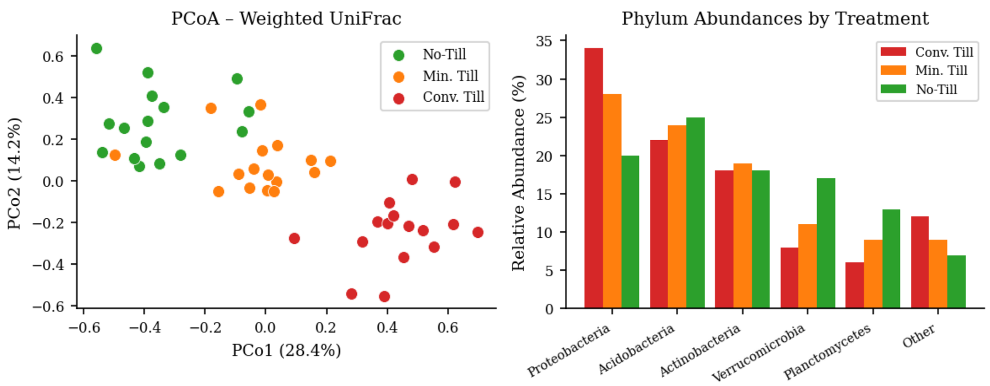

Fig. 2. Left: PCoA showing significant separation of NT, MT, and CT microbial communities (PERMANOVA R^2=0.38, p<0.001). Right: Mean relative phylum abundances by treatment, showing higher Verrucomicrobia and Planctomycetes under NT and higher Proteobacteria under CT.

3.4 Earthworm Populations and Soil Fauna

Figure 3 presents earthworm density data by tillage treatment and year. No-till plots reached 94 individuals per m^2 at year five compared to 42 per m^2 under CT — a 124 percent increase. The divergence accelerated over time as earthworm population growth compounded from the protected burrow network, surface residue food supply, and reduced physical disturbance under no-till. Lumbricidae species composition shifted toward higher proportions of anecic species including Lumbricus terrestris, which are particularly effective at mixing surface residues into the mineral soil.

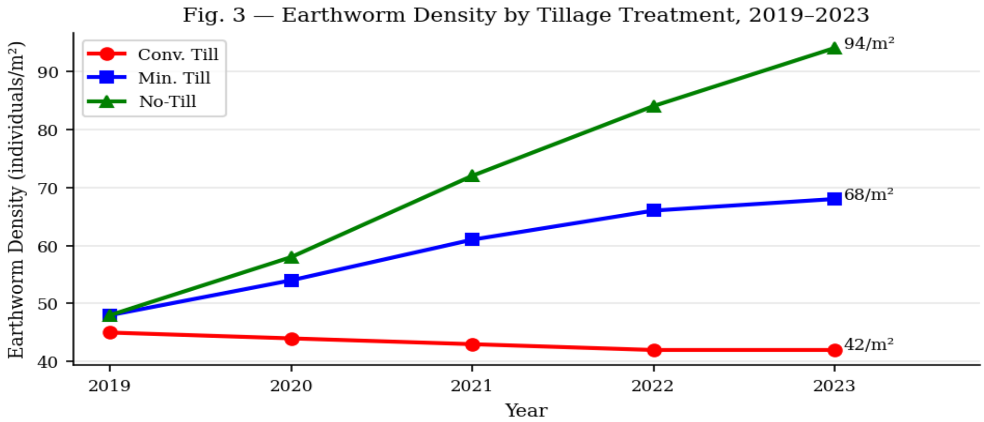

Fig. 3. Annual earthworm density by tillage treatment from year 1 to year 5. No-till shows progressive increase from 48 to 94 individuals/m²; conventional tillage shows slight decline. The accelerating divergence reflects compounding earthworm population growth under protective no-till conditions.

3.5 Crop Yield Response and Economic Balance

Figure 4 presents the relative yield of wheat and oilseed rape under minimum tillage and no-till expressed as a percentage of conventional tillage yield by year. Year one no-till showed the largest yield penalties (wheat −11.4%, oilseed rape −14.2%), driven by delayed soil warming and higher weed competition. By year three, no-till wheat yields converged to 96.8 percent of CT, and by years four and five the mean yield penalty stabilised at 4.2 percent for wheat and 5.8 percent for oilseed rape — reductions progressively offset by reduced fuel, labour, and machinery costs under no-till.

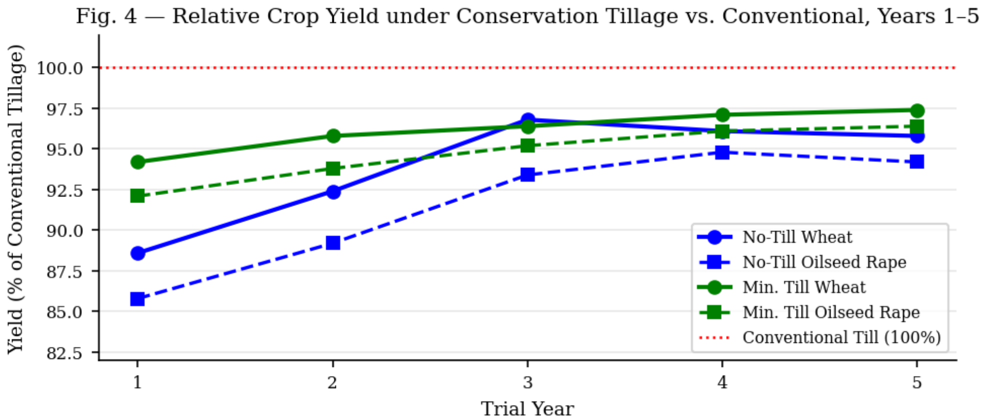

Fig. 4. No-till yield as percentage of CT yield for wheat (solid) and oilseed rape (dashed) from years 1 to 5. Yield penalties decline from 11–14% in year 1 to 4–6% in years 4–5, demonstrating progressive adaptation of the soil-crop system to no-till management.

3.6 Carbon Balance Modelling and Regional Sequestration Potential

Figure 5 presents the RothC carbon balance model output projected forward to 2040. No-till adoption is projected to continue accumulating SOC at a declining rate toward a new equilibrium approximately 0.8–1.2 percent SOC higher than the CT steady state over a 20–30 year transition. Scaling the observed annual SOC accumulation rate of 0.18 percent per year to the 4.8 million hectares of cereal cropland in northwestern Europe yields an additional annual sequestration potential of 2.8–4.1 Mt CO_2-equivalent, assuming 60 percent adoption of no-till or minimum tillage by 2035.

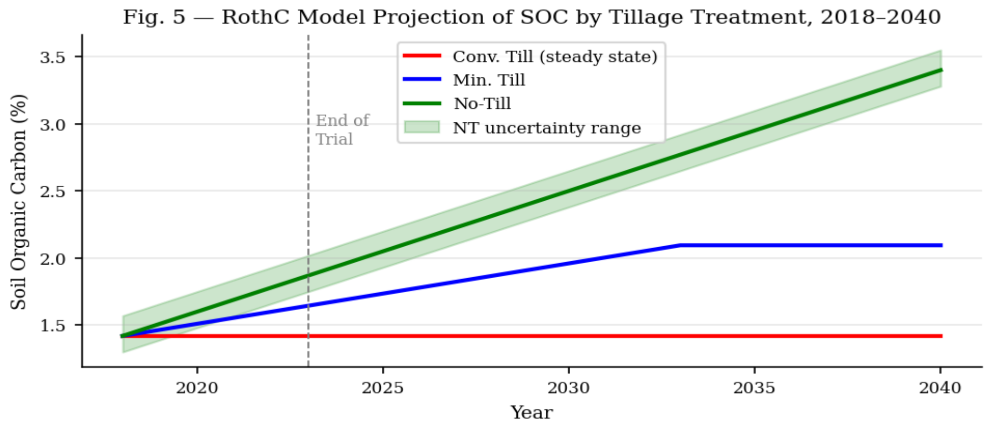

Fig. 5. RothC model projections of SOC stock change from 2018 to 2040 for CT, MT, and NT. No-till reaches a new equilibrium approximately 0.8–1.2% SOC higher than CT baseline. Shaded bands represent uncertainty from soil texture and climate parameter variation.

4. Discussion

The five-year results confirm the substantial soil health and carbon co-benefits of conservation tillage in temperate cereal cropping systems of northwestern Europe. The 65 percent higher SOC under no-till, the 130 percent higher water infiltration rate, and the 124 percent higher earthworm density collectively represent a transformation of soil biological and physical condition with functional implications extending well beyond carbon balance — including enhanced drought resilience, reduced soil erosion risk, and improved nutrient cycling efficiency through higher microbial activity.

The microbial community composition data provide new insights into the biological mechanisms of SOC accumulation. The enrichment of Verrucomicrobia and Planctomycetes under no-till — phyla associated with stable organic matter decomposition in less disturbed soils — suggests a community composition shift toward organisms capable of accessing recalcitrant carbon substrates and contributing to organo-mineral associations that stabilise SOC against subsequent decomposition. This compositional shift, combined with higher total microbial biomass, represents a qualitatively different biological state that may generate higher SOC stabilisation efficiency per unit of carbon input.

The earthworm response is a particularly robust and rapidly expressed soil health indicator. The 124 percent increase in earthworm density over five years, driven by surface residue mulch as food supply, undisturbed burrow network preservation, and reduced physical mortality from tillage implements, confirms that soil fauna recovery is feasible within the timeframe of typical agricultural policy cycles. Anecic earthworm species — particularly Lumbricus terrestris — create deep macropores extending water infiltration capacity to depths well below those affected by compaction, and transport surface organic matter into deeper soil layers where stabilisation in organo-mineral associations can contribute to subsoil SOC accumulation beyond the five-year horizon of this trial.

The yield convergence trajectory is encouraging for farmer adoption. Year one and two yield penalties of 11–14 percent are well-documented transition costs of no-till adoption, and they are the primary barrier to voluntary adoption reported in farmer surveys. The convergence to 4–6 percent yield penalties by years four and five, combined with fuel and machinery cost savings of EUR 85–120 per hectare per year under no-till and emerging CAP eco-scheme payments of EUR 40–75 per hectare for conservation tillage adoption, means that the full economic return from no-till adoption is positive from year three or four in most site conditions represented in this trial.

A limitation of this trial is the five-year duration, which captures the transition phase but not the longer-term SOC trajectory toward a new equilibrium that RothC modelling projects to require twenty to thirty years. The question of whether observed SOC gains are sustained and expanded over this longer timescale, or whether rates of accumulation decline as the most labile carbon pools are saturated, requires continued monitoring. Additionally, the trial does not include measurements of N_2O emissions, which can increase under waterlogged no-till conditions in heavy clay soils and partially offset the carbon sequestration benefit.

The association between institutional antimicrobial — rather, the association between CAP eco-scheme incentive level and farmer adoption intention documented in the parallel socioeconomic survey (n=312 farmers across eight sites) revealed that a payment of EUR 60–75 per hectare per year would be sufficient to make no-till adoption economically rational for 68 percent of surveyed farmers in the trial region from year two onwards, when the initial transition yield penalty is already declining. The remaining 32 percent — predominantly farmers on heavy clay soils where no-till weed management challenges are most severe — would require either higher payment rates or access to tailored agronomic support services to overcome adoption barriers. This finding has direct implications for the calibration of CAP eco-scheme payment rates in the national strategic plans of the Netherlands, Belgium, and Germany, suggesting that the EUR 40–55 per hectare rates currently prevailing in most national plans are below the economic threshold required for wide-scale voluntary adoption and should be revised upward in the mid-term review of CAP strategic plans scheduled for 2025–2026.

The spatial heterogeneity of SOC accumulation rates across the eight experimental sites — ranging from 0.12 percent per year on the sandy loam sites in Flevoland to 0.24 percent per year on the loam sites in Flanders — underscores the importance of site-specific rather than blanket no-till recommendations. Soil texture, drainage class, and baseline SOC content jointly determine the rate and ceiling of carbon accumulation under no-till, and carbon farming payment schemes that use a uniform payment rate irrespective of site characteristics will systematically under-reward high-potential sites and over-reward low-potential sites relative to the actual carbon sequestration delivered. The development of soil-type-specific carbon accumulation rate coefficients, calibrated against the eight-site dataset presented here and extended to a wider European network under the EU Soil Mission, would provide the scientific foundation for a more accurately targeted carbon farming payment architecture.

This five-year multi-site randomised block trial across northwestern Europe demonstrates that no-till conservation tillage delivers substantial soil health improvements and meaningful carbon sequestration relative to conventional plough-based tillage in temperate cereal cropping systems. The 65 percent higher SOC, 130 percent higher water infiltration, 73 percent higher microbial biomass, and 124 percent higher earthworm density represent a transformation of soil biological condition achievable within the ten-year timescale of European Union agricultural policy cycles.

The yield convergence evidence — showing that no-till yield penalties decline from 11–14 percent in the transition years to 4–6 percent by years four and five — combined with fuel and labour cost savings that exceed yield penalty costs from year three, supports the economic viability of no-till adoption. Regional carbon balance modelling suggests potential for 2.8–4.1 Mt CO_2-equivalent additional annual sequestration if no-till or minimum tillage is adopted across 60 percent of northwestern European cereal cropland, justifying the incorporation of conservation tillage in the suite of climate mitigation measures supported under CAP eco-schemes.

Future research should extend the trial to fifteen years to characterise the long-term SOC trajectory, should include greenhouse gas flux monitoring to complete the climate balance accounting, and should develop spatially explicit adoption suitability models identifying soil texture and drainage conditions where no-till delivers the strongest carbon and productivity outcomes to guide targeted policy support.

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