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Zero Tillage and Soil Carbon Sequestration: Mechanisms, Evidence, Limitations and Implications for Climate Change Mitigation

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Abstract

Soil organic carbon (SOC) is a major component of the terrestrial carbon cycle and plays an important role in soil fertility, ecosystem functioning, water regulation and climate feedbacks. Intensive tillage can disrupt soil aggregates, expose protected organic matter to decomposition, accelerate erosion and stimulate short-term carbon dioxide (CO₂) losses. Zero tillage (ZT), also termed no-tillage (NT), has consequently been promoted as a component of conservation agriculture because it reduces mechanical soil disturbance and generally maintains crop residues at the soil surface. The proposed carbon-sequestration mechanisms include reduced aggregate disruption, greater residue and root-carbon inputs, enhanced aggregate stability, microbial transformation of organic substrates, physical protection of carbon and reduced erosion. Evidence from long-term experiments indicates that ZT can increase SOC, particularly in surface soil, and can alter the chemical and physical protection of organic matter. However, the magnitude of whole-profile carbon sequestration remains uncertain. Surface SOC accumulation may partly represent vertical redistribution and stratification rather than a net increase in soil carbon throughout the profile. Recent global meta-analyses have further demonstrated that SOC responses depend on soil depth, duration of ZT, climate, precipitation, initial SOC, soil texture and cropping system. The climate benefit of ZT also cannot be evaluated from SOC alone because changes in CO₂, methane (CH₄), nitrous oxide (N₂O), fossil-fuel consumption and crop productivity must be considered together. Some experiments report lower net global warming potential under ZT despite increased N₂O emissions, whereas other syntheses indicate that the global atmospheric mitigation contribution of NT is relatively limited. Accurate carbon accounting therefore requires long-term experiments, adequate sampling depth, bulk-density measurements and, preferably, equivalent-soil-mass approaches. Overall, ZT should be considered primarily a soil-health and sustainable-management practice with potential climate-mitigation co-benefits rather than a universally effective carbon-removal technology. Its benefits are most likely to be maximized when combined with residue retention, crop diversification, cover crops, balanced nutrient management and integrated weed management.

Keywords: Zero tillage; no-tillage, soil organic carbon, carbon sequestration, conservation agriculture, greenhouse gases, climate change, soil health

Introduction

Agricultural soils are an important component of the global carbon cycle because they contain large quantities of organic carbon and respond directly to land-management decisions. Soil organic carbon influences aggregate stability, cation exchange, nutrient cycling, microbial activity, water-holding capacity and crop productivity. Management practices that increase the amount or persistence of carbon stored in soil have therefore attracted attention as potential climate-mitigation measures as well as strategies for improving soil quality (Lal, 2004^[15]; Lal *et al.*, 2007)^[16].

Tillage is one of the most important management factors affecting soil carbon dynamics. Repeated intensive tillage physically disrupts aggregates and changes soil pore structure, which can increase the exposure of previously protected organic substrates to microbial decomposition. Tillage also promotes erosion and requires fossil-fuel-intensive machinery operations. The supplied literature describes large short-term CO₂ losses following conventional ploughing and identifies reduced soil disturbance as one pathway through

which conservation tillage can reduce carbon loss (Reicosky & Saxton, 2000) ^[24]. Zero tillage represents the most intensive form of reduced soil disturbance. In a ZT system, crops are established without conventional ploughing or seedbed inversion, usually with direct-drilling equipment. Crop residues commonly remain at the soil surface. The practice can improve soil cover, reduce erosion, conserve water and reduce the number of tractor operations. These benefits have led to the widespread perception that ZT is simultaneously a soil-health practice and a climate-change mitigation strategy.

The scientific evidence, however, is more nuanced. Surface SOC commonly increases under NT, but deeper soil responses may differ. Cai *et al.* (2022) ^[5], using 1,061 paired observations, found that NT increased SOC storage in surface soil during the early adoption period but reduced SOC in deeper layers; the net whole-profile difference approached zero at approximately 14 years. Mondal *et al.* (2023) ^[20] likewise found a strong surface SOC response but concluded that the contribution of NT to global atmospheric mitigation is relatively limited. These findings do not negate the agronomic value of ZT; rather, they demonstrate that carbon sequestration claims must be based on complete carbon balances and appropriate sampling strategies.

This review therefore examines the mechanisms through which ZT influences SOC, the evidence for surface and whole-profile carbon storage, interactions with CO₂, CH₄ and N₂O, effects on soil physical and biological properties, crop productivity, methodological issues, limitations and opportunities for integrating ZT into climate-smart agriculture.

2. Concept and Principles of Zero Tillage

Zero tillage is a crop-establishment system in which soil inversion and conventional seedbed preparation are eliminated or reduced to a minimum. Seed is placed directly into untilled soil using specialized planters or seeders. In practical terms, ZT usually operates together with surface residue retention, although the amount and management of residue vary among crops and regions.

Conservation agriculture is broader than ZT alone. Its commonly recognized principles are minimum mechanical disturbance, continuous soil cover and crop diversification. The distinction is important because the productivity and environmental outcomes of NT may depend on residue retention and rotation. Pittelkow *et al.* (2015) ^[21] showed that conservation agriculture outcomes were more consistent when no-till was combined with residue management and crop diversification rather than being implemented as an isolated practice. The physical consequences of ZT include less disruption of soil aggregates, greater continuity of biological pores and increased surface protection. Residue cover reduces the direct impact of raindrops and wind, limits evaporation and moderates soil temperature. The supplied literature also reports improvements in hydraulic conductivity, infiltration and water storage under long-term NT in several soil environments. These changes can indirectly influence carbon dynamics because water and oxygen availability regulate microbial decomposition and greenhouse-gas production.

3. Soil Organic Carbon: Pools, Inputs and Losses

SOC occurs in pools that differ in chemical composition, accessibility to microorganisms and turnover time.

Particulate organic matter is generally more labile and responds relatively rapidly to management, whereas mineral-associated organic carbon and some aggregate-protected fractions can persist for substantially longer periods. Microbial biomass carbon represents an active biological pool that responds to substrate availability, soil moisture and disturbance. Carbon enters agricultural soil primarily through crop residues, roots and rhizodeposition. The quantity and quality of these inputs depend on crop productivity, root distribution, residue C:N ratio, crop rotation, nutrient availability and climate. Carbon leaves the system through microbial respiration as CO₂, erosion, dissolved losses, harvest removal and, indirectly, conversion to other greenhouse gases. The balance between these inputs and outputs determines whether SOC increases or declines. Carbon sequestration must be distinguished from simple carbon storage. Powlson *et al.* (2011) ^[22] emphasized that an increase in SOC contributes to climate mitigation only when the management change produces an additional net transfer of carbon from the atmosphere to land. Soil carbon storage is finite and reversible, and changes in SOC can be accompanied by changes in N₂O and CH₄ emissions. Therefore, a scientifically defensible assessment of ZT should report both SOC stocks and the broader greenhouse-gas balance.

4. Mechanisms of Carbon Sequestration under Zero Tillage

4.1 Reduced soil disturbance and aggregate protection

The most direct mechanism proposed for ZT-induced carbon retention is reduced mechanical disruption. Conventional ploughing breaks aggregates and redistributes organic matter, while ZT allows aggregates and pore networks to develop with less mechanical interference. Organic compounds enclosed within aggregates may become less accessible to microbial enzymes and decomposers. The literature on aggregate dynamics indicates that physical protection is a major component of SOC stabilization (Six *et al.*, 2004) ^[27].

4.2 Crop-residue retention

Surface residue retention provides a continuing source of organic carbon and protects soil from erosion. Residues can reduce evaporation, moderate temperature, improve infiltration and supply carbon substrates to microbial communities. However, residue carbon is not equivalent to permanent sequestration. A proportion is rapidly mineralized and returned to the atmosphere as CO₂, while another fraction enters particulate and mineral-associated pools. The net effect depends on residue quantity, quality, decomposition environment and the capacity of the soil to stabilize new carbon.

4.3 Root-derived carbon

Roots and rhizodeposits are important carbon inputs that can be especially relevant for subsoil carbon. Crop roots transfer photosynthetically assimilated carbon below the surface, where it can interact with microbial communities and soil minerals. Crop rotation and cover crops may therefore complement ZT by increasing the amount and vertical distribution of carbon inputs.

4.4 Aggregate-associated and mineral-associated carbon

ZT can increase aggregate stability and the physical protection of organic matter. Microbial products, root-

derived compounds and fungal hyphae contribute to aggregate formation. Over longer periods, carbon can also become associated with mineral surfaces. These mechanisms help explain why some long-term ZT experiments show not only more SOC but a greater proportion of chemically or physically protected carbon.

4.5 Microbial biomass and microbial processing

Reduced soil disturbance and greater residue availability can increase microbial biomass, especially near the surface. Mondal *et al.* (2023) [20] reported marked increases in microbial biomass carbon in the 0–5 and 5–10 cm layers under NT. Microorganisms are not simply agents of carbon loss; microbial processing converts plant material into microbial residues and metabolites that can subsequently become stabilized. Consequently, increased microbial activity can contribute to both decomposition and longer-term carbon formation depending on carbon-use efficiency and soil mineral protection.

4.6 Soil pore architecture

Tillage alters pore-size distribution and connectivity. Long-term ZT can preserve continuous biopores produced by roots and soil fauna, while also increasing the relative importance of smaller pores. Mangalassery *et al.* (2014) [18] showed that three-dimensional pore structure was strongly related to CO₂ and CH₄ fluxes. Thus, soil structure provides an important physical link between tillage, carbon turnover and greenhouse-gas exchange.

5. Evidence for SOC Accumulation under Zero Tillage

Numerous field experiments report greater SOC concentration or stock under ZT than under conventional tillage, particularly in the surface soil. Long-term studies are particularly important because SOC changes are slow and may not be detectable reliably during the first few years. Cooper *et al.* (2021a) [7] reported that long-term ZT enhanced soil carbon protection in tropical agriculture, with changes in aggregate structure and organic-matter chemistry becoming more evident with increasing duration of ZT. Ussiri and Lal (2009) [6, 30] found greater SOC storage and differences in CO₂ emissions after long-term NT in continuous corn on an Alfisol in Ohio. West and Post (2002) [32] also demonstrated through global analysis that tillage and crop rotation can influence SOC sequestration rates. These studies support the principle that reducing disturbance can conserve or increase SOC under appropriate management.

However, the magnitude of the effect is not universal. Christopher *et al.* (2009) [6] found no significant whole-profile SOC difference between NT and CT at most of their Midwestern sites. Their findings emphasized the importance of sampling depth and the distinction between concentration and stock. More recent global syntheses have strengthened this caution.

6. Surface Stratification versus Whole-Profile Carbon Sequestration

A characteristic feature of ZT is SOC stratification. Because residues are concentrated at the soil surface and soil is not mixed mechanically, SOC concentration often increases strongly in the upper 5–10 cm. In CT, residues are incorporated and organic matter is more evenly distributed within the cultivated layer. Consequently, a comparison

based only on surface concentration can make the apparent carbon benefit of ZT seem larger than the whole-profile difference.

Luo *et al.* (2010) [17] demonstrated that conclusions about NT-induced SOC accumulation were sensitive to soil depth and study design. Cai *et al.* (2022) [5] provided particularly strong evidence for temporal redistribution: early NT adoption increased surface SOC but was accompanied by deeper SOC reductions, while these differences diminished with time. The study therefore challenges the interpretation of surface SOC increases as automatic evidence of permanent atmospheric CO₂ removal.

The distinction between stratification and sequestration is central to carbon-market accounting. A soil-management practice should not receive credit for carbon that has simply moved from one depth to another. Whole-profile measurements and consistent bulk-density corrections are therefore necessary for reliable estimates.

7. Soil Bulk Density and Equivalent-Soil-Mass Approaches

SOC concentration is usually expressed as grams of carbon per kilogram of soil, whereas a carbon stock is expressed per unit land area, such as Mg C ha⁻¹. To convert concentration to stock, soil mass must be considered. Because tillage affects bulk density, comparisons based on a fixed soil depth can be biased. Wendt and Hauser (2013) [34] described an equivalent-soil-mass procedure in which equal masses of mineral soil are compared rather than equal geometric depths. This approach is particularly important where ZT has increased bulk density relative to CT. The supplied literature similarly emphasizes that changes in bulk density must be considered when monitoring soil carbon stocks. Equivalent-soil-mass calculations are therefore recommended for long-term ZT experiments. A robust carbon study should report SOC concentration, bulk density, sampling depth, carbon stock and the calculation method used. Where possible, soil should be sampled to sufficient depth to include the principal rooting and carbon-storage zone rather than limiting measurement to the surface layer.

8. Duration of Zero Tillage and Carbon Saturation

The duration of ZT strongly influences observed SOC responses. During the transition from CT to ZT, residue accumulation and changes in microbial and physical processes can produce relatively rapid surface changes. As soil carbon approaches a new equilibrium, the annual rate of additional storage should decline. West and Six (2007) [33] emphasized that estimates of sequestration potential should account for both the duration of storage and the finite carbon-saturation capacity of soils. The supplied literature contains evidence of greater carbon protection with longer ZT duration. Cooper *et al.* (2021a) [7] observed stronger changes in carbon stability and aggregate formation under long-term tropical ZT, while Cai *et al.* (2022) [5] showed that the initial whole-profile decline in SOC under NT diminished over time. These apparently different observations can be reconciled by recognizing that soil carbon is dynamic and that the response is time-dependent. Consequently, annual sequestration rates measured during the first few years should not be extrapolated indefinitely. Carbon-credit systems should distinguish between transition-period accumulation and long-term steady-state storage.

9. Influence of Climate, Soil and Cropping System

ZT responses are controlled by environmental and management conditions. Climate affects plant productivity and decomposition; soil texture controls mineral protection; precipitation influences soil moisture and microbial activity; and initial SOC influences the remaining capacity for additional storage. Cai *et al.* (2022) [5] identified annual precipitation and initial SOC among the influential variables affecting the NT response.

Soil texture is particularly important because clay-rich soils generally have greater capacity to stabilize organic matter than coarse-textured soils. The supplied literature also indicates that sequestration rates can differ between tropical and temperate conditions and can vary with crop rotation, soil drainage and clay content. These observations argue against applying a single global sequestration factor to every ZT field.

Cropping system is equally important. Systems with high biomass production, diverse rotations and greater root inputs may provide more carbon for stabilization than low-input monocultures. Cover crops and diversified rotations can therefore strengthen the carbon-management function of ZT.

10. Zero Tillage and Greenhouse Gas Emissions

10.1 Carbon dioxide

Tillage can cause an immediate CO₂ pulse by exposing organic substrates and changing soil aeration. Reicosky and Saxton (2000) [24] described large tillage-induced CO₂ emissions and linked them to the disturbance of soil organic matter. ZT avoids most of these mechanical disturbances and therefore can reduce short-term CO₂ losses associated with field preparation.

In the supplied experimental study, Mangalassery *et al.* (2014) [18] measured lower potential CO₂ flux under ZT than under tilled soil. Mean potential CO₂ flux was approximately 141 mg m⁻² h⁻¹ under ZT compared with 171 mg m⁻² h⁻¹ under tilled soil. The study also found that soil porosity, bulk density and microbial biomass carbon explained a substantial proportion of variation in potential CO₂ flux.

10.2 Methane

Aerated upland soils often consume atmospheric CH₄ through methanotrophic microorganisms. Tillage alters soil aeration, moisture and pore connectivity and can therefore modify CH₄ uptake. Mangalassery *et al.* (2014) [18] reported lower potential CH₄ flux under ZT than under tilled soil. However, the direction and magnitude of CH₄ responses depend on soil moisture, oxygen availability, crop system and climate, so a universal decrease should not be assumed.

10.3 Nitrous oxide

N₂O is a critical uncertainty in the climate assessment of ZT. Greater soil moisture and reduced gas diffusion can create anaerobic microsites that favour denitrification. The supplied experimental evidence showed approximately 54% greater N₂O emissions on an area basis and 77% greater emissions on a soil-mass basis under ZT compared with tilled soil. This demonstrates why SOC gains cannot be evaluated independently of nitrogen cycling.

10.4 Net global warming potential

Mangalassery *et al.* (2014) [18] found that conventional tillage produced approximately 26–31% greater net global

warming potential than ZT, despite the higher N₂O emissions under ZT. The lower CO₂ and CH₄ fluxes were sufficient to produce a lower overall GWP in that experiment. This result illustrates the importance of evaluating all major GHGs together rather than using a single gas or SOC concentration as the climate indicator.

11. Fuel Consumption and Farm-Level Carbon Footprint

ZT can provide a direct reduction in fossil-fuel emissions because ploughing, harrowing and repeated seedbed preparation are eliminated. Fewer machinery passes reduce diesel consumption, machinery wear and labour requirements. This climate benefit is independent of whether soil carbon increases and can therefore remain relevant even where whole-profile SOC gains are small. The economic value of reduced fuel and labour use is also an important adoption driver. In regions with high fuel costs or narrow planting windows, direct drilling can improve operational efficiency. Nevertheless, the carbon footprint of ZT should include the energy used for herbicides, fertilizers, specialized machinery and residue management, rather than assuming that reduced tillage automatically produces a lower total footprint.

12. Effects on Soil Physical Properties and Soil Health

ZT can improve several soil-health attributes. Long-term systems may show greater aggregate stability, improved infiltration, greater water retention and lower erosion. Residue cover protects the soil surface from raindrop impact and reduces evaporation. Biological pores created by roots and earthworms can contribute to water movement and root exploration. The supplied literature reports that long-term NT can increase hydraulic conductivity and infiltration under several soil conditions. However, ZT can also increase surface penetration resistance and bulk density during the transition period, particularly in wet or poorly drained soils. These effects are strongly site-specific and highlight the importance of adapting ZT to soil type and drainage conditions. Soil health should therefore be evaluated using a suite of indicators rather than SOC alone. Useful indicators include aggregate stability, bulk density, infiltration, available water, microbial biomass, earthworm activity, nutrient cycling and erosion loss.

13. Microbial and Biological Responses

ZT modifies the biological environment by increasing residue availability and reducing physical disturbance. Greater microbial biomass is commonly observed near the surface, where residue-derived carbon is concentrated. Microbial communities participate in decomposition, aggregate formation and the production of microbial residues that can contribute to stable SOC. Long-term ZT can also support soil fauna such as earthworms by maintaining a more continuous food supply and reducing mechanical disturbance. Earthworm channels can improve porosity and create pathways for root growth and water infiltration. However, the biological response depends on climate, residue availability, pesticide use and crop rotation, so ZT should be integrated with broader soil-biological management.

14. Crop Productivity under Zero Tillage

Climate mitigation cannot be separated from food production. A practice that increases SOC but substantially reduces crop yield may have a less favourable climate

outcome if additional land or inputs are required elsewhere. Crop yield responses to ZT are therefore an important part of sustainability assessment.

The literature reports both positive and negative yield responses. Long-term experiments have shown yield increases in some crops and yield penalties in others. Mangalassery *et al.* (2015)^[19] reviewed this issue and noted that weed pressure, soil conditions and crop-specific responses strongly influence productivity. Pittelkow *et al.* (2015)^[21] concluded that the productivity advantages of conservation agriculture are most reliable when no-till is combined with residue retention and crop diversification.

Potential causes of lower early-season yield under ZT include greater weed competition, slower soil warming, nitrogen immobilization, residue interference with planting, compaction and disease carryover. These constraints can often be addressed through integrated weed management, appropriate planters, crop rotation, residue management and balanced fertilization.

15. Weed and Residue Management

Weed management is one of the major operational challenges of ZT. Because soil inversion is avoided, weed seeds are not buried and redistributed in the same manner as under conventional tillage. Depending on the seedbank and cropping system, this can increase weed pressure and herbicide dependence.

Residue management presents a similar trade-off. Residues protect soil and supply carbon but may interfere with planting or increase pest and disease risks if poorly managed. In South Asian rice–wheat systems, direct drilling of wheat into rice residues has demonstrated the potential to reduce residue burning while conserving soil cover and lowering tillage requirements. The supplied literature highlights the environmental importance of avoiding residue burning because burning releases CO₂, CH₄, N₂O and other pollutants.

Integrated weed and residue management is therefore essential. Appropriate crop rotations, cover crops, competitive cultivars, residue distribution, timely herbicide use and suitable seeding equipment can help preserve the environmental benefits of ZT while reducing agronomic constraints.

16. Zero Tillage as a Climate-Smart Agriculture Practice

Climate-smart agriculture aims to increase productivity, strengthen resilience and reduce or remove greenhouse-gas emissions where feasible. ZT can contribute to all three objectives, but its contribution depends on system design. Reduced erosion and improved soil moisture can strengthen resilience, while fuel savings can reduce direct emissions. Carbon storage may provide an additional mitigation benefit, but recent global evidence indicates that this component is variable.

A more robust climate-smart strategy is therefore to integrate ZT with residue retention, crop diversification, cover crops, balanced nutrient management, efficient irrigation and integrated weed management. These practices can increase carbon inputs, reduce soil disturbance, improve nutrient-use efficiency and strengthen water conservation simultaneously.

Bai *et al.* (2019)^[1] demonstrated that climate-smart agricultural practices can influence SOC sequestration, but the magnitude depends on practice combinations and

environmental conditions. This supports a systems approach rather than a single-practice approach to climate mitigation.

17. Carbon Accounting and Methodological Requirements

Reliable assessment of ZT-induced carbon sequestration requires rigorous sampling and accounting. Studies should measure SOC concentration and bulk density at multiple depths and report carbon stocks on an area basis. Where bulk density differs among treatments, equivalent-soil-mass calculations should be preferred.

Sampling should extend beyond the surface layer whenever possible. At minimum, studies intended to make climate claims should report several soil-depth intervals so that surface accumulation can be separated from redistribution or deeper losses. Long-term monitoring is also essential because the direction and magnitude of SOC responses can change with time.

Carbon accounting should additionally include residue and root inputs, crop removal, erosion, fuel consumption and major GHG fluxes. A full climate assessment should consider CO₂, CH₄ and N₂O together and express them using a clearly stated global-warming-potential framework.

Advanced approaches such as stable-isotope tracing, soil spectroscopy, X-ray computed tomography, automated gas chambers, remote sensing and process-based models can complement conventional soil sampling. These approaches can help identify carbon sources, residence times, stabilization mechanisms and spatial variability.

18. Limitations and Challenges

Surface SOC accumulation may not represent equivalent whole-profile sequestration.

Changes in bulk density can bias fixed-depth carbon-stock comparisons.

SOC responses vary with climate, soil texture, initial SOC, crop rotation and duration of ZT.

N₂O emissions can increase under some soil-moisture and nitrogen-management conditions.

Weed pressure may increase and can lead to greater herbicide dependence.

Residue accumulation can create establishment, pest or disease-management problems.

ZT can increase penetration resistance or compaction in some soils, particularly during transition.

Carbon storage is finite and reversible; sequestration rates decline as soils approach equilibrium.

Short-duration experiments may capture transient changes rather than long-term carbon stabilization.

Carbon-credit systems require robust measurement, reporting and verification to distinguish real sequestration from carbon redistribution.

19. Research Gaps and Future Directions

The most important research gap is the limited number of long-term, whole-profile experiments that simultaneously measure SOC stocks, carbon fractions, GHG fluxes and crop productivity. More studies are required to determine whether surface SOC gains persist, whether deeper SOC compensates for surface changes and how long it takes to reach a new equilibrium. Future studies should place greater emphasis on carbon quality rather than carbon quantity alone. Measurements of particulate organic carbon, mineral-associated organic carbon, microbial necromass, aggregate-

associated carbon and radiocarbon or isotope-based turnover would provide stronger evidence of permanence. The interaction between carbon sequestration and nitrogen cycling also deserves greater attention. Improved nitrogen management may reduce N₂O emissions and increase nitrogen-use efficiency, potentially improving the net climate benefit of ZT. Similarly, crop diversification and cover crops can increase root-derived carbon inputs and improve the vertical distribution of carbon. Regional research is particularly important in tropical, subtropical, semi-arid and rainfed systems where soil and climate conditions differ substantially from temperate systems. Long-term experiments in major Indian cropping systems, including rice–wheat, maize–wheat, soybean–wheat, cotton-based, pulse-based and dryland cereal systems, would improve the evidence base for national climate and soil-health programs. Carbon-market methodologies should also adopt conservative accounting. Credits should be based on measured changes in soil carbon stocks using appropriate bulk-density corrections and sufficient depth, with permanence and reversal risk explicitly considered. Claims should be based on net climate benefit rather than SOC concentration alone.

20. Conclusion

Zero tillage is a valuable component of sustainable agriculture because it reduces mechanical disturbance, protects soil structure, limits erosion, conserves water and reduces machinery-related fuel consumption. It can also increase surface SOC, microbial biomass and aggregate-

associated carbon through reduced disturbance, residue retention, root-carbon inputs and physical protection of organic matter.

Nevertheless, the evidence does not justify describing ZT as a universally effective carbon-removal technology. Surface SOC gains can be accompanied by changes in deeper soil carbon, and the magnitude of whole-profile sequestration is strongly influenced by duration, climate, soil texture, initial SOC and management. Cai *et al.* (2022) ^[5] demonstrated that early surface gains can coexist with deeper losses, while Mondal *et al.* (2023) ^[20] concluded that NT has important soil-health benefits but relatively limited global atmospheric-mitigation potential.

The climate effect of ZT must also be evaluated using the complete GHG balance. Reduced CO₂ emissions and lower fuel consumption can be beneficial, while N₂O emissions may increase under some conditions. Mangalassery *et al.* (2014) ^[18] showed that the combined GHG balance can nevertheless favour ZT even when N₂O is higher.

The strongest conclusion is therefore that ZT should be promoted as a soil-health and sustainable-management practice that can provide climate-mitigation co-benefits. Its carbon and climate benefits are likely to be greatest when ZT is integrated with residue retention, crop diversification, cover crops, balanced nutrient management and effective weed management. Future climate policies should consequently evaluate ZT within whole-system carbon and GHG budgets rather than treating it as a stand-alone carbon-sequestration solution.

Table 1: Principal Mechanisms through which zero tillage can influence soil carbon

Mechanism	Expected response under ZT	Implication for SOC/climate
Reduced soil disturbance	Less aggregate disruption	Greater physical protection of organic matter
Residue retention	Greater surface carbon input	Potential increase in SOC
Root-derived carbon	Greater belowground C input	Potential increase in subsoil and rhizosphere C
Aggregate stabilization	Greater persistence of aggregates	Reduced accessibility of protected C
Microbial processing	Changes in biomass and residue formation	Potential stabilization of microbial-derived C
Reduced erosion	Lower particulate C loss	Conservation of existing SOC
Reduced fuel use	Fewer machinery operations	Lower fossil-fuel CO ₂ emissions
Changed pore structure	Altered aeration and moisture	Can affect CO ₂ , CH ₄ and N ₂ O fluxes

Table 2: Major greenhouse-gas pathways affected by zero tillage

Gas	Potential response	Main controlling processes	Interpretation
CO ₂	Often lower after reducing soil disturbance	Aggregate disruption, substrate exposure, microbial respiration	Potential mitigation benefit
CH ₄	Variable; may alter uptake	Aeration, moisture, methanotrophy	Site-specific
N ₂ O	May increase under some conditions	Denitrification, moisture, oxygen limitation, N availability	Important offset risk
Net GWP	Variable	Combined CO ₂ , CH ₄ and N ₂ O balance	Must be assessed directly

Table 3: Factors controlling SOC response to zero tillage

Factor	Possible influence
Climate	Controls plant production, decomposition and soil moisture
Precipitation	Influences biomass inputs and microbial activity
Initial SOC	Determines remaining storage capacity
Soil texture	Controls mineral protection and carbon stabilization
Crop rotation	Controls biomass and root-carbon inputs
Residue retention	Increases carbon inputs and surface protection
Duration of ZT	Determines transition versus long-term equilibrium response
Nutrient management	Controls biomass production and N ₂ O emissions
Cover crops	Increase root-derived carbon and soil cover

Table 4: Methodological requirements for robust SOC assessment

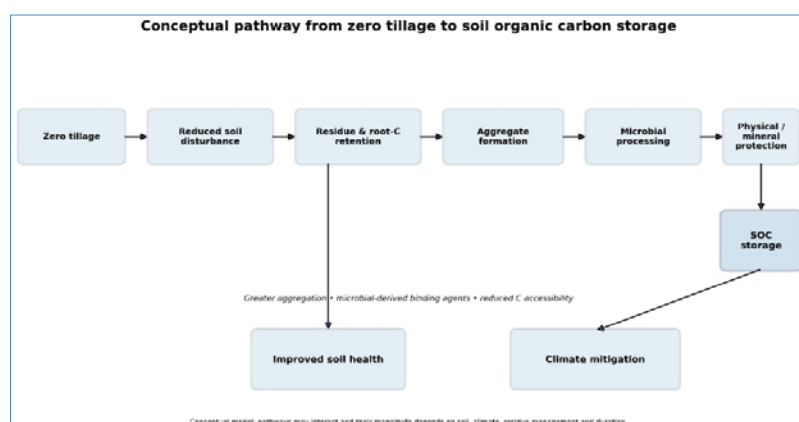
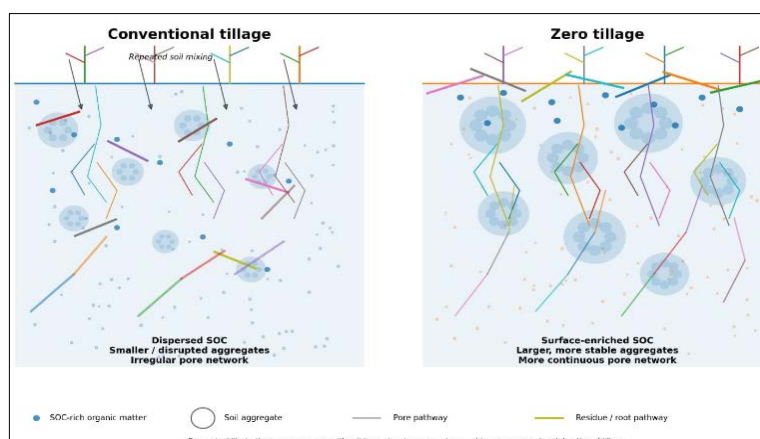
Requirement	Why it is important
a	Provides carbon concentration but not total stock
Bulk density	Required for area-based carbon-stock calculation
Multiple soil depths	Separates surface stratification from whole-profile change
Equivalent soil mass	Reduces bias from bulk-density differences
Long-term monitoring	Captures transient and equilibrium responses
Carbon fractions	Provides information on carbon quality and persistence
GHG measurements	Allows complete climate assessment
Residue/root inputs	Quantifies major carbon sources
Fuel and input accounting	Captures indirect farm-level emissions

Table 5: Major limitations and possible management responses

Limitation	Potential response
Weed pressure	Integrated weed management and crop rotation
Residue interference	Residue distribution and adapted planters
N immobilization	Balanced and well-timed nutrient management
Compaction	Controlled traffic, rooting diversity and suitable soil moisture at planting
N ₂ O increase	Improved N management, drainage and timing
Carbon-accounting uncertainty	Long-term whole-profile and equivalent-mass measurements
Yield reduction in some systems	Combine ZT with residue retention and diversification

Table 6: Research priorities for zero-tillage carbon management

Research priority	Recommended approach
Whole-profile SOC	Long-term sampling below 30 cm where relevant
Carbon permanence	Measure stable and mineral-associated fractions
GHG balance	Simultaneous CO ₂ , CH ₄ and N ₂ O monitoring
Regional variability	Multi-location experiments across soils and climates
Carbon markets	Conservative MRV based on measured stock change
Systems integration	Evaluate ZT + residue + rotation + cover crops + nutrient management
Digital monitoring	Combine spectroscopy, remote sensing, modelling and field observations

**Fig 1:** Conceptual pathway from zero tillage to soil organic carbon storage**Fig 2:** Comparison of conventional tillage and zero tillage showing contrasting soil-carbon distribution, aggregate structure, residue position and pore architecture

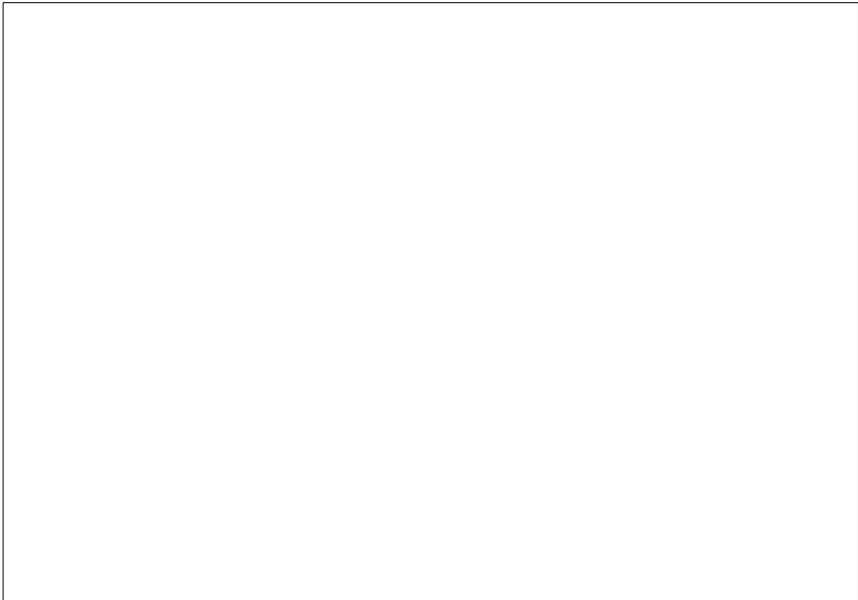


Fig 3: Mechanistic diagram of SOC stabilization under zero tillage, including particulate organic matter, aggregate-associated carbon, microbial residues and mineral-associated organic carbon

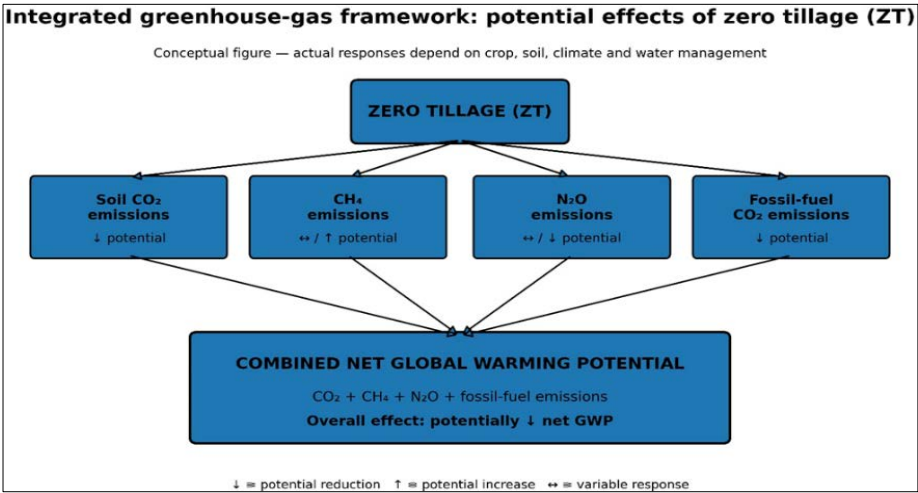


Fig 4: Integrated greenhouse-gas framework showing the potential effects of ZT on CO₂, CH₄, N₂O and fossil-fuel emissions and their combined contribution to net global warming potential

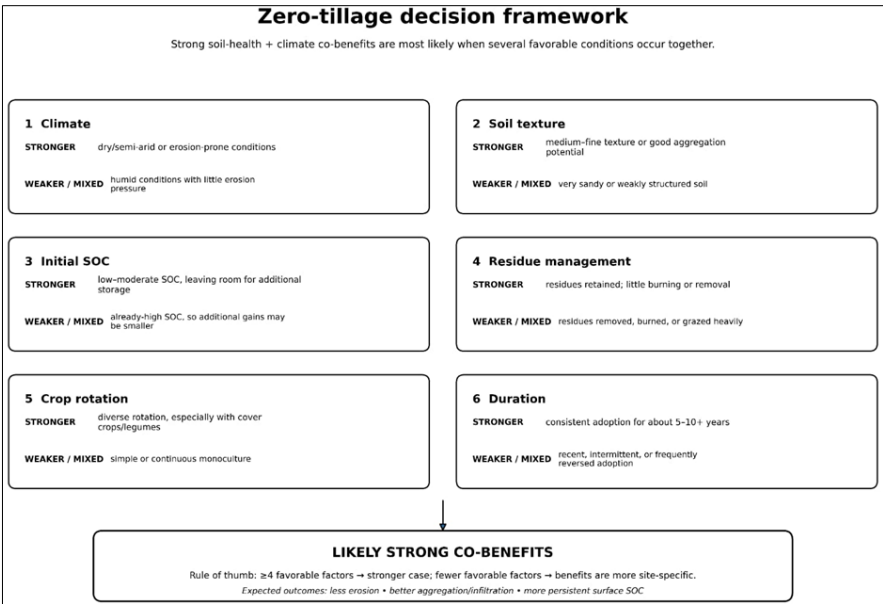


Fig 5: Decision framework showing when zero tillage is most likely to provide strong soil-health and climate co-benefits based on climate, soil texture, initial SOC, residue management, crop rotation and duration of adoption.

Highlights

Zero tillage generally increases SOC concentration in surface soil and improves several soil-health attributes.

Carbon accumulation under ZT is controlled by reduced disturbance, residue and root inputs, aggregate protection and microbial processing.

Surface SOC gains do not necessarily represent equivalent whole-profile carbon sequestration.

CO₂ and fuel emissions may decrease under ZT, whereas N₂O responses can be positive or negative depending on soil and nitrogen conditions.

Whole-profile, equivalent-soil-mass and long-term measurements are essential for credible carbon accounting.

The greatest climate and soil-health benefits are likely when ZT is integrated with residue retention, crop diversification, cover crops and balanced nutrient management.

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