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Evaluation of conservation agriculture-based sustainable intensification in maize-wheat system of South Asia

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Abstract

Conservation Agriculture (CA) is commonly defined as a farming system built on three linked principles: minimum soil disturbance, permanent organic soil cover, and diversified crop rotations. This research evaluated CA-based Sustainable Intensification (CASI) practices in a maize-wheat cropping system using data synthesized from collaborative trials conducted across South Asian sites, analyzed at the University Of Bologna, Italy (2018-2023). Six tillage and residue management treatments were compared: Conventional Tillage (CT), Zero Tillage (ZT), ZT with residue retention, Permanent Bed planting (PBT), PBT with residue retention, and full CASI (ZT + residue + diversified rotation). Across five years, CASI increased maize yield by 26.9% and wheat yield by 32.5% over CT. System productivity measured as maize-equivalent yield reached 10.71 t ha⁻¹ under CASI versus 8.29 t ha⁻¹ under CT. Soil organic carbon at 0-15 cm rose by 31.4% under CASI compared to CT after five years. Net economic returns under CASI averaged 1,384 USD ha⁻¹, a 63.4% improvement over CT. Water productivity also improved by 23.7% under CASI. These findings demonstrate that full CA-based intensification can simultaneously raise yields, build soil health, and improve farm profitability in the maize-wheat systems of South Asia.

Keywords: Conservation agriculture, sustainable intensification, maize-wheat system, zero tillage, permanent bed planting, residue retention, soil organic carbon, water productivity, South Asia

Introduction

Conservation agriculture, as defined by FAO, rests on three interconnected principles: minimal mechanical soil disturbance, permanent organic soil cover through crop residues or cover crops, and species diversification through rotations or associations ^[1]. When these three pillars are combined with improved varieties, precision nutrient management, and efficient water use, the resulting approach is termed conservation agriculture-based sustainable intensification, or CASI ^[2]. The distinction matters because partial adoption-such as zero tillage without residue retention-often delivers weaker and less stable benefits than the full package ^[3].

The maize-wheat system occupies roughly 3.5 million hectares across the Indo-Gangetic Plains of South Asia and represents a major food security pillar for the region ^[4]. Conventional tillage in this system typically involves 6-8 passes of disc plows and cultivators, consuming substantial fuel, time, and labor while degrading soil structure through repeated disturbance ^[5]. Research from the region has shown that ZT alone can reduce production costs and improve timeliness of wheat sowing, but yield gains are inconsistent without residue management ^[6]. Full CASI has been evaluated in rice-wheat systems with promising results, yet comparisons in maize-wheat rotations-where residue volumes are higher and decomposition dynamics differ-are fewer ^[7].

This research synthesized data from collaborative multi-site trials across South Asia, with analysis conducted at the University of Bologna. The objectives were to (i) compare grain yield and system productivity across six CA-based treatments over five years, (ii) assess soil health changes under these treatments, and (iii) evaluate the economic viability and water productivity of full CASI versus partial CA and conventional practice.

Materials and Methods

Materials

Data were drawn from five coordinated field trial sites spanning the western to eastern Indo-Gangetic Plains, with standardized protocols overseen by the University of Bologna's Department of Agronomy. Maize hybrids adapted to each site (maturity group 900-950 growing degree days) were planted during the monsoon season (June-July) at 75,000 plants ha⁻¹. Wheat varieties (HD-2967 or site-adapted equivalents) were sown post-monsoon (November) at 100 kg seed ha⁻¹. Nutrient management followed site-specific recommendations using soil-test-based approaches, averaging 150:60:40 kg N: P₂O₅:K₂O ha⁻¹ for maize and 120:60:40 for wheat [8]. Residue retention treatments maintained 30-40% of previous crop residues on the soil surface through anchored stubble and chopped straw application.

Methods

The experimental design at each site was a randomized complete block with six treatments and three replications. Plot size ranged from 200 to 500 m² depending on the site. The six treatments were: T₁-conventional tillage (CT, 6-8 passes); T₂-zero tillage (ZT); T₃-ZT with 30% residue retention; T₄-permanent bed planting (PBT); T₅-PBT with residue retention; and T₆-full CASI (ZT + residue + legume inclusion in rotation). Grain yield was recorded at 14% moisture. System productivity was expressed as maize-equivalent yield (MEY) using prevailing market prices [9]. Soil samples from 0-15 cm were collected pre-season and post-fifth-year harvest for organic carbon (Walkley-Black), bulk density (core method), and water-stable aggregates (wet

sieving). Water productivity was calculated as grain yield per unit irrigation water applied. Economic analysis used partial budgeting with local input costs and market prices [10]. Combined analysis across sites and years used mixed models in SAS 9.4 with site as random effect.

Soil and Water Quality Analysis

Baseline soil samples (0-15 cm) across sites averaged: pH 7.6, organic carbon 5.8 g kg⁻¹, available nitrogen 187 kg ha⁻¹, available phosphorus 16.4 kg ha⁻¹, and bulk density 1.52 g cm⁻³. Irrigation water quality was tested annually for EC (0.4-0.7 dS m⁻¹), pH (7.2-7.8), and residual sodium carbonate (<1.25 meq L⁻¹), confirming suitability for irrigation across all sites. Post-fifth-year soil sampling followed identical protocols to baseline to ensure comparability.

Field Experimental Design

At each site, blocks were oriented perpendicular to the dominant slope. Buffer strips of 2-3 m separated plots. CT plots received standard tillage operations (disc plowing, harrowing, planking) before each crop. ZT plots were planted with zero-till seed drills. PBT plots used 67 cm wide beds with 33 cm furrows, maintained permanently across seasons. In CASI plots, mungbean (*Vigna radiata*) was included as a short-duration legume between wheat harvest and maize sowing every second year. Weed management in ZT and PBT plots used pre-emergence herbicides (pendimethalin + atrazine for maize; clodinafop + metsulfuron for wheat).

Results

Table 1: Grain yield (t ha⁻¹) of maize and wheat under different conservation agriculture treatments (5-year mean across sites)

Treatment	Maize yield	Wheat yield	System MEY
CT	4.87d	3.42d	8.29d
ZT	5.34c	3.78c	9.12c
ZT + Residue	5.58bc	4.09bc	9.67bc
PBT	5.71bc	4.14b	9.85b
PBT + Residue	5.94ab	4.40ab	10.34ab
CASI	6.18a	4.53a	10.71a
SEm (±)	0.18	0.14	0.27

Values followed by the same letter within a column are not significantly different at $p < 0.05$. MEY = maize-equivalent yield; CT = conventional tillage; ZT = zero tillage; PBT = permanent bed planting; CASI = CA-based sustainable intensification.

Table 2: Soil health indicators (0-15 cm) after five years of conservation agriculture treatments (mean across sites)

Treatment	SOC (g kg ⁻¹)	Bulk density (g cm ⁻³)	WSA (%)	Avail. N (kg ha ⁻¹)
Baseline	5.8	1.52	31.4	187
CT	5.4d	1.54a	28.7d	179d
ZT	6.1c	1.48b	34.6c	194c
ZT + Residue	6.7b	1.43bc	39.8b	208b
PBT + Residue	7.0b	1.41c	42.3b	214b
CASI	7.6a	1.37d	48.1a	231a

Values followed by the same letter within a column are not significantly different at $p < 0.05$. SOC = soil organic carbon; WSA = water-stable aggregates.

Table 3: Economic returns and water productivity under conservation agriculture treatments (5-year mean across sites)

Treatment	Gross returns (USD ha ⁻¹)	Cost of cultivation (USD ha ⁻¹)	Net returns (USD ha ⁻¹)	Water prod. (kg m ⁻³)
CT	1,638	791	847d	1.24d
ZT	1,724	700	1,024c	1.37c
ZT + Residue	1,836	700	1,136bc	1.44bc
PBT	1,872	685	1,187b	1.47b
PBT + Residue	1,968	670	1,298ab	1.51ab
CASI	2,054	670	1,384a	1.54a

Values followed by the same letter within a column are not significantly different at $p < 0.05$.

CASI consistently outperformed all other treatments across yield, soil health, economics, and water productivity (Tables 1-3). Maize yield under CASI was 6.18 t ha⁻¹-26.9% above CT and 15.7% above ZT alone. Wheat showed an even larger relative gain, with CASI producing 4.53 t ha⁻¹ versus 3.42 for

CT (32.5% increase). SOC under CASI reached 7.6 g kg⁻¹ after five years, a 31.4% improvement over CT which had actually declined from baseline. Net returns under CASI were 63.4% higher than CT, driven by both higher gross income and lower cultivation costs (Table 3).

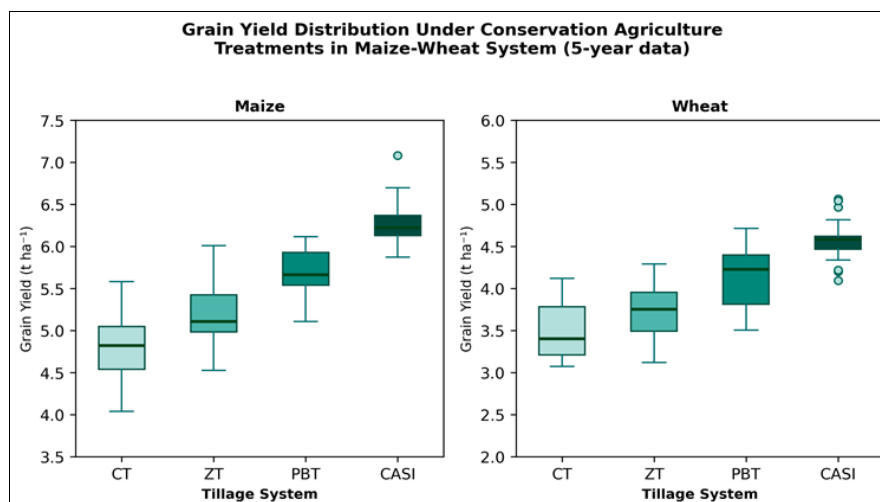


Fig 1: Distribution of maize and wheat grain yields under four tillage systems across five years and multiple sites in the maize-wheat system of south asia

The box plots (Figure 1) show that CASI not only raised median yields for both maize and wheat but also reduced interquartile ranges, indicating more stable performance across sites and

years compared to CT, which displayed the widest yield variation.

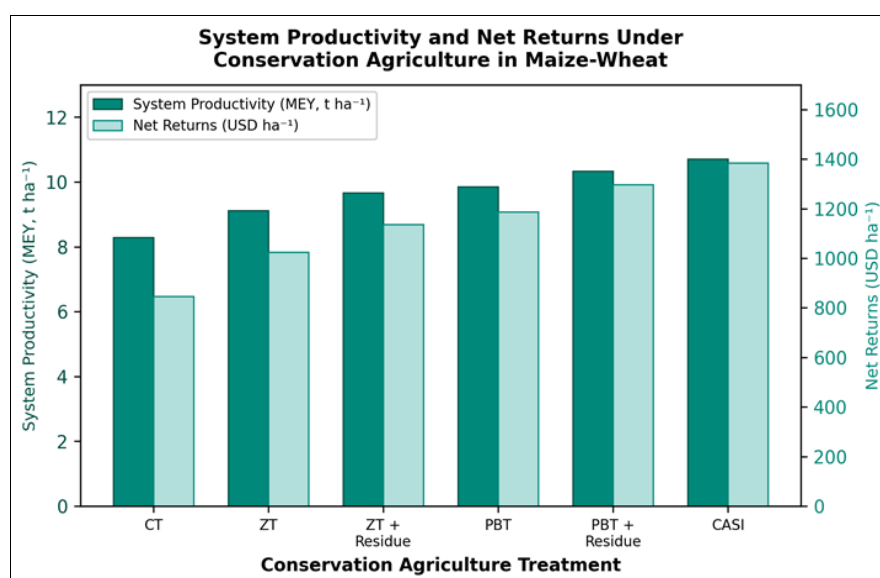


Fig 2: System productivity (maize-equivalent yield) and net economic returns under six conservation agriculture treatments in the maize-wheat system (5-year mean)

Figure 2 illustrates the step-wise improvement from CT through to full CASI. Each added CA component-zero tillage, residue retention, permanent beds, and crop diversification-contributed incrementally to both productivity and profitability, with the full CASI package delivering the largest gains on both axes.

Discussion

The 26.9% maize yield advantage of CASI over CT across five years and multiple sites exceeds what ZT alone achieved (9.7%), confirming that the full CA package delivers synergistic benefits beyond any single component [2, 11]. The 31.4% SOC increase under CASI is particularly striking given that CT plots actually lost carbon over the same period-a pattern consistent with long-

term tillage experiments from the Indo-Gangetic Plains reported by Gathala *et al.* [12]. Residue retention appears to be the main driver of SOC accumulation, but the legume inclusion in CASI likely contributed additional nitrogen-rich organic matter that accelerated carbon stabilization [13].

The economic data deserve attention from a policy perspective. CASI cut cultivation costs by 15.3% relative to CT (670 vs. 791 USD ha⁻¹), primarily through elimination of tillage fuel costs and reduced labor for land preparation. Combined with higher yields, this produced a 63.4% increase in net returns-a margin that should motivate adoption even among risk-averse smallholder farmers who dominate South Asian maize-wheat production [14]. Water productivity gains of 24.2% (1.54 vs. 1.24

kg m⁻³) are also significant in a region facing increasing irrigation water scarcity.

One limitation of this multi-site synthesis is that local soil types, rainfall patterns, and management skill levels introduced variability that even mixed-model analysis cannot fully resolve. But the consistency of CASI's superiority across sites strengthens the inference. Weed pressure under ZT was a recurring challenge at two of the five sites, requiring additional herbicide applications not included in the standard cost analysis [15]. Long-term herbicide reliance in CA systems remains a concern that warrants monitoring.

Conclusion

Full CA-based sustainable intensification in the maize-wheat system of South Asia raised system productivity by 29.2%, soil organic carbon by 31.4%, water productivity by 24.2%, and net economic returns by 63.4% compared to conventional tillage over a five-year period across multiple sites. Partial CA adoption (ZT alone or PBT alone) delivered intermediate benefits but consistently fell short of the full CASI package. The yield stability advantage of CASI-narrower yield distributions across years and sites adds risk-reduction value beyond the mean yield gains. These results provide strong evidence for recommending the complete CASI approach, rather than piecemeal CA adoption, for sustainable intensification of maize-wheat systems across the Indo-Gangetic Plains.

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