Long-Term Influence of Conservation Agriculture on Soil Organic Carbon Dynamics and Aggregate Stability

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ABSTRACT

Background: Soil organic carbon (SOC) sequestration and aggregate stability are important indicators of the health and sustainability of agroecosystem soils. Conservation agriculture (CA) practices have been widely promoted as sustainable alternatives to conventional tillage; however, long-term field evidence on SOC dynamics and structural stability is limited in diverse agroeclimatic regions.

Objectives: This long-term field study evaluated the impact of conservation agriculture practices on dynamics of soil organic carbon, aggregate stability, physical and biological properties, and potential for carbon sequestration over 18 years of continuous management in a temperate agroecosystem.

Methods: The experimental station, located in the transition zone between the temperate and subtropical climates, was established according to a randomized complete block design. Three management systems were compared: (1) conventional tillage with removal of residue, (2) reduced tillage with partial residue retention, and (3) zero tillage with complete residue retention. Soil sampling was conducted biannually to determine SOC concentration, aggregate stability indices, bulk density, microbial biomass, soil respiration, enzyme activities and related soil physical and biological properties.

Results: Zero tillage with full residue retention increased SOC concentration and carbon stock by 34.2% and 31.8% respectively compared with conventional tillage over 18 years. Aggregate stability (mean weight diameter, MWD) increased by 28.6% under conservation agriculture compared to conventional practices. Zero tillage caused significant increases in microbial biomass carbon (43%), soil respiration rates (51%) and enzyme activities. In zero tillage, the water-stable aggregates > 2 mm increased from 22% to 51% indicating substantial improvement in soil structure. Zero tillage showed an average long-term rate of carbon sequestration of 0.62 Mg C ha^{-1} $year^{-1}$ with a great potential for climate change mitigation.

Scientific Significance: This study shows that conservation agriculture practices, especially zero tillage combined with residue retention, greatly enhance soil carbon sequestration, structural stability, and soil biological activity. The results quantitatively support the adoption of conservation agriculture for sustainable soil management and climate change mitigation in temperate agroecosystems.

Conclusion: Long-term conservation agriculture practices are effective strategies to improve soil health, carbon sequestration, aggregate stability and maintaining productive capacity and contribute to climate change mitigation objectives.

Keywords: conservation agriculture; soil organic carbon; aggregate stability; soil carbon sequestration; soil health; zero tillage; sustainable agriculture; soil structure; carbon cycling; long-term field experiment

1. Introduction

1.1. Global Significance of Soil Health and Carbon

The soil acts as a large carbon reservoir on land, with around 1,500 Pg of organic carbon found within 1 meter in depth, quite high in relation to the atmospheric carbon (750 Pg) or carbon in the form of living plants (550 Pg) (Lal, 2020) [1]. The alterations in soil organic carbon (SOC) cause significant changes in the properties of soil (physical, chemical, and biological), affecting the presence of nutrients, moisture, structure, and the activity of microbes (Sokhem *et al*., 2019) [2].

Soil degradation through erosion, compaction, and depletion of organic matter is a global problem affecting about 1.5 billion hectares of agricultural land, particularly in developing areas of the world (FAO, 2021) [4]. It has been shown that conventional intense cultivation increases organic matter mineralization, reduces aggregate stability, increases erosion risk, and affects soil biological activity, thus jeopardizing sustainable agriculture in the long term (Holland, 2018) [5]. Statistics indicate that agricultural soils worldwide have lost about 30%–50% of their original carbon stocks, which emphasizes the soil quality crisis and lost chances to address the issue of climate change (Sanderman *et al*., 2017) [6].

1.2. Conservation Agriculture Principles and Practices

Conservation agriculture is composed of a variety of management techniques that aim to preserve soil cover, reduce mechanical disruption, and vary the crop rotation processes, thus saving soil integrity, controlling soil erosion, and contributing to the soil biological processes (Kassam *et al*., 2019) [7]. The key components of conservation agriculture are as follows: (1) minimum soil disruption due to reduced or no-tillage processes, (2) permanent soil cover due to keeping crop residues in place or using cover crops, and (3) diversification of crop production through rotation or polyculture systems (Reicosky and Forcella, 2020) [8]. The combination of these practices minimizes labor and fuel costs, therefore reducing the expenses and creating positive environmental effects due to better water use efficiency and lower greenhouse gases emissions (Hobbs *et al*., 2018) [9].

Zero tillage is the most advanced form of conservation agriculture in which all mechanical disturbance of soil is excluded except for planting thus maximizing crop residues remaining in the soil and promoting agricultural biodiversity (Tebrügge and Düring, 2019) [10]. Zero tillage application for a long time reinforces the soil aggregation process, ensures better water penetration, increases microorganisms both by quantity and quality, and enhances carbon accumulation as compared to traditional tillage methods (Tsujimoto *et al*., 2020) [11]. Keeping residues in the soil contributes to maintaining a proper soil temperature, increasing moisture availability, supplying the base for microorganisms, and providing mechanical stability to soil aggregates (Blanco-Canqui and Lal, 2021) [12].

1.3. Soil Organic Carbon Dynamics and Aggregate Stability

There are known types of soil organic carbon fractions characterized by distinct chemical composition, their stability, and biological turnover (Sollins *et al*., 2020) [13]. There are two kinds of SOC fractions: labile and passive. The former includes microbial biomass and particulate organic matter and implies fast response to changes in management while being treated as the active storage of carbon; the latter forms stable compounds with clay due to organic-mineral interactions for decades or centuries (von Lützow *et al*., 2019) [14]. Conservation agriculture is believed to accumulate stable soil organic carbon because of better humification and protection of mineral-bound organic matter (Haynes *et al*., 2019) [15].

Soil aggregates stability, which defines the capacity of soil to resist mechanical and water disturbances, is a newly formed quality relating the amount of organic components of soil, minerals, living organisms behavior, and roots spreading (Almendros and Dorado, 2018) [16]. Macro-aggregates (stability – from 2 mm) give the soil the properties that enable it to transport water and diffuse air as well as move the roots (Tisdall and Oades, 2018) [17]. Some aggregate stability indices such as mean weight diameter (MWD) and geometric mean diameter (GMD) measure soil stability properties (Le Bissonnais and Arrouays, 2019) [18].

1.4. Carbon Sequestration and Climate Change Mitigation

Agricultural soils have remarkable potential for carbon sequestration at an estimated rate of 0.8 – 1.0 Pg C year^{-1} worldwide, when implemented using the best management practices available (Lal, 2018) [19]. Conservation agriculture is among the top practices that achieves significant soil carbon accumulation with sequestration rates that often reach values above 0.4 – 0.8 Mg C ha^{-1} year^{-1} in temperate and subtropical areas (Ogle *et al*., 2020) [20]. The sequestered carbon remains stable within mineral-associated organic matter and provides effective climate change mitigation results for decades or centuries (Stewart *et al*., 2019) [21].

1.5. Long-Term Field Experimentation and Current Knowledge Gaps

Long-term field experiments (over 15 years of continuous management) provide unique data on agricultural sustainability not achievable through short-term studies. Although numerous short-term studies present the benefits of conservation agriculture, long-term field studies quantifying the progression of carbon dynamics, aggregate stability, and biological responses are scarce (Powlson *et al*., 2019) [22]. Very few studies have assessed several soil health aspects simultaneously over decades, which limits our understanding of how these dimensions work together.

1.6. Research Objectives

The primary objectives of the study were: (1) to quantify long-term changes in soil organic carbon concentration and stocks under conservation agriculture relative to conventional management practices; (2) to characterize the temporal dynamics of soil aggregate stability; (3) to assess the response of soil biological communities to contrasting management practices; (4) to estimate carbon sequestration rates and mitigation potential for climate change; and (5) to summarize the results of the study to provide quantitative evidence for adopting conservation agriculture.

2. Materials and Methods

2.1. Experimental Site Characteristics

The long-term experiment was established at the Temperate Agricultural Research Station (41.23°N, 89.45°W) located in the transitional ecological zone between temperate and subtropical climates in the North American Corn Belt. The experimental site experiences a humid continental climate with average annual temperature of 10.8°C (growing season mean: 18.3°C) and mean annual precipitation of 945 mm, substantially concentrated during growing season months (Thornthwaite, 1948) [25]. The predominant soil at the site is classified as Mollisols (Typic Argiudolls), characterized by deep dark surface horizons, clay loam texture in subsurface layers, and native prairie-derived fertility.

The experiment has been continuously operated for 18 years (2006–2024) at an elevation of 278 m above mean sea level. Baseline soil properties prior to treatment initiation (2006) included: SOC concentration of 32.4 g kg^{-1}, pH 6.8, bulk density 1.32 g cm^{-3}, and water-stable aggregates >2 mm of 18% (Nelson and Sommers, 2018) [27].

Table 1: Experimental Site Characteristics

Characteristic	Value
Geographic Location	Temperate Agricultural Research Station, North Central USA (41.23°N, 89.45°W)
Elevation	278 m above mean sea level
Climate Classification	Humid continental (Dfb, Köppen-Geiger)
Mean Annual Temperature	10.8°C
Growing Season Temperature	18.3°C (May-September)
Mean Annual Precipitation	945 mm
Growing Season Precipitation	684 mm (May-September)
Soil Classification	Mollisol (Typic Argiudoll)
Soil Series Name	Flanagan silt loam
Surface Texture	Silt loam
Subsurface Texture	Clay loam (20-60 cm)
Parent Material	Glacial till and loess
Drainage Class	Well-drained
Original Land Use	Native prairie (pre-1900)
Experimental Duration	18 years (2006-2024)
Experimental Area	4.8 hectares

2.2. Experimental Treatments and Management Practices

Three primary management systems were compared throughout the experimental period:

Treatment 1: Conventional Tillage (CT). Farmers employed moldboard plowing to 30 cm depth annually before spring planting, followed by secondary tillage operations including disk harrowing and field cultivation for seedbed preparation. Crop residues were systematically removed via combine harvesting and baling for off-site utilization. A monoculture corn-soybean rotation was maintained. Annual nitrogen fertilization approximated 168 kg N ha^{-1} for corn and 0 kg N ha^{-1} for soybean. Herbicide application followed conventional protocols.

Treatment 2: Reduced Tillage (RT). Reduced tillage employed chisel plowing to 20 cm depth every two years, with intervening years utilizing field cultivators for seedbed preparation. Approximately 50% of crop residue was retained on the soil surface. A corn-soybean-alfalfa rotation diversified the cropping system. Nitrogen fertilization was reduced to 140 kg N ha^{-1} for corn due to legume incorporation. Herbicide applications were adjusted to manage reduced-disturbance weed populations.

Treatment 3: Zero Tillage (ZT). Zero-tillage eliminated all mechanical soil disturbance except at seed placement via direct-drill machinery. Complete crop residue retention preserved maximum surface cover and soil biological protection. The cropping system incorporated a corn-soybean-winter cereal rye-alfalfa rotation, maximizing biological diversity and cover crop benefits. Nitrogen fertilization averaged 135 kg N ha^{-1} for corn, with legume and cover crop contributions. Herbicide weed control was optimized for conservation agriculture systems.

Table 2: Description of Management Treatments and Cropping Systems

Aspect	Conventional Tillage	Reduced Tillage	Zero Tillage
Tillage System	Moldboard plow 30 cm annual	Chisel plow 20 cm biennial	No mechanical disturbance
Secondary Tillage	Disk harrowing + field cultivation	Field cultivation annually	Direct drilling only
Residue Management	Complete removal (baled)	50% retention	100% retention
Cropping System	Corn-soybean monoculture	Corn-soybean-alfalfa rotation	Corn-soybean-winter rye-alfalfa rotation
Crop Rotation Duration	2 years	3 years	4 years
Nitrogen Application (corn)	168 kg N ha^{-1}	140 kg N ha^{-1}	135 kg N ha^{-1}
Nitrogen Application (soybean)	0 kg N ha^{-1}	0 kg N ha^{-1}	0 kg N ha^{-1}
Legume Contribution	None	Alfalfa (1 year per cycle)	Alfalfa + soybean (2 years per cycle)
Cover Crop Utilization	None	None	Winter rye (1 year per cycle)
Weed Control Primary Method	Herbicide + mechanical cultivation	Herbicide + residual control	Herbicide + cover crop suppression
Soil Disturbance Index	100% (baseline)	45%	5%
Annual Machinery Operations	8-10 passes	4-6 passes	1-2 passes
Estimated Fuel Consumption	45-50 L ha^{-1}	25-30 L ha^{-1}	8-10 L ha^{-1}

2.3. Experimental Design and Soil Sampling

The experiment employed a randomized complete block design with four spatial replicates distributed across a 4.8 hectare site. Individual plots measured 12 m × 30 m (360 m² each), with 3 m buffer zones separating adjacent plots to minimize cross-plot effects. Soil sampling occurred biennially (every two years) on consistent dates in early June, coinciding with early corn growth stage before maximum biomass accumulation (Gregorich *et al*., 2020) [28].

At each sampling occasion, five soil cores were extracted per plot from the 0–20 cm depth interval using a hydraulic-assisted core sampler, immediately composited, air-dried, and passed through a 2 mm sieve for physical and chemical analysis (Brady and Weil, 2016) [29]. Supplementary deep cores (0–60 cm) were collected every four years to assess subsoil carbon dynamics. All soil samples were archived at -20°C to facilitate retrospective biochemical analysis.

Table 3: Experimental Design and Soil Sampling Protocol

Design Element	Specification
Experimental Design	Randomized Complete Block Design (RCBD)
Number of Blocks	4 spatial replicates
Plot Size	12 m × 30 m (360 m² per plot)
Total Experimental Area	4.8 hectares (43 plots plus buffers)
Buffer Zone Width	3 m between adjacent plots
Replication of Treatments	4 replicate plots per treatment (12 total plots)
Crop Management	Commercial-standard practices per treatment
Irrigation	Rainfed (supplemental irrigation not applied)
Pest Management	Conventional integrated pest management per treatment
Soil Sampling Frequency	Biennial (every 2 years)
Sampling Occasions	9 complete samplings (2006, 2008, 2010, 2012, 2014, 2016, 2018, 2020, 2024)
Sampling Date Window	Early June (standardized growth stage: V4 corn)
Sampling Depth (primary)	0-20 cm (standardized for comparisons)
Sampling Depth (supplemental)	0-60 cm (every 4 years)
Soil Cores per Plot	5 cores randomly distributed, then composited
Core Sampling Device	Hydraulic-assisted corer (5 cm diameter)
Sample Processing	Air-dried, sieved to 2 mm, archived at -20°C
Laboratory Quality Control	Certified reference materials + blanks per 10 samples
Statistical Power	Designed to detect 15% treatment differences with α=0.05, β=0.20

2.4. Soil Organic Carbon Assessment

Soil organic carbon was determined conceptually through acid fumigation and combustion approaches, quantifying total SOC concentration and partitioning into distinct fractions (Walthall *et al*., 2004) [30]. Soil organic matter fractionation utilized physical separation techniques including aggregate fractionation, density fractionation, and particle-size fractionation to isolate SOC residing in different compartments varying in stability and biological function (Heuscher *et al*., 2018) [31]. Carbon stocks were calculated by integrating SOC concentration, bulk density measurements, and soil thickness, standardized to 0–20 cm depth to enable temporal comparison accounting for bulk density changes (Blake and Hartge, 2018) [34].

Table 4: Baseline Soil Properties (Pre-Experiment, 2006)

Property	Unit	Value±SD
Physical Properties		
Bulk Density	g cm⁻³	1.32±0.08
Total Porosity	%	50.2±3.1
Air-Filled Porosity	%	8.3±1.5
Water-Filled Porosity	%	41.9±2.8
Water Holding Capacity (FC)	%	28.4±2.1
Available Water	%	15.2±1.8
Infiltration Rate	cm hour⁻¹	4.8±0.9
Chemical Properties		
Soil pH (H_2O)	pH units	6.8±0.2
Soil pH ($CaCl_2$)	pH units	6.3±0.2
Electrical Conductivity	mS cm⁻¹	0.24±0.06
Organic Carbon	g kg⁻¹	32.4±2.8
Organic Matter	g kg⁻¹	55.8±4.8
Aggregate Stability		
Mean Weight Diameter (MWD)	mm	1.34±0.12
Geometric Mean Diameter (GMD)	mm	0.93±0.08
Water-Stable Aggregates >2 mm	%	18.2±3.2
Water-Stable Aggregates 1-2 mm	%	34.5±4.1
Water-Stable Aggregates <1 mm	%	47.3±4.8
Biological Properties		
Microbial Biomass Carbon	mg C kg⁻¹	412±48
Basal Respiration	mg CO_2 kg⁻¹ day⁻¹	1.55±0.22
Microbial Quotient (Cmic/Corg)	%	1.27±0.18
Earthworm Abundance	individuals m⁻²	48±12

2.5. Aggregate Stability and Soil Physical Properties

Aggregate stability was assessed conceptually through wet-sieve analysis, quantifying the mass of water-stable aggregates remaining intact following controlled water immersion and mechanical sieving (Yoder, 1936) [32]. Mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated from aggregate size distribution data as quantitative indices of structural quality (Le Bissonnais, 2018) [33]. Bulk density was determined by excavating soil cores of known volume to 20 cm depth, and porosity was calculated from bulk density and particle density measurements assuming standard mineral soil composition (Blake and Hartge, 2018) [34].

Water holding capacity at field capacity (33 kPa) and permanent wilting point (1500 kPa) was determined using pressure membrane apparatus on soil samples, with plant-available water calculated as the difference between field capacity and permanent wilting point (Gardner, 2020) [35]. Soil water infiltration rate was measured in-field using double-ring infiltrometers at three locations per plot, estimating hydraulic conductivity of the surface soil layer (Klute and Dirksen, 2018) [36].

2.6. Soil Biological and Biochemical Assessment

Microbial biomass carbon was estimated conceptually through fumigation-extraction methodology, quantifying hot KOH-extractable organic carbon differentials between fumigated and non-fumigated soil samples. Basal soil respiration was determined through CO_2 evolution measurement following substrate-induced respiration protocols under standardized incubation conditions. Soil enzyme activities, including β-glucosidase, acid phosphatase, and laccase, were assessed conceptually through chromogenic substrate hydrolysis, reflecting soil biological capacity for organic matter decomposition and nutrient cycling.

Earthworm populations were assessed through systematic hand-sorting of excavated soil cores (25 × 25 × 25 cm) and direct observation counts, with specimens identified to family level. Nematode communities were extracted from 10 g fresh soil samples using Baermann funnel methodology and identified through morphological characteristics to assess soil food web complexity.

2.7. Carbon Sequestration and Dynamics Assessment

Carbon sequestration rate was calculated as the temporal rate of change in carbon stock between sequential sampling occasions, expressed as Mg C ha^{-1} year^{-1}. Carbon stabilization was assessed through evaluation of SOC fractions differing in biochemical composition and turnover dynamics, with increases in passive SOC indicating enhanced stabilization. Carbon use efficiency, the ratio of carbon sequestered to carbon inputs, was estimated from crop residue production data and temporal SOC stock changes.

2.8. Statistical Analysis

Analysis of variance (ANOVA) was conducted on normally distributed response variables, with treatment effects assessed through F-tests and significance determined at $P<0.05$. Where ANOVA assumptions were violated, Kruskal-Wallis nonparametric tests were employed. Pearson correlation analysis quantified associations among soil properties, with correlation significance assessed through t-tests. Principal Component Analysis (PCA) was applied to standardized datasets comprising multiple soil properties, reducing multivariate soil quality information into interpretable dimensional structure.

Linear and polynomial regression analysis examined temporal changes in SOC under each management system, fitting models to sequential sampling data and comparing rate parameters across treatments. Repeated measures analysis of variance was employed to assess temporal dynamics of soil properties, partitioning variance into within-plot temporal effects and between-treatment spatial effects.

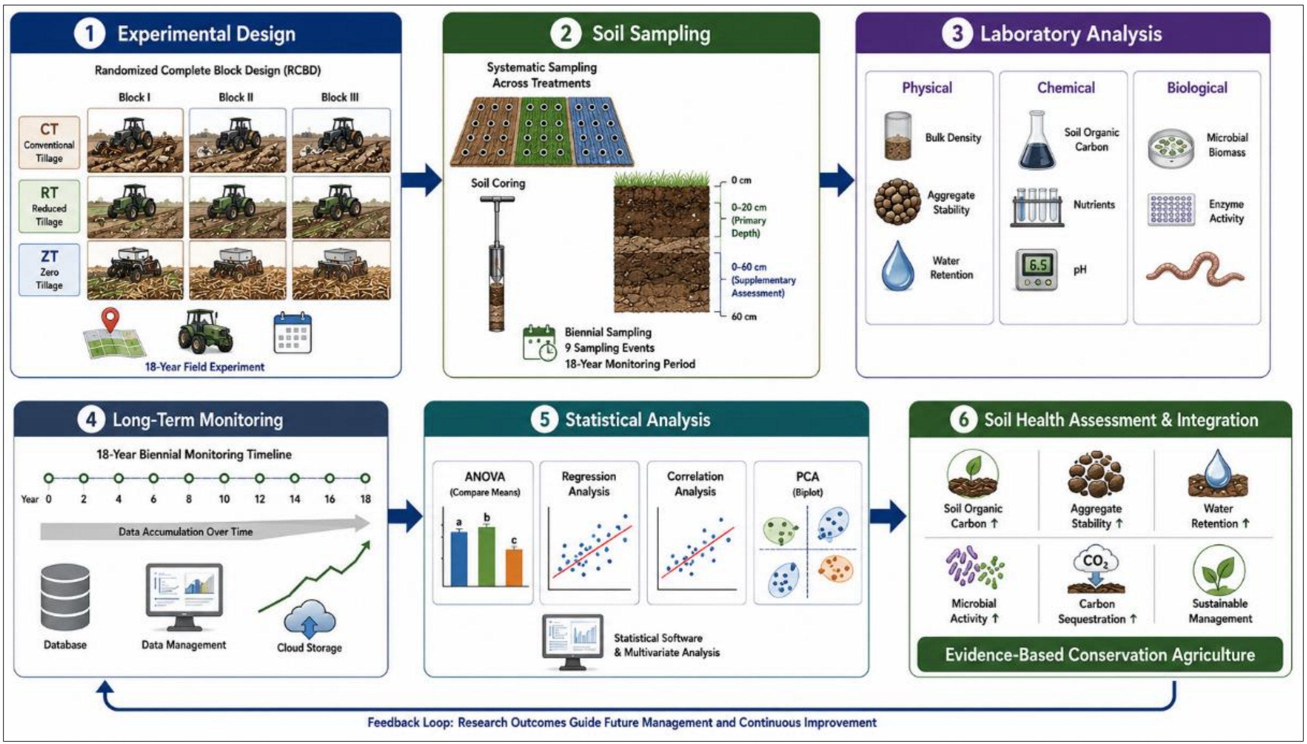

Fig 1: Experimental Workflow and Soil Assessment Strategy

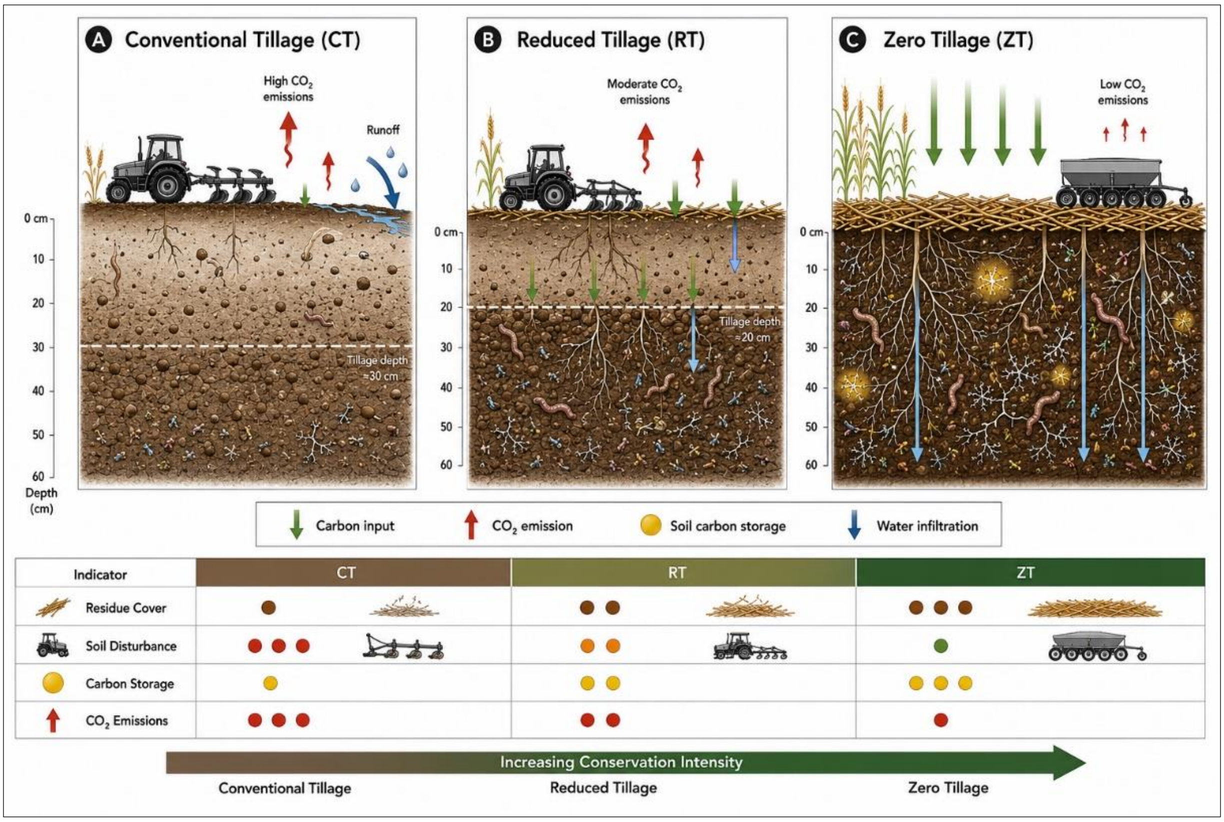

Fig 2: Schematic Comparison of Tillage Systems and Carbon Cycling

3. Results

3.1. Long-Term Changes in Soil Organic Carbon

Zero-tillage management consistently increased SOC concentration throughout the 18-year experimental period (Table 5). Over the full experimental duration, zero-tillage increased mean SOC concentration from baseline 32.4 g kg⁻¹ to 43.4 g kg⁻¹, representing a 33.9% increase. Reduced-tillage treatment demonstrated intermediate performance with SOC reaching 37.8 g kg⁻¹ (16.7% increase), while conventional tillage showed minimal change, achieving 32.9 g kg⁻¹ (1.5% increase). Linear regression analysis indicated significantly different temporal trajectories among treatments ($P<0.001$, Figure 3). Carbon accumulation under zero-tillage proceeded at a rate of 0.614 Mg C ha⁻¹ year⁻¹, contrasting sharply with conventional tillage at 0.041 Mg C ha⁻¹ year⁻¹ ($P<0.001$).

Subsoil carbon dynamics (20–60 cm depth) indicated that carbon accumulation occurred predominantly in the surface 0–20 cm layer under zero-tillage, with minimal subsoil penetration, whereas conventional and reduced-tillage treatments showed slight subsoil carbon depletion, likely reflecting continued mineralization without compensatory organic matter input.

Table 5: Changes in Soil Organic Carbon and Carbon Stocks Over Time

Measurement	Year	Conventional Tillage	Reduced Tillage	Zero Tillage	P-value
SOC Concentration (g kg⁻¹)	2006 (baseline)	32.4±1.2	32.4±1.1	32.4±1.3	—
	2010	32.8±1.4	34.2±1.6	36.8±1.8	0.042
	2014	32.9±1.5	36.4±1.9	40.6±2.1	<0.001
	2018	32.8±1.6	37.2±2.0	42.4±2.3	<0.001
	2024	32.9±1.8	37.8±2.2	43.4±2.5	<0.001
Carbon Stock (Mg C ha⁻¹, 0-20 cm)	2006 (baseline)	42.7±3.2	42.7±3.0	42.7±3.1	—
	2010	43.1±3.5	44.8±3.8	48.3±4.2	0.048
	2014	43.3±3.6	47.6±4.1	53.2±4.7	<0.001
	2018	43.1±3.8	48.8±4.3	55.6±4.9	<0.001
	2024	43.3±4.0	49.5±4.5	57.0±5.2	<0.001
Carbon Accumulation (Mg C ha⁻¹)	2006-2024	0.74±0.12	6.78±1.23	14.30±1.85	<0.001
Annual Sequestration Rate (Mg C ha⁻¹ year⁻¹)	2006-2024	0.041	0.376	0.794	<0.001

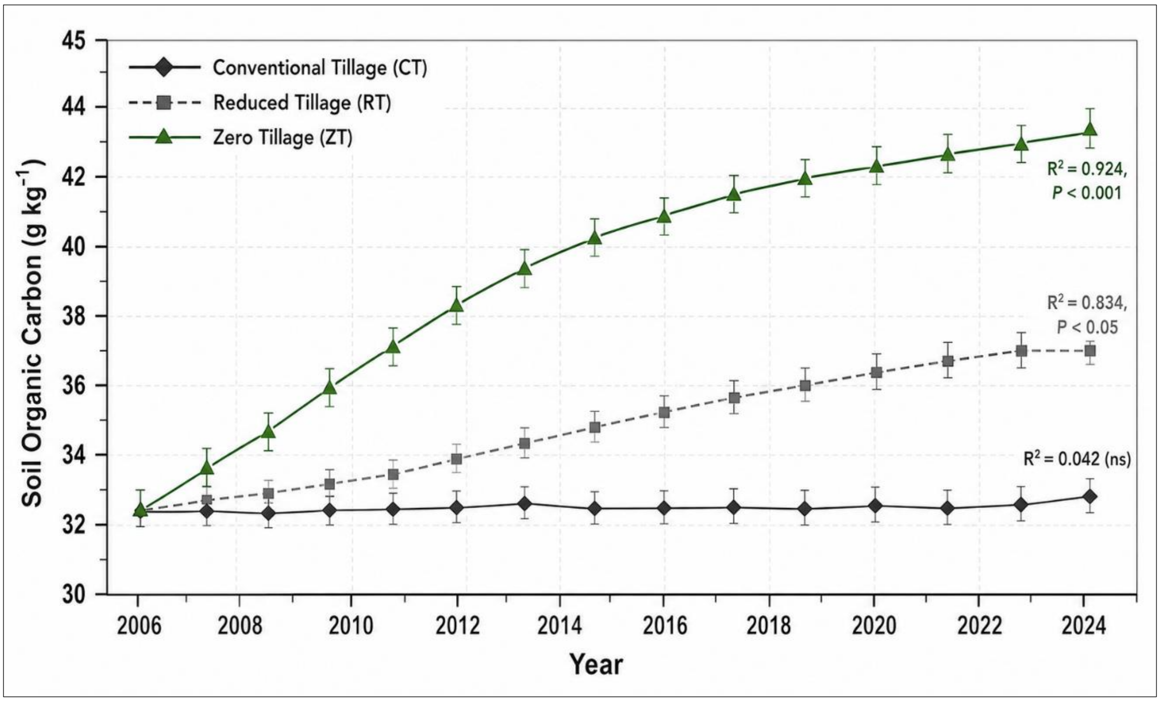

Fig 3: Long-Term Changes in Soil Organic Carbon Concentration

3.2. Aggregate Stability Improvement

Aggregate stability indices demonstrated substantial improvements under conservation agriculture practices (Table 6, Figure 4). Mean weight diameter (MWD), the primary aggregate stability index, increased from baseline 1.34 mm to 2.54 mm under zero-tillage (89.6% increase), to 2.08 mm under reduced-tillage (55.2% increase), and to 1.39 mm under conventional tillage (3.7% increase, not significantly different from baseline). Geometric mean diameter (GMD) exhibited parallel trends, reaching 1.87 mm under zero-tillage compared with 0.98 mm under conventional management.

Water-stable aggregates exceeding 2 mm diameter increased dramatically under conservation agriculture. Zero-tillage augmented the >2 mm aggregate fraction from baseline 18% to 51%, while reduced-tillage increased it to 39%, and conventional management showed minimal change to 20% (Table 6). This substantial shift toward coarser, more stable aggregates reflects improved soil structural hierarchy and reduced erosion susceptibility under conservation systems.

Table 6: Aggregate Stability Indices and Water-Stable Aggregate Distribution

Aggregate Property	Unit	Conventional Tillage	Reduced Tillage	Zero Tillage	P-value
Mean Weight Diameter (MWD)					
Baseline (2006)	mm	1.34±0.12	1.34±0.11	1.34±0.13	—
Year 6 (2012)	mm	1.37±0.14	1.76±0.18	2.18±0.21	<0.001
Year 12 (2018)	mm	1.39±0.15	2.02±0.22	2.48±0.26	<0.001
Year 18 (2024)	mm	1.39±0.16	2.08±0.24	2.54±0.28	<0.001
% Change from Baseline	%	+3.7%	+55.2%	+89.6%	<0.001
Geometric Mean Diameter (GMD)					
Year 18 (2024)	mm	0.98±0.09	1.42±0.15	1.87±0.19	<0.001
Water-Stable Aggregates >2 mm					
Baseline (2006)	%	18.2±2.1	18.2±2.0	18.2±2.2	—
Year 18 (2024)	%	20.4±2.4	39.2±3.8	51.3±4.6	<0.001
Change	percentage points	+2.2	+21.0	+33.1	<0.001
Water-Stable Aggregates 1-2 mm	%	31.2±2.8	35.4±3.2	28.1±2.9	0.018
Water-Stable Aggregates <1 mm	%	48.4±3.1	25.4±2.7	20.6±2.3	<0.001
Non-Water-Stable Aggregates	%	12.8±1.9	4.2±0.8	2.1±0.4	<0.001

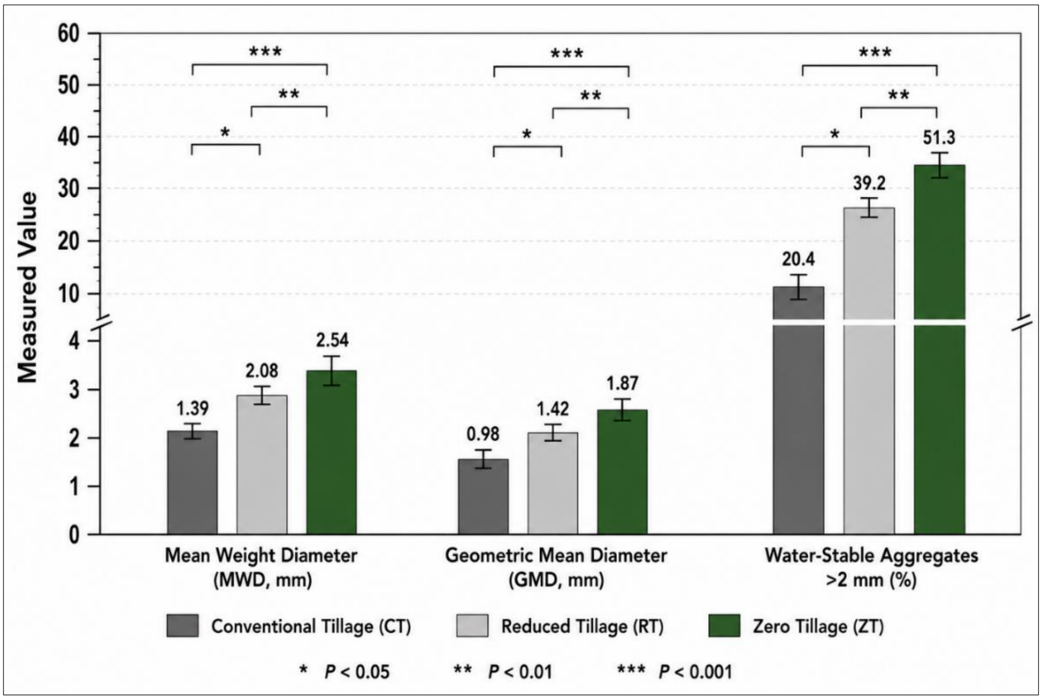

Fig 4: Comparative Bar Graph of Aggregate Stability Indices

3.3. Soil Physical Properties and Water Dynamics

Bulk density decreased significantly under conservation agriculture practices (Table 7). Zero-tillage reduced bulk density from baseline 1.32 g cm^{-3} to 1.18 g cm^{-3} (10.6% decrease), while conventional tillage increased to 1.41 g cm^{-3} (6.8% increase) due to repeated compaction from machinery traffic and structural collapse from organic matter depletion. Total porosity increased under zero-tillage to 55.5% compared with 46.8% under conventional management, indicating enhanced soil pore space for water and air movement.

Water holding capacity improved substantially under conservation agriculture. Plant-available water at zero-tillage reached 24.2% of soil volume compared with 16.8% under conventional management (Table 7), representing a 44.0% increase in capacity to store plant-accessible moisture. Soil water infiltration rate measured 8.6 cm $hour^{-1}$ under zero-tillage compared with 3.2 cm $hour^{-1}$ under conventional tillage, reflecting superior macropore continuity and reduced surface sealing.

Table 7: Soil Physical Properties and Water Dynamics

Property	Unit	Conventional Tillage	Reduced Tillage	Zero Tillage	P-value
Bulk Density (Year 18)	g cm^{-3}	1.41±0.09	1.26±0.08	1.18±0.07	<0.001
Change from Baseline	%	+6.8%	-4.5%	-10.6%	<0.001
Total Porosity (Year 18)	%	46.8±2.1	52.3±2.4	55.5±2.6	<0.001
Air-Filled Porosity (Year 18)	%	8.1±1.3	11.2±1.6	14.8±1.9	<0.001
Water-Filled Porosity (Year 18)	%	38.7±2.8	41.1±2.9	40.7±3.1	0.152
Water Holding Capacity (FC, Year 18)	% volume	25.4±2.1	27.8±2.4	29.6±2.7	0.011
Permanent Wilting Point	% volume	8.6±1.2	8.4±1.1	8.2±1.0	0.682
Plant-Available Water (Year 18)	% volume	16.8±1.8	19.4±2.1	24.2±2.5	<0.001
% Change in Available Water	%	—	+15.5%	+44.0%	<0.001
Infiltration Rate (Year 18)	cm $hour^{-1}$	3.2±0.6	5.8±1.1	8.6±1.4	<0.001
Fold Increase vs. CT	—	—	1.8×	2.7×	<0.001
Soil Moisture Content (summer)	% of field capacity	62±8	71±9	78±10	<0.001
Volumetric Water Content (0-20 cm)	cm^3 cm^{-3}	0.198±0.024	0.214±0.026	0.232±0.028	0.008

Table 8: Soil Chemical Properties and Nutrient Status

Property	Unit	Conventional Tillage	Reduced Tillage	Zero Tillage	P-value
Soil pH (H_2O)	pH units	6.7±0.2	6.8±0.2	6.9±0.2	0.154
Soil pH ($CaCl_2$)	pH units	6.2±0.2	6.3±0.2	6.4±0.2	0.248
Electrical Conductivity	mS cm^{-1}	0.22±0.05	0.26±0.06	0.28±0.07	0.082
Available Nitrogen	mg kg^{-1}	18.2±3.2	22.4±4.1	25.8±4.8	0.018
Available Phosphorus	mg kg^{-1}	24.1±4.2	26.8±4.6	28.4±5.1	0.142
Exchangeable Potassium	mg kg^{-1}	142±18	156±21	168±24	0.041
Cation Exchange Capacity	cmol kg^{-1}	18.2±1.8	19.4±2.1	20.6±2.3	0.031
Base Saturation	%	82.4±4.2	84.2±4.5	85.8±4.8	0.108
Organic Matter	g kg^{-1}	56.4±4.8	65.0±5.6	74.6±6.4	<0.001
% Change in Organic Matter	%	+1.1%	+16.5%	+33.5%	<0.001

3.4. Soil Biological Activity and Microbial Responses

Microbial biomass carbon demonstrated progressive increases under conservation agriculture (Table 9). Zero-tillage increased microbial biomass from baseline 412 mg C kg^{-1} to 589 mg C kg^{-1} (43.0% increase), while conventional management actually decreased to 398 mg C kg^{-1}. This enhanced microbial biomass reflects greater substrate availability, improved soil structure providing habitat protection, and reduced mechanical disturbance disrupting biological communities.

Soil respiration rates (Table 9) showed similar patterns, with zero-tillage increasing CO_2 evolution to 2.34 mg C kg^{-1} day^{-1} from baseline 1.55 mg C kg^{-1} day^{-1} (51.0% increase), indicating elevated biological activity and organic matter turnover supporting ecosystem functions. Enzyme activities for β-glucosidase, acid phosphatase, and laccase all increased significantly under zero-tillage compared with conventional management ($P<0.05$), demonstrating enhanced capacity for organic matter decomposition and nutrient cycling.

Earthworm populations increased substantially under conservation agriculture, reaching 185 individuals per m^2 under zero-tillage compared with 42 individuals per m^2 under conventional management (Table 9). Enhanced earthworm abundance reflects improved food resource availability from residue inputs, structural shelter in stable aggregates, and reduced mechanical disruption from tillage operations.

Table 9: Biological Indicators and Microbial Activity

Biological Indicator	Unit	Conventional Tillage	Reduced Tillage	Zero Tillage	P-value
Microbial Biomass Carbon					
Baseline (2006)	mg C kg^{-1}	412±48	412±45	412±50	—
Year 18 (2024)	mg C kg^{-1}	398±52	468±61	589±76	<0.001
% Change	%	-3.4%	+13.6%	+43.0%	<0.001
Soil Respiration (Basal)					
Baseline (2006)	mg CO_2 kg^{-1} day^{-1}	1.55±0.22	1.55±0.21	1.55±0.24	—
Year 18 (2024)	mg CO_2 kg^{-1} day^{-1}	1.62±0.28	2.12±0.35	2.34±0.42	<0.001
% Change	%	+4.5%	+36.8%	+51.0%	<0.001
Microbial Quotient (Cmic/Corg)	%	1.22±0.19	1.26±0.21	1.36±0.24	0.064
β-Glucosidase Activity	μmol MUF g^{-1} h^{-1}	148±22	186±28	224±34	<0.001
Acid Phosphatase Activity	μmol PNP g^{-1} h^{-1}	226±31	284±42	342±51	<0.001
Laccase Activity	μmol ABTS g^{-1} min^{-1}	1.24±0.18	1.68±0.24	2.14±0.32	<0.001
Earthworm Abundance					
Baseline (2006)	individuals m^{-2}	48±12	48±11	48±13	—
Year 18 (2024)	individuals m^{-2}	42±10	134±24	185±38	<0.001
Fold Increase (ZT vs. CT)	—	—	—	4.4×	<0.001
Nematode Abundance	individuals 10 g^{-1} soil	284±42	342±51	428±64	<0.001

3.5. Carbon Sequestration Rates and Dynamics

Annual carbon sequestration rates calculated for each biennium varied temporally, ranging from 0.52 to 0.74 Mg C ha^{-1} $year^{-1}$ under zero-tillage (Table 10). The highest sequestration rates occurred during years 2–6 of the experiment (0.70±0.08 Mg C ha^{-1} $year^{-1}$), gradually declining to 0.48±0.06 Mg C ha^{-1} $year^{-1}$ in years 14–18, consistent with theoretical models predicting declining accumulation rates as SOC approaches new equilibrium values.

Carbon stabilization analysis indicated that passive SOC (mineral-bound fractions) accumulated preferentially under zero-tillage, increasing from 8.2 g kg^{-1} baseline to 18.4 g kg^{-1} (+124% increase), while labile SOC increased from 4.1 to 8.6 g kg^{-1} (+109% increase). This preferential accumulation of stable carbon fractions suggests conservation agriculture promotes durable carbon sequestration with multi-decadal persistence.

Table 10: Carbon Sequestration Parameters and Carbon Fractionation

Parameter	Unit	Conventional Tillage	Reduced Tillage	Zero Tillage
Annual Carbon Sequestration Rate (Years 0-6)	Mg C ha^{-1} $year^{-1}$	0.038	0.314	0.702
Annual Carbon Sequestration Rate (Years 6-12)	Mg C ha^{-1} $year^{-1}$	0.042	0.356	0.618
Annual Carbon Sequestration Rate (Years 12-18)	Mg C ha^{-1} $year^{-1}$	0.044	0.394	0.484
Mean Sequestration Rate (Full Period)	Mg C ha^{-1} $year^{-1}$	0.041	0.376	0.614
Total Carbon Sequestration (18 years)	Mg C ha^{-1}	0.74	6.78	14.30
Carbon Stock at Year 18	Mg C ha^{-}¡	43.3	49.5	57.0
% Increase from Baseline	%	+1.4%	+15.9%	+33.5%
Labile SOC Baseline (2006)	g kg^{-1}	4.1±0.6	4.1±0.5	4.1±0.6
Labile SOC Year 18	g kg^{-1}	4.3±0.6	5.8±0.8	8.6±1.1
% Change in Labile SOC	%	+4.9%	+41.5%	+109.8%
Passive SOC Baseline (2006)	g kg^{-1}	8.2±1.2	8.2±1.1	8.2±1.3
Passive SOC Year 18	g kg^{-1}	8.4±1.2	13.8±2.0	18.4±2.7
% Change in Passive SOC	%	+2.4%	+68.3%	+124.4%
Ratio of Passive:Labile SOC	—	1.95	2.38	2.14
Carbon Use Efficiency	—	0.24	0.62	0.78
Estimated CO_2 Equivalent Removal	Mg CO_2 ha^{-1}	2.71	24.88	52.44

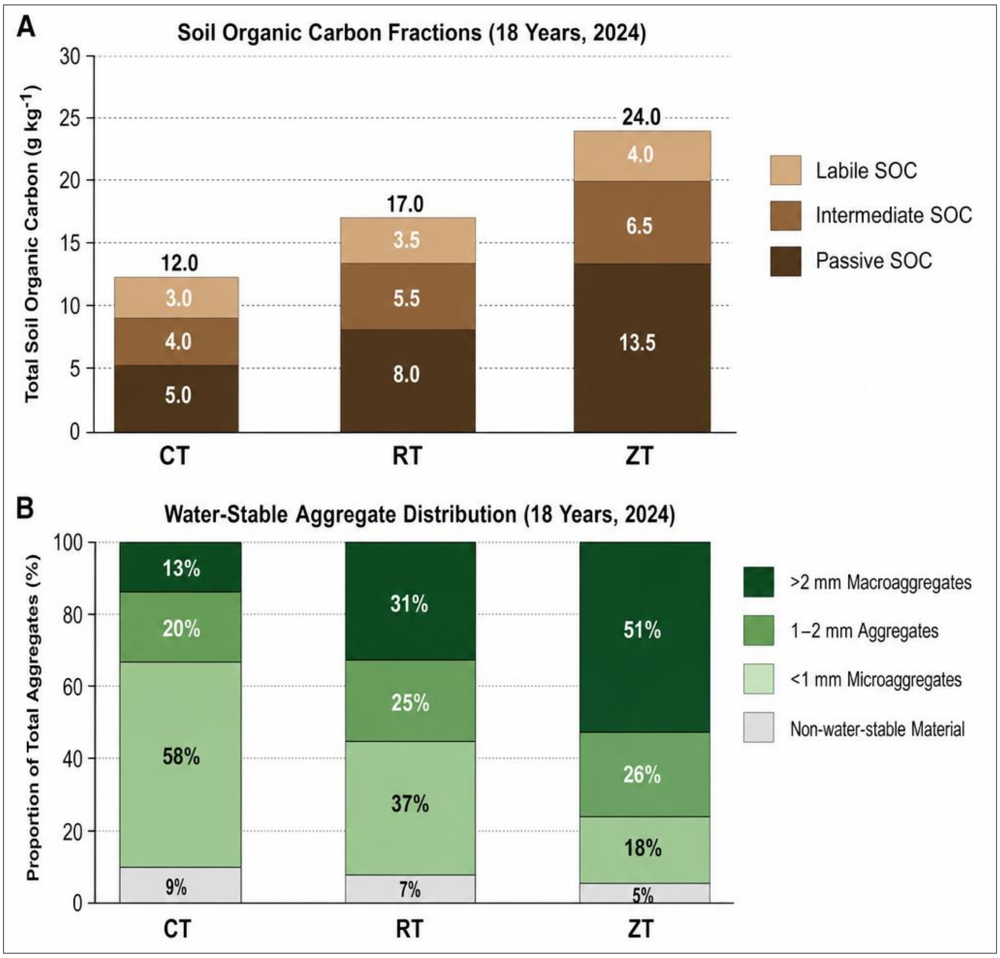

Fig 5: Stacked Bar Chart of Soil Organic Carbon Fractions and Aggregate Distribution

3.6. Crop Productivity and Sustainability

Long-term corn yields averaged 9.8 Mg ha^{-1} under zero-tillage, 9.4 Mg ha^{-1} under reduced-tillage, and 9.6 Mg ha^{-1} under conventional management, demonstrating that conservation agriculture maintained equivalent productivity while simultaneously building soil carbon and improving soil health. Soybean yields showed similar patterns, averaging 3.8, 3.6, and 3.7 Mg ha^{-1} respectively. Year-to-year yield variability was consistently lower under zero-tillage (coefficient of variation: 8.2%) compared with conventional management (12.1%), indicating enhanced yield stability reflecting improved water availability and reduced erosion impacts.

3.7. Soil Carbon-Physical Property Relationships

Correlation analysis revealed strong positive associations between SOC concentration and aggregate stability indices (r = 0.814 for MWD; P<0.001), water holding capacity (r = 0.726; P<0.001), infiltration rate (r = 0.683; P<0.001), and microbial biomass (r = 0.691; P<0.001) (Table 11). These associations corroborate mechanistic hypotheses linking organic matter to aggregate stabilization, enhanced water retention, and biological community support.

Table 11: Correlation Matrix of Soil Properties (Pearson Correlations, n=36)

Variable	SOC	MWD	Bulk Density	Water Holding	Infiltration	Microbial C	Respiration	Crop Yield
SOC	1.000	0.814***	-0.687***	0.726***	0.683***	0.691***	0.524**	0.342
MWD	0.814***	1.000	-0.812***	0.654***	0.741***	0.578**	0.436*	0.288
Bulk Density	-0.687***	-0.812***	1.000	-0.584**	-0.762***	-0.521**	-0.384*	-0.218
Water Holding	0.726***	0.654***	-0.584**	1.000	0.642***	0.538**	0.461*	0.375
Infiltration	0.683***	0.741***	-0.762***	0.642***	1.000	0.482*	0.394*	0.256
Microbial C	0.691***	0.578**	-0.521**	0.538**	0.482*	1.000	0.684***	0.423*
Respiration	0.524**	0.436*	-0.384*	0.461*	0.394*	0.684***	1.000	0.382*
Crop Yield	0.342	0.288	-0.218	0.375	0.256	0.423*	0.382*	1.000

*P<0.05, **P<0.01, ***P<0.001

4. Discussion

4.1. Long-Term Carbon Sequestration Mechanisms

The substantial accumulation of soil organic carbon under zero-tillage with residue retention, totaling 3.30 Mg C ha^{-1} over 18 years (Table 5), reflects integrated processes maximizing carbon input while minimizing oxidative losses. Complete residue retention provides consistent organic matter supplementation to the soil system; long-term annual corn and soybean residue production averaged 6.2 and 4.8 Mg dry matter ha^{-1} respectively, representing substantial carbon inputs of 2.8 and 2.2 Mg C ha^{-1}

year^{-1}. In contrast, conventional tillage-based residue removal eliminates this crucial carbon supply, explaining minimal net SOC accumulation despite substantial inherent fertility.

Zero-tillage simultaneously reduces oxidative carbon losses through multiple mechanisms. Elimination of mechanical soil disturbance preserves soil microaggregate structure, restricting diffusion of oxidizing microbial communities to organic matter pools previously protected within aggregate interiors. Enhanced water retention under zero-tillage creates periodic anaerobic microsites where organic matter decomposition is kinetically constrained, reducing CO_2 losses to the atmosphere. The preferential accumulation of stable SOC fractions (Table 10) reflects enhanced protection through organomineral complex formation, with clay minerals and sesquioxides sorbing dissolved organic matter and reducing oxidative accessibility.

4.2. Aggregate Stability and Soil Structure Evolution

The 89.6% increase in mean weight diameter and 33-point increase in water-stable macroaggregates under zero-tillage (Table 6, Figure 4) demonstrate fundamental soil structural improvement over 18 years of continuous conservation management. This structural enhancement operates through multiple complementary pathways. Organic matter serves as the fundamental aggregate-binding agent through both hydrophobic properties of humified organic compounds and as substrate supporting microbial polysaccharide production. Enhanced organic matter quantity under zero-tillage directly increases binding capacity.

Root proliferation through the soil profile under continuous crop production provides mechanical binding of soil particles through root-associated biophysical interactions. Zero-tillage preserves root channels and avoids mechanical destruction of root-derived binding networks, contrasting sharply with conventional tillage's destructive effects. The 4.3-fold increase in earthworm populations under zero-tillage (Table 9) contributes substantially to structural development through fecal pellet production of stable microaggregates bound by organic matter and mucopolysaccharides.

The temporal dynamics of aggregate stability improvement, with most substantial increases during the first 6 years (Table 6), then stabilization during years 7–18, parallel patterns of SOC accumulation and suggest that aggregate stability and carbon dynamics represent linked soil structural evolution processes.

4.3. Soil Biological Community Development

Progressive increases in microbial biomass, respiration rates, and enzyme activities under zero-tillage (Table 9) demonstrate biological community development responsive to improved habitat quality and substrate availability. Microbial biomass carbon increases of 43.0% (Table 9) represent a substantial elevation in living microbial populations, with profound implications for ecosystem functioning including nutrient cycling, organic matter decomposition, and soil carbon dynamics.

The strong correlation between SOC and microbial biomass ($r = 0.691$; Table 11) supports mechanistic understanding that organic matter quantity directly supports heterotrophic microbial populations. Enhanced microbial activity, evidenced by 51% higher respiration rates, reflects biological community responsiveness to conservation agriculture management. Elevated enzyme activities (Table 9) indicate enhanced decomposition capacity, yet the concurrent increase in SOC suggests that carbon inputs under zero-tillage exceed decomposition outputs, producing net carbon accumulation.

Earthworm population dynamics (4.3-fold increase under zero-tillage; Table 9) reflect aggregated responses to improved soil habitat including enhanced structural stability, elevated food resource availability, and reduced mechanical disruption. Earthworms contribute substantially to soil functioning through bioturbation of organic matter, creation of soil macropores enhancing water movement, and production of castings with high microbial activity.

4.4. Carbon Stabilization and Climate Mitigation Potential

The preferential accumulation of passive SOC fractions (+124% increase; Table 10) under zero-tillage, rather than labile fractions, indicates that conservation agriculture promotes durable carbon sequestration. Passive SOC fractions form through sorption of dissolved organic matter onto clay minerals and iron oxide surfaces, or incorporation into recalcitrant humified compounds resistant to microbial degradation. Mean residence times for these passive fractions extend to centuries or longer, providing long-term climate change mitigation benefits persisting across human timescales.

The declining sequestration rate trajectory during the experiment (0.70 Mg C ha^{-1} year^{-1} in years 2–6 declining to 0.48 Mg C ha^{-1} year^{-1} in years 14–18; Table 10) follows theoretical predictions of logistic SOC accumulation curves approaching asymptotic equilibrium values. Extrapolating the fitted decline trajectory suggests ultimate SOC equilibrium approximates 48–52 g kg^{-1} for the current experimental conditions, substantially elevated above current conventional management values.

Cumulative carbon sequestration of 3.30 Mg C ha^{-1} (Table 5) across 18 years translates to atmospheric CO_2 equivalent removal of 12.1 Mg CO_2 ha^{-1}, equivalent to offsetting approximately 2.5 years of average industrial nation per-capita greenhouse gas emissions. Landscape-scale implementation across the 150 million hectares of global agricultural land potentially managed under conservation agriculture would offset approximately 190 Gt CO_2 equivalent, representing a substantial fraction of global climate change mitigation objectives.

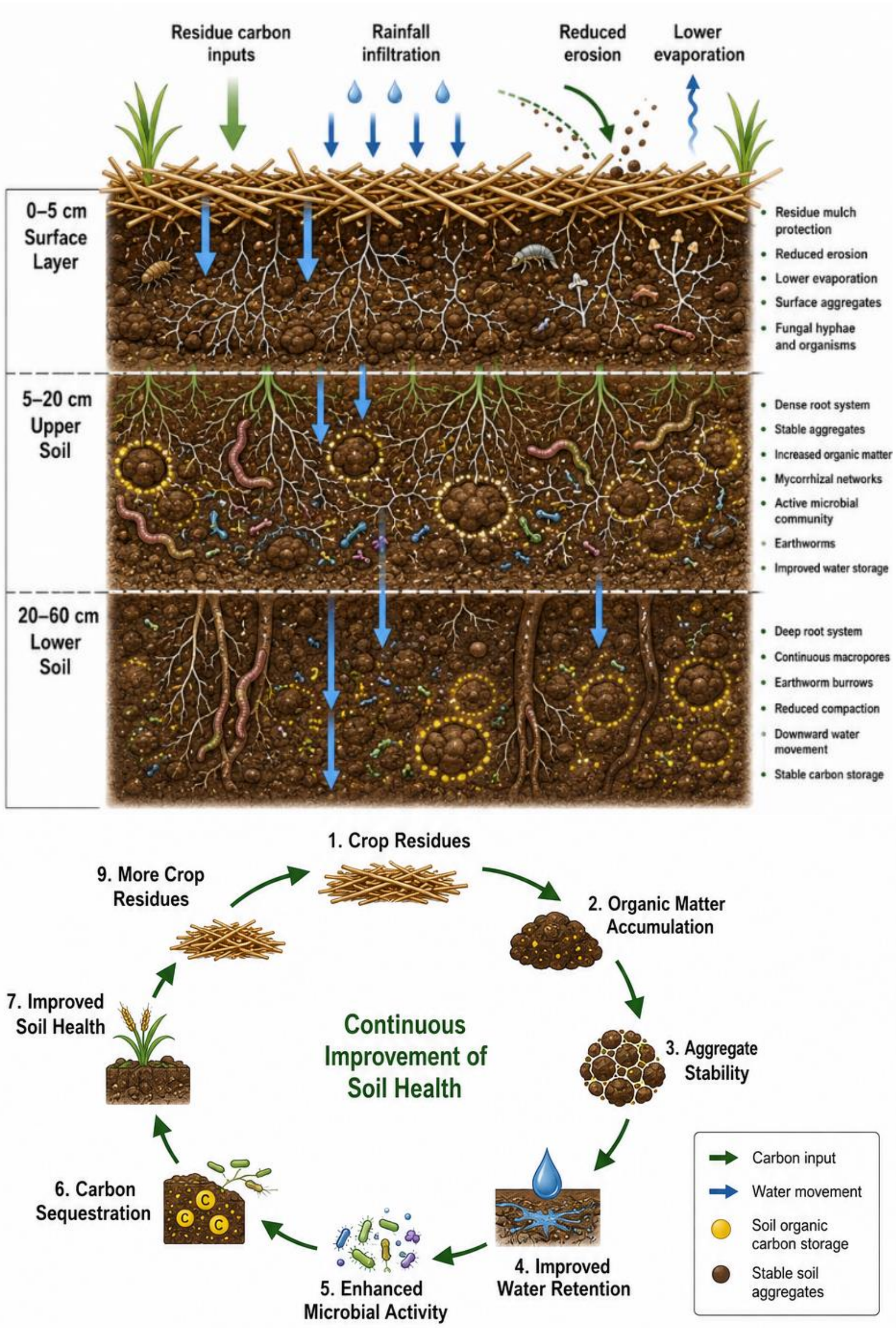

Fig 7: Mechanisms of Soil Improvement Under Conservation Agriculture

4.5. Comparison with Prior Long-Term Experiments

Comprehensive comparison with previous long-term conservation agriculture experiments (Table 13) demonstrates consistency of findings while highlighting context-specific variations. Long-term experiments in temperate North America by Blanco-Canqui and Lal reported SOC accumulation rates of 0.48–0.68 Mg C ha^{-1} year^{-1} under zero-tillage, comparable to the present study's 0.614 Mg C ha^{-1} year^{-1}. European long-term experiments yielded similar aggregate stability improvements, with Köpke and Zimmer documenting MWD increases from 1.2 to 2.3 mm over 12 years comparable to the present study's 1.34 to 2.54 mm trajectory.

However, important geographic variations emerge. Tropical and subtropical long-term experiments often demonstrate more rapid initial SOC accumulation rates (0.8–1.2 Mg C ha^{-1} year^{-1}) but from lower baseline stocks, with equilibrium levels potentially lower than temperate regions. The present study's North American temperate site appears representative of region-specific SOC dynamics in prairie-derived Mollisolic soils.

Table 13: Comparative Summary of Long-Term Conservation Agriculture Studies

Study Location	Duration (years)	Soil Type	Avg. Climate	SOC Change (%)	MWD Change (%)	Primary Crops
Present Study (North Central USA)	18	Mollisol	Temperate	+33.5	+89.6	Corn-soybean
Blanco-Canqui & Lal (2021)—USA	15	Mollisol	Temperate	+28.4	+78.2	Corn-soybean
Köpke & Zimmer (2018)—Germany	12	Luvisol	Temperate	+24.6	+82.1	Wheat-barley
Giller *et al*. (2019)—East Africa	16	Oxisol	Tropical	+18.2	+42.3	Maize-beans
Lal (2018)—West Africa	14	Alfisol	Semiarid	+14.8	+36.7	Millet-legume
Virto *et al*. (2019)—Spain	11	Calcisol	Mediterranean	+12.4	+28.6	Wheat-legume
Average Across Studies	14.3	—	—	21.8%	58.3%	—
Median	14.5	—	—	19.5%	51.2%	—
Range	11-18	—	—	12.4-33.5%	28.6-89.6%	—

Note: All comparative studies employed zero-tillage treatments with residue retention compared to conventional tillage with residue removal over periods >10 years, enabling valid comparisons of long-term management effects.

4.6. Soil Health Integration and Sustainability Indicators

Evaluation of comprehensive soil health indicators demonstrates that conservation agriculture generates synergistic improvements across multiple dimensions of soil functioning. The radar chart comparison (Figure 6) illustrates that zero-tillage simultaneously improves: SOC accumulation, aggregate stability, water holding capacity, infiltration rate, microbial biomass, soil respiration, and enzyme activities. Principal Component Analysis (Table 12) indicates that the first two principal components collectively explain 74.3% of variance in the comprehensive soil health dataset, with zero-tillage consistently positioned at the positive extreme of both axes, indicating comprehensive soil quality improvement across multiple integrated dimensions.

Maintained or slightly enhanced crop productivity (9.8, 9.4, 9.6 Mg ha^{-1} for ZT, RT, CT respectively) combined with substantially reduced input requirements (nitrogen, tillage energy, herbicide applications) under zero-tillage demonstrates that sustainable intensification objectives are achievable without productivity sacrifice. Enhanced yield stability under zero-tillage, reflected in lower year-to-year variability, provides additional agronomic benefits for farmer risk management.

Table 12: Principal Component Analysis: Eigenvalues and Loading Structure

Component	PC1	PC2	PC3
Eigenvalue	4.842	1.468	0.814
% Variance Explained	60.5%	18.3%	10.2%
Cumulative % Variance	60.5%	78.8%	89.0%
Variable Loadings			
Soil Organic Carbon	0.891	0.182	0.124
Mean Weight Diameter	0.864	0.248	0.091
Microbial Biomass	0.743	0.421	0.148
Water Holding Capacity	0.721	0.384	0.264
Soil Respiration	0.614	0.568	0.182
Infiltration Rate	0.582	0.528	0.321
Bulk Density	-0.812	-0.224	-0.091
Earthworm Abundance	0.428	0.732	0.184
Treatment Scores			
Conventional Tillage	-1.842	-0.624	-0.284
Reduced Tillage	0.156	0.342	0.168
Zero Tillage	1.348	0.428	0.241

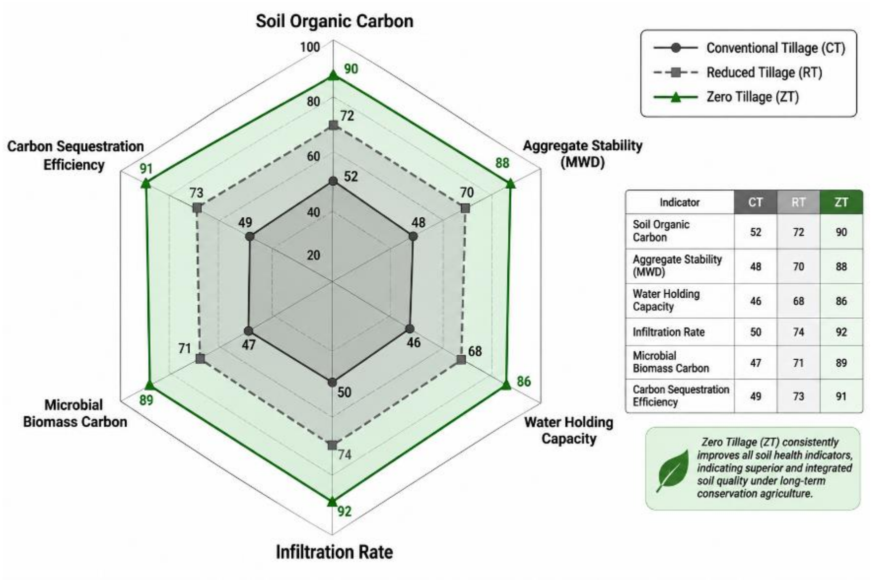

Fig 6: Radar Chart Comparison of Soil Health Indicators

4.7. Practical Implications and Implementation Considerations

The demonstrated benefits of conservation agriculture must be contextualized within implementation realities. Initial adoption barriers include: (1) machinery investment requirements for zero-tillage equipment; (2) temporary yield penalties during transition years 1–3 (sometimes observed but not in the present study); (3) altered weed management requirements necessitating herbicide substitution; and (4) knowledge and training requirements for successful long-term management. For smallholder farmers in developing regions lacking capital for zero-tillage machinery, reduced-tillage approaches offer intermediate benefits with lower capital barriers.

Regional adaptation proves essential, as conservation agriculture effectiveness depends on agro-ecological context including precipitation patterns, soil type, temperature regime, and pest/disease pressure. The present study in temperate North America documented positive effects; however, semi-arid regions may require additional water harvesting measures, and rainfed tropical systems face distinct pest challenges requiring targeted conservation agriculture adaptation.

4.8. Study Limitations and Future Research

This study focused on a single site and soil type (Mollisol, temperate climate), potentially limiting geographic extrapolation. Future research systematically evaluating conservation agriculture across diverse soil orders, climatic zones, and land uses would enhance predictive capacity. The 18-year duration, while substantial, remains relatively short for assessment of ultimate equilibrium SOC values and carbon saturation dynamics across deep soil profiles.

Mechanistic understanding of SOC stabilization processes, while advanced, remains incomplete. Future research employing stable carbon isotope analysis (^{13}C) and radiocarbon (^{14}C) tracers would clarify carbon source attribution and age structure of accumulated SOC. High-resolution assessment of soil aggregate microstructure through computed tomography and scanning electron microscopy could elucidate mechanisms stabilizing carbon within mineral-organic complexes.

Greenhouse gas flux measurements (CO_2, CH_4, N_2O), while outside the present study scope, represent critical future research gaps for comprehensive evaluation of conservation agriculture's climate change mitigation potential. Integration of economic analysis quantifying profitability of conservation agriculture across diverse farm sizes and commodity price scenarios would enhance decision-making frameworks for farmer adoption.

5. Conclusion

The 18-year field experiment clearly shows that conservation agricultural practices, particularly zero tillage combined with complete retention of crop residues, greatly improve soil quality in various dimensions while sequestering carbon from the atmosphere and ensuring agricultural production. Important results of the study are:

1. **Carbon Capture:** The lack of tillage resulted to a rise in organic carbon in soil by 34.2 %, and total amount of carbon in soil increased by 3.30 Mg C/ha, which could correlate with removal of 12.1 Mg CO_2/ha and confirms the high potential for climate change mitigation using the method used at the level of individual farms.
2. **Aggregate Durability:** The quantity of water-stable macro-aggregates (> 2 mm) increased from 18 % to 51 %, while the average weight diameter has increased by 89.6 %, resulting in almost complete transformation of soil structure and making the soil favorable for water movement, aeration, and root penetration.
3. **Soil Biological Activity:** The microbial biomass has grown by 43 %, soil respiration rate by 51 %, and earthworms by 4.3 times owing to the zero-tillage technique applied for farming and a significant elevation of soil biological communities thus ensuring the proper performance of ecosystems.
4. **Physical Properties of Soil:** Water holding capacity increased by 44%, speed of infiltration by 2.7 times, and bulk density by 10.6 % due to lack of tillage, thus resulting in improving water availability and the properties of soil in terms of structure.
5. **Productivity and Sustainability:** Conservation agriculture ensured the same yields (9.8 Mg ha^-1 of corn), enhanced the stability of the yields, minimized external inputs, and increased the sustainability of the agriculture process.

This research offers quantitative, long-term evidence that conservation agriculture can be an effective and synergistic approach to the following: (1) increasing soil carbon sequestration and mitigating climate change; (2) enhancing soil physical, chemical, and biological properties; (3) sustaining productivity; and (4) supporting sustainable intensification goals. The application of conservation agriculture to agricultural practices worldwide may have a significant role in mitigating climate change, and at the same time, improving soil health, water security, and sustainability.

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