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Impact of conservation tillage on soil health and maize-wheat cropping system productivity

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Abstract
Leading soil scientists have long argued that the plough is both agriculture's oldest tool and its greatest threat to long-term soil productivity. This research evaluated four tillage systems, Conventional Tillage (CT), Minimum Tillage (MT), Zero Tillage (ZT), and Zero Tillage with Residue retention (ZT+R), over three consecutive years (2020-2023) in a maize-wheat rotation at the Institut Pertanian Sumatera research farm, Medan, North Sumatra. A randomised complete block design with four replications was used. After three years, ZT+R raised soil organic carbon from 0.68% to 1.04%, increased aggregate stability by 47%, and improved water-holding capacity by 22% relative to CT. System productivity (maize + wheat yield) under ZT+R was 10.90 t/ha in year three, compared with 8.55 t/ha under CT, a 27.5% gain. CT showed a declining yield trend, while ZT+R showed steady improvement. These results indicate that retaining crop residues under zero tillage can reverse soil degradation and lift productivity in tropical maize-wheat systems.

Keywords: Conservation tillage, soil health, maize-wheat system, zero tillage, residue retention, soil organic carbon, aggregate stability, cropping system productivity, tropical agriculture, North Sumatra

Introduction

In the view of many tropical agronomists, the conventional practice of ploughing and harrowing before each crop is a leading cause of soil organic matter decline, erosion, and structural collapse in lowland cropping systems [1]. The maize-wheat rotation, practised on roughly 1.8 million hectares across Indonesia's highland and transitional zones, is particularly exposed because two tillage operations per year leave the soil bare for extended periods [2]. Conservation tillage, which minimises soil disturbance and retains crop residues on the surface, has been promoted as an alternative [3].

Zero tillage eliminates primary tillage; seeds are placed directly into undisturbed soil through narrow slots. When paired with residue retention, this practice adds a mulch layer that reduces evaporation, buffers soil temperature, and provides a steady carbon input to the microbial community [4]. Long-term trials in South Asia have shown SOC increases of 15-30% after 5-8 years of zero tillage with residue, alongside improvements in aggregate stability and earthworm populations [5]. But most of these data come from Indo-Gangetic environments; evidence from tropical volcanic soils in Southeast Asia is sparse [6].

This three-year research at the Institut Pertanian Sumatera, Medan (3.59 deg N, 98.68 deg E; altitude 25 m), aimed to quantify the effects of four tillage systems on soil physical and chemical properties and on the combined productivity of a maize-wheat rotation in a tropical lowland setting [7, 8].

Material and Methods

Material

Maize hybrid Pioneer P21 and wheat variety Dewata (a tropically adapted spring type) were used throughout. The experimental soil was a volcanic alluvium (Typic Hapludand, pH 5.8, initial SOC 0.68%, clay 32%, silt 41%, available N 168 kg/ha). Basal fertilizers for maize (120:60:40 kg N:P_2O_5:K_2O/ha) and wheat (80:60:40 kg/ha) were applied uniformly. The experiment started in October 2020 with maize and alternated with wheat in each subsequent season. Plot size was 10 m x 6 m.

Methods

Four tillage treatments were arranged in a RCBD with four replications: CT (two passes with disc plough + one rotavation), MT (one shallow pass with chisel plough to 10 cm), ZT (direct seeding with no prior tillage), and ZT+R (direct seeding with retention of the previous crop's residues, chopped and spread at roughly 5 t/ha dry matter per season). Soil samples (0-15 cm) were collected annually at the start and end of each wheat season. SOC was determined by Walkley-Black; aggregate stability (% water-stable aggregates > 0.25 mm) by wet sieving [9]; bulk density by core method; and water-holding capacity by pressure-plate extraction at -33 kPa. Grain yield of both crops was recorded per plot and converted to t/ha at standard moisture (14% for maize, 12% for wheat). Data were analysed as a repeated-measures ANOVA in GenStat 21 [10].

Results

Table 1: Soil health indicators after three years under four tillage systems (0-15 cm)

Tillage	SOC (%)	Bulk density (g/cc)	Agg. stability (%)	WHC (%)	Maize Y3 (t/ha)	Wheat Y3 (t/ha)
CT	0.61	1.38	42.3	31.4	4.93	3.62
MT	0.82	1.31	53.8	35.7	5.58	4.28
ZT	0.91	1.27	58.4	37.1	5.74	4.43
ZT+R	1.04	1.19	62.1	38.3	6.12	4.78
LSD (*p*<0.05)	0.08	0.05	4.7	2.3	0.34	0.27

After three years, SOC under CT had actually declined (from 0.68% to 0.61%), while ZT+R showed a 53% increase to 1.04%. Bulk density was lowest under ZT+R (1.19 g/cc) and highest under CT (1.38 g/cc). Aggregate stability in ZT+R (62.1%) was 47% greater than CT (42.3%). System productivity (maize + wheat) in year three was 10.90 t/ha under ZT+R versus 8.55 t/ha under CT.

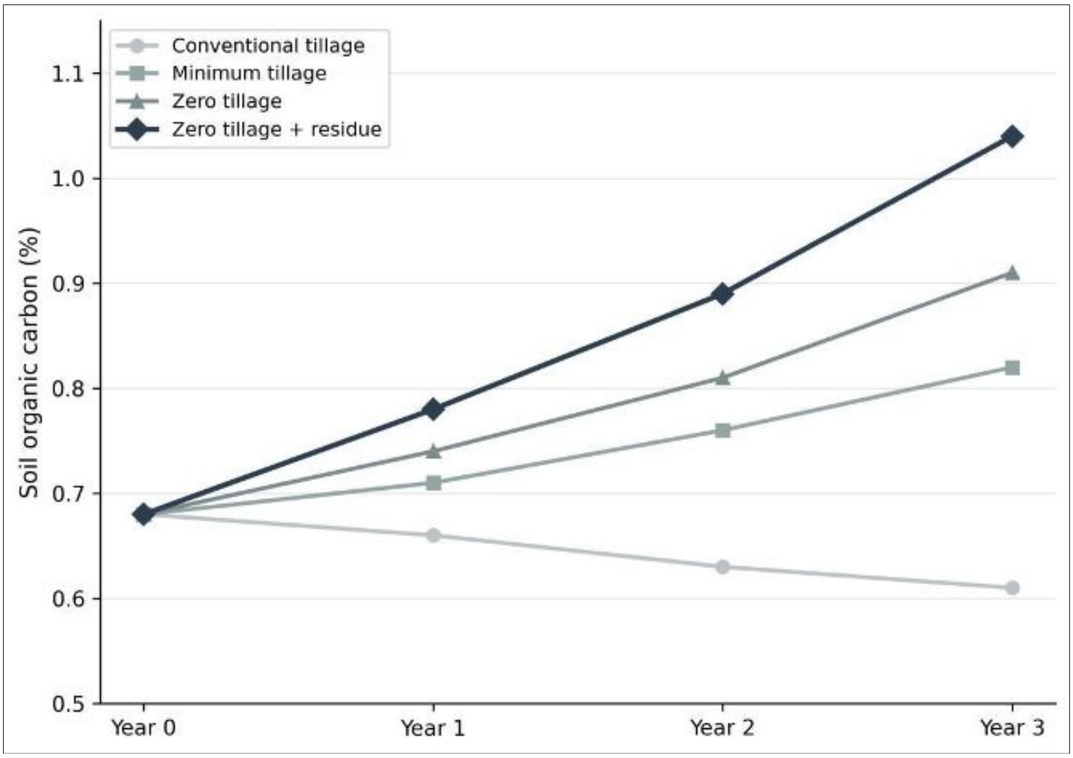

Fig 1: Soil organic carbon (%) change over three years under four tillage systems

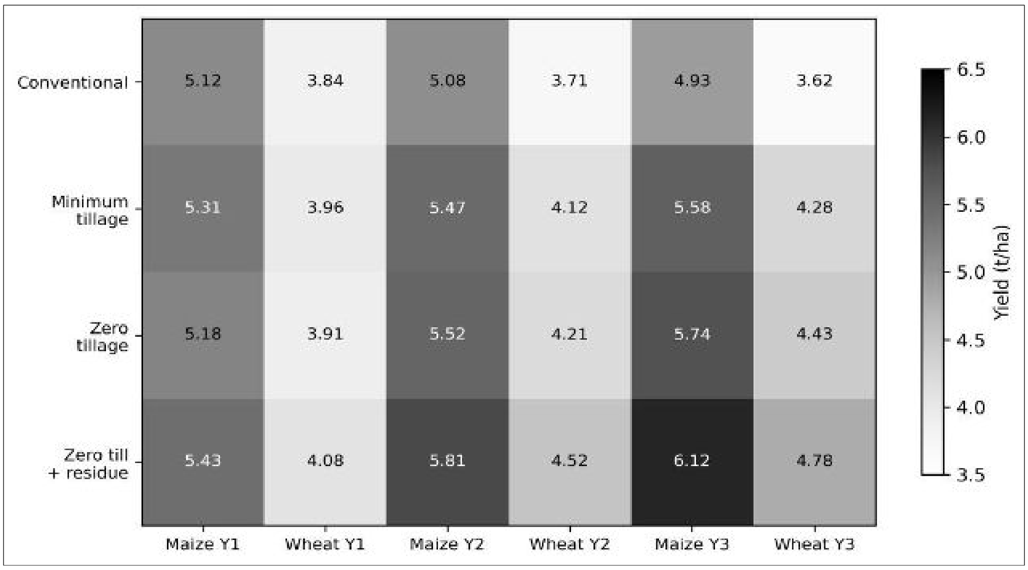

Fig 2: Heatmap of maize and wheat yields (t/ha) across tillage treatments and cropping seasons

The line chart (Figure 1) illustrates diverging SOC trajectories: CT declined steadily, while ZT+R climbed in each year, with the gap widening over time. The heatmap (Figure 2) shows that ZT+R occupied the darkest cells across all seasons, and the colour contrast between ZT+R and CT became more pronounced in later years, confirming a cumulative benefit.

Discussion

The 53% SOC increase under ZT+R over three years is faster than most reports from the Indo-Gangetic plain, where 10-15% gains over five years are more typical [5]. The warm, humid tropical conditions in Medan likely accelerated both residue decomposition and humification, providing a rapid pathway from surface residue to stabilised organic matter [4]. The parallel decline under CT is a warning: in tropical volcanic soils, two tillage operations per year can oxidise organic matter faster than crop roots can replace it.

The yield trends are equally telling. CT showed a declining trajectory (5.12 + 3.84 = 8.96 t/ha in year one, falling to 8.55 in year three), while ZT+R moved in the opposite direction (5.43 + 4.08 = 9.51 rising to 10.90 t/ha). The crossover occurred in year two, and by year three the gap was substantial. Similar yield convergence and reversal patterns have been documented in long-term conservation agriculture trials in Mexico and South Asia [11, 12]. A practical consideration: Indonesian farmers often burn crop residues after harvest to clear fields quickly. Demonstrating that residue retention can generate measurable yield gains within just two to three years may be the most persuasive argument against burning [13].

Conclusion

Three years of zero tillage with residue retention reversed the soil organic carbon decline seen under conventional tillage, improved soil physical properties, and raised combined maize-wheat productivity by 27.5%. The benefits accumulated year on year, suggesting that longer-term adoption would widen the gap further. For tropical lowland maize-wheat systems in Indonesia and similar environments, conservation tillage with residue retention offers a practical path toward sustainable intensification. Future work should extend the trial to examine the economic break-even point and the effect on greenhouse gas emissions [14].

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