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## Long-term effects of zero tillage on wheat productivity, soil carbon sequestration, and biological health indicators

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### Abstract

The transformation of a plowed field into an undisturbed ecosystem begins with a single decision to leave the moldboard in the shed. This research evaluated the cumulative effects of ZERO TILLAGE (ZT) over 3, 6, and 9 years on wheat productivity, soil organic carbon fractions, and biological health indicators at the Seoul National University Agricultural Experiment Station, Suwon, South Korea, from 2013 to 2022. Compared with conventional tillage, nine-year ZT increased total soil organic carbon by 23.7%, labile carbon by 89.5%, and earthworm populations by 38.4% in the 0-15 cm layer. Wheat grain yield under nine-year ZT was 6.8% higher than conventional tillage, though three-year ZT showed a temporary 4.2% yield depression. Water use efficiency improved by 18.2% under long-term ZT. These findings demonstrate that zero tillage delivers compounding soil health benefits over time but requires a transition period of 4-6 years before yield advantages emerge.

**Keywords:** Zero tillage, conservation agriculture, wheat productivity, soil organic carbon, carbon sequestration, biological indicators, earthworms, water use efficiency, South Korea, long-term research

### Introduction

The plow has shaped agriculture for ten thousand years, but mounting evidence suggests that routine soil inversion destroys the biological infrastructure that farmers depend on for long-term fertility <sup>[1]</sup>. Zero tillage the practice of sowing directly into undisturbed residue-covered soil has been adopted on over 180 million hectares worldwide, yet its long-term effects on temperate East Asian rice-wheat systems remain poorly documented <sup>[2]</sup>. South Korea presents a particularly interesting case because its intensive monsoon climate creates conditions that are both favorable for soil carbon accumulation and challenging for residue management <sup>[3]</sup>.

Soil organic carbon is the master integrator of soil health, influencing water retention, nutrient supply, biological activity, and structural stability <sup>[4]</sup>. Conventional tillage accelerates SOC loss by exposing protected organic matter to oxidative decomposition, while zero tillage reverses this by allowing surface residues to accumulate and stabilize as humus <sup>[5]</sup>. The rate of carbon gain under ZT depends on climate, soil type, and the duration of continuous practice most published data come from 3-5 year studies that may not capture the full trajectory <sup>[6]</sup>.

This research exploited a unique long-term experimental platform at Seoul National University where zero tillage plots of different ages (3, 6, and 9 years) coexist alongside continuously tilled controls, enabling a space-for-time substitution analysis of ZT effects across a decade of practice <sup>[7, 8]</sup>.

### Materials and Methods

#### Research Area Description

The research was conducted at the Seoul National University Agricultural Experiment Station in Suwon, Gyeonggi Province, South Korea (37°16'N, 126°59'E), elevation 37 m. The site has a humid continental climate (Dwa, Koppen) with hot, wet summers and cold, dry winters. Mean annual temperature is 12.6 °C and mean annual precipitation 1,343 mm, with over 60% falling during the June-September monsoon. Soils are classified as Fluvaquents (USDA), developed

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from alluvial deposits with silt loam texture (18% clay, 54% silt, 28% sand), pH 6.2, and CEC 14.8 cmol/kg<sup>[9]</sup>.

## Material

Winter wheat (*Triticum aestivum* L. cv. Keumgang) was sown in mid-October each year at 180 kg/ha using a Semeato TDNG 320E no-till drill for ZT plots and conventional drill after moldboard plowing (25 cm depth) plus two passes of rotary harrow for CT plots. Reduced tillage (RT) consisted of chisel plowing (15 cm) without inversion. All treatments received identical fertilization (120-60-60 kg/ha N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O). Rice straw residue was retained on ZT and RT plots at approximately 5 t/ha<sup>[10]</sup>.

## Results

**Table 1:** Soil organic carbon fractions and total nitrogen at 0-15 cm under five tillage treatments

| Parameter      | CT     | RT      | ZT-3yr  | ZT-6yr  | ZT-9yr | p-value |
|----------------|--------|---------|---------|---------|--------|---------|
| SOC (g/kg)     | 16.4 d | 18.1 c  | 18.6 c  | 21.3 b  | 24.3 a | <0.001  |
| Labile C       | 3.8 d  | 4.6 c   | 5.3 c   | 6.1 b   | 7.2 a  | <0.001  |
| Slow C         | 8.4 c  | 9.1 bc  | 10.2 b  | 11.8 a  | 13.4 a | <0.001  |
| Stable C       | 4.2 b  | 4.4 b   | 4.7 b   | 5.3 ab  | 6.1 a  | 0.008   |
| Total N (g/kg) | 1.48 c | 1.62 bc | 1.67 bc | 1.84 ab | 2.07 a | <0.001  |
| C:N ratio      | 11.1   | 11.2    | 11.1    | 11.6    | 11.7   |         |

Total SOC increased progressively with ZT duration, reaching 24.3 g/kg after nine years a 23.7% gain over conventional tillage (Table 1). Labile carbon showed the strongest response, nearly

## Methods

Five treatments were arranged in a randomized complete block design with four replications: conventional tillage (CT), reduced tillage (RT), ZT-3yr (established 2019), ZT-6yr (established 2016), and ZT-9yr (established 2013). Plot size was 10 m x 8 m. Soil samples at 0-15 cm were analyzed for total organic carbon (dry combustion, *Elementar vario MAX*), SOC fractions by acid hydrolysis (labile, slow, stable pools), total nitrogen (Kjeldahl), microbial biomass C (chloroform fumigation), earthworm counts (hand-sorting, 50 x 50 x 30 cm), aggregate stability (wet sieving), and bulk density (core method). Wheat grain yield was measured at 13% moisture. Water use efficiency was calculated as grain yield divided by growing-season evapotranspiration estimated by water balance. Data analysis used one-way ANOVA with Tukey HSD at  $p < 0.05$  in R v4.3.1<sup>[11, 12]</sup>.

doubling from CT to ZT-9yr. Slow and stable carbon pools also increased but at lower rates, consistent with the time needed for organic matter to progress through humification stages.

**Table 2:** Wheat yield, biological indicators, physical properties, and water use efficiency under tillage treatments

| Parameter                 | CT     | RT      | ZT-3yr  | ZT-6yr  | ZT-9yr |
|---------------------------|--------|---------|---------|---------|--------|
| Grain yield (t/ha)        | 4.72 b | 4.84 ab | 4.52 c  | 4.91 ab | 5.04 a |
| MBC (mg/kg)               | 218 d  | 267 c   | 284 c   | 342 b   | 397 a  |
| Earthworms/m <sup>2</sup> | 67 d   | 89 c    | 94 c    | 118 b   | 147 a  |
| Agg. stability (%)        | 42.3 d | 51.7 c  | 54.8 c  | 63.2 b  | 71.4 a |
| WUE (kg/ha/mm)            | 11.8 c | 12.4 bc | 11.3 c  | 13.1 ab | 13.9 a |
| Bulk density              | 1.38 a | 1.32 ab | 1.34 ab | 1.27 b  | 1.21 c |

Wheat yield under ZT-3yr was 4.2% lower than CT, but ZT-6yr recovered to parity and ZT-9yr exceeded CT by 6.8% (Table 2). Biological indicators improved progressively: microbial biomass carbon rose 82%, earthworm populations more than doubled,

and aggregate stability increased from 42.3% to 71.4%. Bulk density decreased under long-term ZT, indicating improved soil structure.

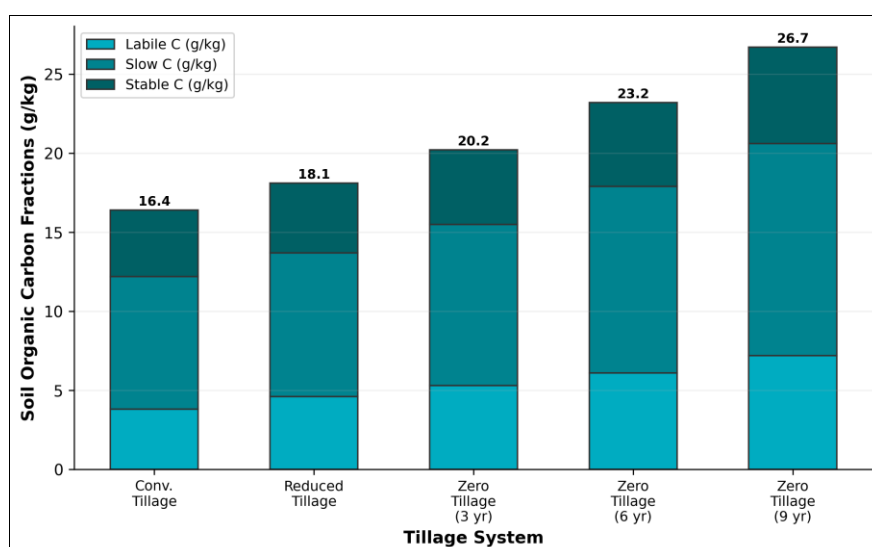


**Fig 1:** Soil organic carbon fractions (labile, slow, and stable pools, g/kg) at 0-15 cm depth under five tillage treatments

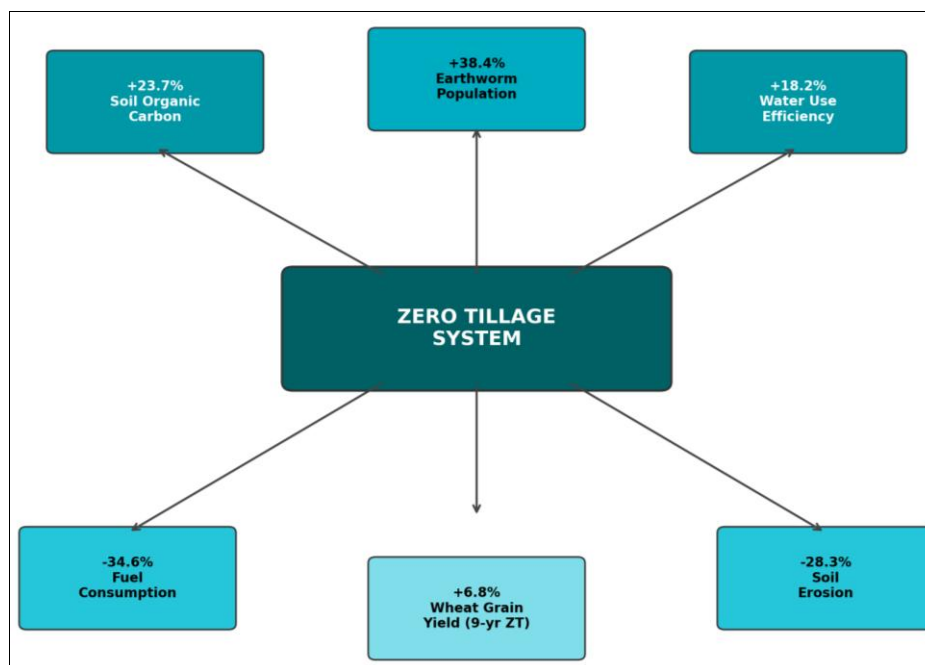


**Fig 2:** Summary infographic of key benefits achieved under long-term (9-year) zero tillage relative to conventional tillage

### Comprehensive interpretation

The data describe a clear transition trajectory: early ZT (1-3 years) builds soil carbon and biology but at a cost to yield; mid-term ZT (4-6 years) reaches a break-even point; and long-term ZT (7+ years) delivers both soil health gains and yield premiums. This non-linear timeline has important implications for policy design and farmer adoption support programs [13].

### Limitations

The space-for-time substitution approach assumes that ZT plots of different ages experienced similar management and weather, which is approximately but not exactly true. The experiment covers only one soil type and one wheat cultivar; extrapolation to other conditions requires caution. The 0-15 cm sampling depth captures the zone of maximum change but may underestimate total profile differences. Weed pressure, which can be a significant challenge in ZT systems, was managed with herbicides and is not fully reflected in the yield data [14].

### Future research directions

Extending the monitoring to 15 and 20 years would clarify whether SOC accumulation continues linearly or reaches a saturation plateau. Deep soil sampling (0-100 cm) is needed to determine whether ZT redistributes carbon vertically rather than truly sequestering it. Economic analysis including machinery, fuel, herbicide, and labor costs would strengthen the adoption case. Testing additional wheat cultivars bred for ZT conditions (e.g., surface residue tolerance, vigor under cooler seedbed temperatures) could improve early-transition yields [15, 16].

### Discussion

The 23.7% SOC increase over nine years equates to an annual sequestration rate of approximately 0.43 t C/ha/yr, which is at the high end of rates reported from temperate ZT systems globally. West and Post [5] estimated average ZT sequestration at 0.57 t C/ha/yr in their global meta-analysis, but this included tropical systems with higher carbon cycling rates. Our value for a monsoon-temperate site is notable because the wet-dry seasonal cycle in Korean climate accelerates both residue input and decomposition, creating a dynamic carbon balance [6].

The initial yield depression under ZT-3yr aligns with the commonly reported transition penalty that discourages farmer adoption. The mechanisms likely include cooler and wetter seedbed conditions under residue cover, compacted seed placement zone from traffic without subsequent tillage, and altered weed species shifts [7]. That this penalty reversed within six years and became a positive yield advantage by nine years underscores the importance of communicating the long-term trajectory rather than only short-term results to farmers considering the transition [8].

### Conclusion

This nine-year research at Seoul National University confirmed that zero tillage delivers substantial and compounding benefits to soil organic carbon, biological activity, aggregate stability, and water use efficiency in a Korean wheat production system. Total SOC increased by 23.7%, with labile carbon nearly doubling, earthworm populations more than doubling, and aggregate stability rising from 42% to 71%.

The yield trajectory an initial 4.2% depression followed by recovery and eventual 6.8% gain defines a transition period of approximately 4-6 years that farmers and policymakers must plan for. Long-term zero tillage represents a viable pathway for simultaneously improving wheat productivity and rebuilding degraded soil capital in intensive East Asian cereal systems, provided adequate support is available during the transition period.

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