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Long term yield trends and stability of mechanized rice and wheat establishment systems over two decades in the Indo Gangetic Plains

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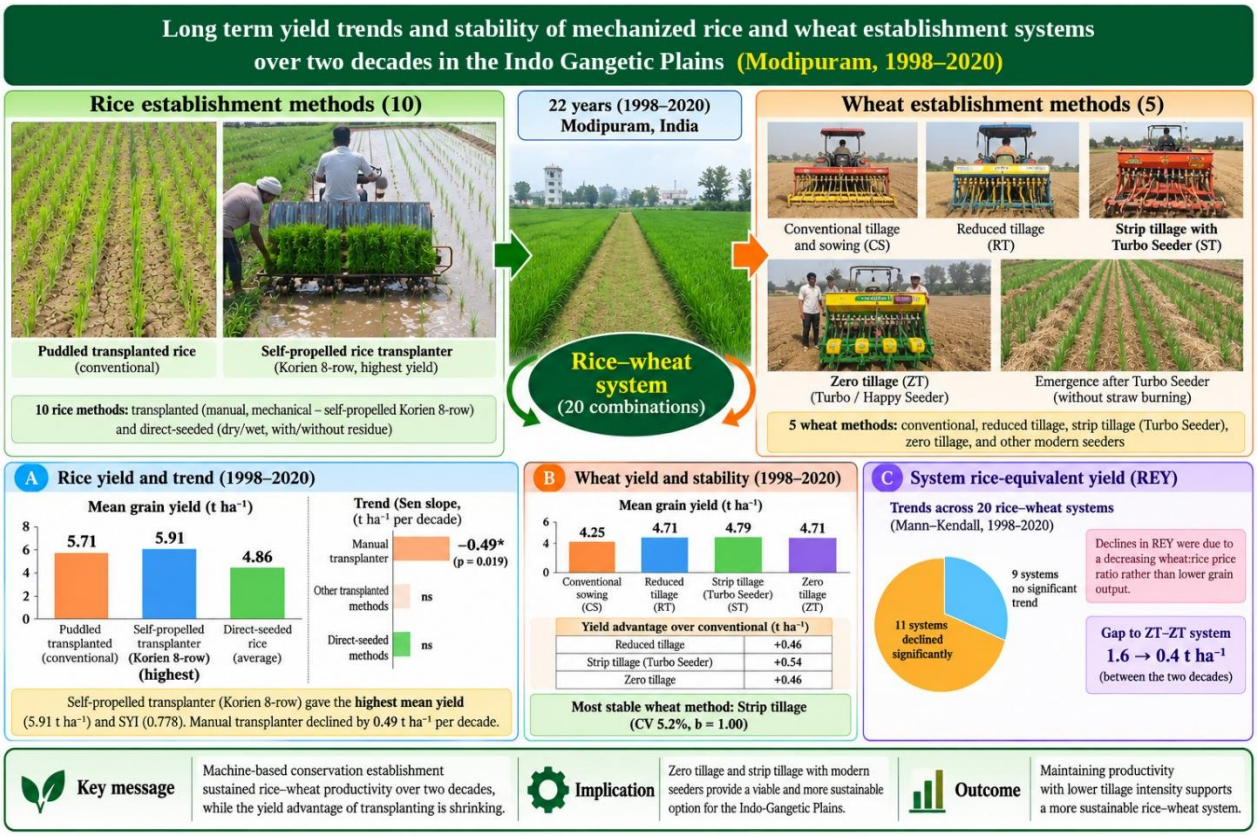
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Abstract

Rice–wheat farmers in the Indo-Gangetic Plains are being encouraged to replace puddled transplanting and repeated tillage with machine-based establishment, yet few field records show how the alternatives perform over decades. We analysed 22 seasons (1998–2020) of a mechanization experiment at Modipuram, India, that compared ten rice and five wheat establishment methods, and we evaluated twenty rice–wheat combinations. Using all seasons with verified records, we estimated yield level, variability, sustainable yield index (SYI), Mann–Kendall trends with Sen slopes and Eberhart–Russell stability, and we tested replicated data from 2016–2019 by analysis of variance. Puddled transplanted rice out-yielded direct-seeded rice by 17% (5.71 vs 4.86 t ha^{-1}). The mechanical transplanter gave the highest mean yield (5.91 t ha^{-1}) and SYI (0.778), whereas rice planted with the manual transplanter declined by 0.49 t ha^{-1} per decade ($p = 0.019$). No direct-seeded method declined significantly. In wheat, reduced tillage, strip tillage with the Turbo Seeder and zero tillage yielded 0.46–0.54 t ha^{-1} more than conventional sowing, and strip tillage was the most stable (CV 5.2%, $b = 1.00$). With season-specific prices, system rice-equivalent yield fell significantly in 11 of 20 systems, but these falls disappeared at a fixed wheat:rice price ratio because they reflected a declining price ratio rather than lower grain output. The gap between the best transplanted system and zero-till rice–wheat narrowed from 1.6 to 0.4 t ha^{-1} between the two decades. Machine-based conservation establishment sustained rice–wheat productivity over two decades, while the yield advantage of transplanting is shrinking.

Keywords Conservation agriculture · Crop establishment · Farm mechanization · Rice–wheat system · Sustainable yield index · Yield stability

Graphical abstract



1 Introduction

The rice–wheat system covers about 13.5 million hectares of the Indo-Gangetic Plains (IGP) and supplies much of the staple grain eaten in South Asia [1]. For more than two decades, however, its productivity has given cause for concern. Long-term experiments across the region have recorded stagnant or declining yields at many sites [2], yield growth in the main rice and wheat areas of India has slowed [3], and the groundwater that supports both crops is being depleted faster than it is recharged [4]. The way the crops are established lies behind several of these problems. Puddling for transplanted rice takes large amounts of water, labour and diesel, damages soil structure for the following wheat crop, and delays wheat sowing because of the time needed to prepare the field after rice harvest [1, 5]. Repeated tillage and residue burning also deplete soil organic carbon, whereas zero tillage with residue retention protects it [6].

Machines offer a way out of some of these constraints. Zero-till drills, bed planters, strip-till seeders such as the Turbo Happy Seeder and mechanical rice transplanters can establish a crop with fewer passes, less labour and, in the case of direct-sown rice, without puddling [7–9]. Conservation agriculture built on these machines has been widely promoted in South Asia [10,

11], and a decade of conservation agriculture in north-west India has given more stable yield trends and better soil health than conventional rice–wheat [12]. Its yield record is uneven, though. A global meta-analysis found that no-till alone usually lowers yields, especially in the first years, and that the penalty narrows only when residue retention and crop rotation are added [13]. In the IGP, direct-sown rice often yields less than puddled transplanted rice, whereas zero-till wheat generally yields as much as or more than conventionally sown wheat, mainly because it is sown earlier [5, 7].

Most of this evidence comes from experiments that ran for three to eight seasons. Short records can show which method yields most in a given period, but they say little about whether yields are stable from year to year or whether they drift over time, which are the properties that determine long-term sustainability [2, 14]. A rice–wheat mechanization experiment that started at Modipuram in 1998 offers a rare chance to examine these questions. Earlier reports from this experiment described machine performance and yields in the first seasons [15, 16] and, later, the energy use and global warming potential of the rice establishment methods [17]. Related work at the same location has dealt with the energy cost of weed management [18], the energy balance of diversified rice–wheat sequences [19] and the energy and greenhouse gas balance of conservation tillage in wheat, in *rabi* crops and in the rice–wheat system [20–22]. None of these studies examined the full yield record for trend and stability.

Here we use 22 seasons of yield data from the experiment to answer three questions. First, how do ten rice and five wheat establishment methods compare in yield level, variability and sustainability? Second, which methods show a significant yield trend over time, and how stable are they across seasons? Third, how do these crop-level patterns combine into the productivity and long-term trend of twenty rice–wheat systems? Because system productivity is usually expressed as rice-equivalent yield, we also examined how the price ratio used to compute it affects the trends. The energy and emission consequences of the same methods have already been reported [17, 21, 22] and are discussed here only where they bear on the yield results.

2 Materials and methods

2.1 Site, soil and experimental design

The experiment was conducted at the research farm of the ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh (29°04′ N, 77°46′ E; 237 m above sea level), in the upper IGP. The climate is semi-arid subtropical. Mean minimum and maximum temperatures are 7.2 and 20.1 °C in January, the coolest month, and 24.2 and 39.8 °C in May,

the hottest. Mean annual rainfall is about 823 mm, three-quarters of which falls during the monsoon between July and September. The surface soil (0–15 cm) is a sandy loam (63.7% sand, 19.1% silt and 17.2% clay) classified as Typic Ustochrept. When the study began it was slightly alkaline (pH 8.2) and non-saline (EC 0.27 dS m^{-1}), low in organic carbon (4.4 g kg^{-1}) and available N (74 kg ha^{-1}), medium in available P (14.1 kg ha^{-1}) and K (125 kg ha^{-1}), and deficient in available Zn (0.73 mg kg^{-1}) [17].

The rice establishment experiment was started in the *kharif* (monsoon) season of 1998 in a randomized block design with three replications and plots of 48 m × 5 m. Each treatment stayed on the same plots throughout, and every operation was repeated each season with the same tractor and implements [17]. Wheat was grown on the same field every *rabi* (winter) season with five establishment methods. In 2004 the rice–wheat comparison was formalized as a split-plot trial with three replications, in which four rice methods (ZT, DS, FPT and MaT) were the main plots and the five wheat methods the sub-plots. Yields were recorded until the *rabi* season of 2019–20, giving 22 rice and 22 wheat seasons.

2.2 Establishment methods and crop management

Ten rice establishment methods were compared (Table 1). Five were dry-seeded into unpuddled soil with tractor-drawn drills at 50 kg seed ha^{-1} in rows 22 cm apart: zero-till drilling without residue (ZT), strip tillage with the Happy Turbo Seeder into retained residue (ST), sowing on reshaped raised beds (BP), sowing with a rotary-till drill (reduced tillage, RT) and conventional sowing after two harrowings, two cultivator passes and one rotavator pass (CS). Two methods used sprouted seed (40 kg ha^{-1}) on puddled soil, sown in 22-cm rows with a drum seeder (DS) or broadcast (BS). The other three were transplanted into puddled fields: manual transplanting of 25-day-old seedlings, two to three per hill, as practised by farmers (FPT, labelled HT in earlier reports), transplanting of 25-day-old seedlings with a manually operated transplanter (MT), and transplanting of 20-day-old mat-nursery seedlings with a self-propelled transplanter (MaT). For DS, BS and the transplanted methods the field was harrowed, cultivated and rotavated once each in dry condition and then puddled with two rotavator passes. The method names follow the earlier report on energy use in this experiment, where the machines and their field capacities are also described [17].

Dry-seeded rice was sown and nurseries were raised in the second week of June (Fig. 1), the direct sowing and the nursery seeding being done on almost the same date; transplanting was done in the first week of July and all plots were harvested in mid-October. Every rice treatment

received 120 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1}, together with 25 kg zinc sulphate ha^{-1}. Where iron deficiency appeared in direct-seeded rice, ferrous sulphate (20 kg ha^{-1}) was applied during the season. Half of the N and the full dose of P were applied at sowing or transplanting through diammonium phosphate (DAP), and K was applied at the same time through muriate of potash. The remaining N was top-dressed as urea in two equal splits at tillering and at the milking stage. In the direct-seeded crops, weeds were controlled with glyphosate before sowing, pendimethalin (1.5 kg a.i. ha^{-1}) as a pre-emergence spray and bispyribac-sodium after emergence, followed by one spot hand weeding. Direct-seeded rice was irrigated by alternate wetting and drying, whereas transplanted rice was kept flooded to about 5 cm. As a result, puddled transplanted rice received 126 ha-cm of water against 64–90 ha-cm for the direct-seeded methods (Table 1) [17]. Grain yield was recorded from the net plot area and expressed at 12% moisture.

In wheat, conventional sowing after repeated tillage (CS, farmers' practice) was compared with bed planting (BP), zero-till drilling (ZT), sowing into rice residue with the Happy Turbo Seeder (ST) and rotary-till drilling (RT). Wheat cultivar PBW-343 was sown at 80 kg seed ha^{-1} under every method between the last week of October and the first week of November each year. The recommended dose of 120 kg N, 60 kg P_2O_5 and 60 kg K_2O ha^{-1} was applied. As in rice, half of the N and the full dose of P were applied as a basal dose through DAP and K as a basal dose through muriate of potash, and the remaining N was top-dressed as granular urea in two equal splits. The crop received five to six flood irrigations of about 5–6 cm each from a tube well. Wheat grain yield was also recorded from the net plot area and expressed at 12% moisture.

Table 1 Rice and wheat establishment methods (treatments) compared in the experiment

Code	Method	Land preparation	Sowing or planting	Irrigation water (ha-cm)
Rice (*kharif*): dry direct seeding, unpuddled				
ZT	Zero tillage	None; residue removed	Zero-till drill; 50 kg seed ha^{-1}; 22 cm rows	80
ST	Strip tillage (Happy Turbo Seeder)	None; residue retained	Happy Turbo Seeder; 50 kg ha^{-1}; 22 cm rows	70
BP	Bed planting	Reshaped raised beds	Bed planter; 50 kg ha^{-1}	64
RT	Reduced tillage	Rotary tilling at sowing	Rotary-till drill; 50 kg ha^{-1}; 22 cm rows	75
CS	Conventional sowing	2 harrow + 2 cultivator + 1 rotavator	Seed drill; 50 kg ha^{-1}; 22 cm rows	75
Rice (*kharif*): sprouted seed, puddled				

Code	Method	Land preparation	Sowing or planting	Irrigation water (ha-cm)
DS	Drum seeding	Dry tillage, then puddling	Drum seeder; 40 kg ha^{-1}; 22 cm rows	90
BS	Broadcast sowing	Dry tillage, then puddling	Broadcast by hand; 40 kg ha^{-1}	90
Rice (*kharif*): transplanted, puddled				
FPT	Manual transplanting (farmers' practice)	Dry tillage, then 2 rotavator passes for puddling	25-day seedlings, 2–3 per hill; nursery 30 kg ha^{-1}	126
MT	Manually operated transplanter	As FPT	25-day seedlings, 2–3 per hill; nursery 30 kg ha^{-1}	126
MaT	Self-propelled mechanical transplanter	As FPT	20-day mat-nursery seedlings, 2–3 per hill; nursery 25 kg ha^{-1}	126
Wheat (*rabi*), cv. PBW-343				
CS	Conventional sowing (farmers' practice)	Repeated tillage	Seed drill; 80 kg ha^{-1}	25–36
BP	Bed planting	Raised beds	Bed planter; 80 kg ha^{-1}	25–36
ZT	Zero tillage	None	Zero-till drill; 80 kg ha^{-1}	25–36
ST	Strip tillage (Happy Turbo Seeder)	None; rice residue retained	Happy Turbo Seeder; 80 kg ha^{-1}	25–36
RT	Reduced tillage	Rotary tilling at sowing	Rotary-till drill; 80 kg ha^{-1}	25–36

Note: Rice details and irrigation water (total for the season) from Chaudhary et al. [17]. Wheat water: five to six flood irrigations of 5–6 cm each.



Fig. 1 Schematic illustration of dry direct seeding and mechanical transplanting of rice, two of the establishment approaches compared in the experiment

2.3 Data set

Grain yields of every establishment method were recorded in each season from replicated plots, and the season means of each method form the long-term data set used here (Fig. 2). Replicate-level yields were analysed for rice in 2018 and 2019 (three replications) and for wheat in 2016–17 to 2018–19 (four replications). The trend and stability analyses were based on the seasons for which the records of all methods could be verified, namely 20 rice seasons (2013 and 2017 not included), 21 wheat seasons (2013–14 not included) and 20 complete rice–wheat seasons. Each season was treated as one observation.

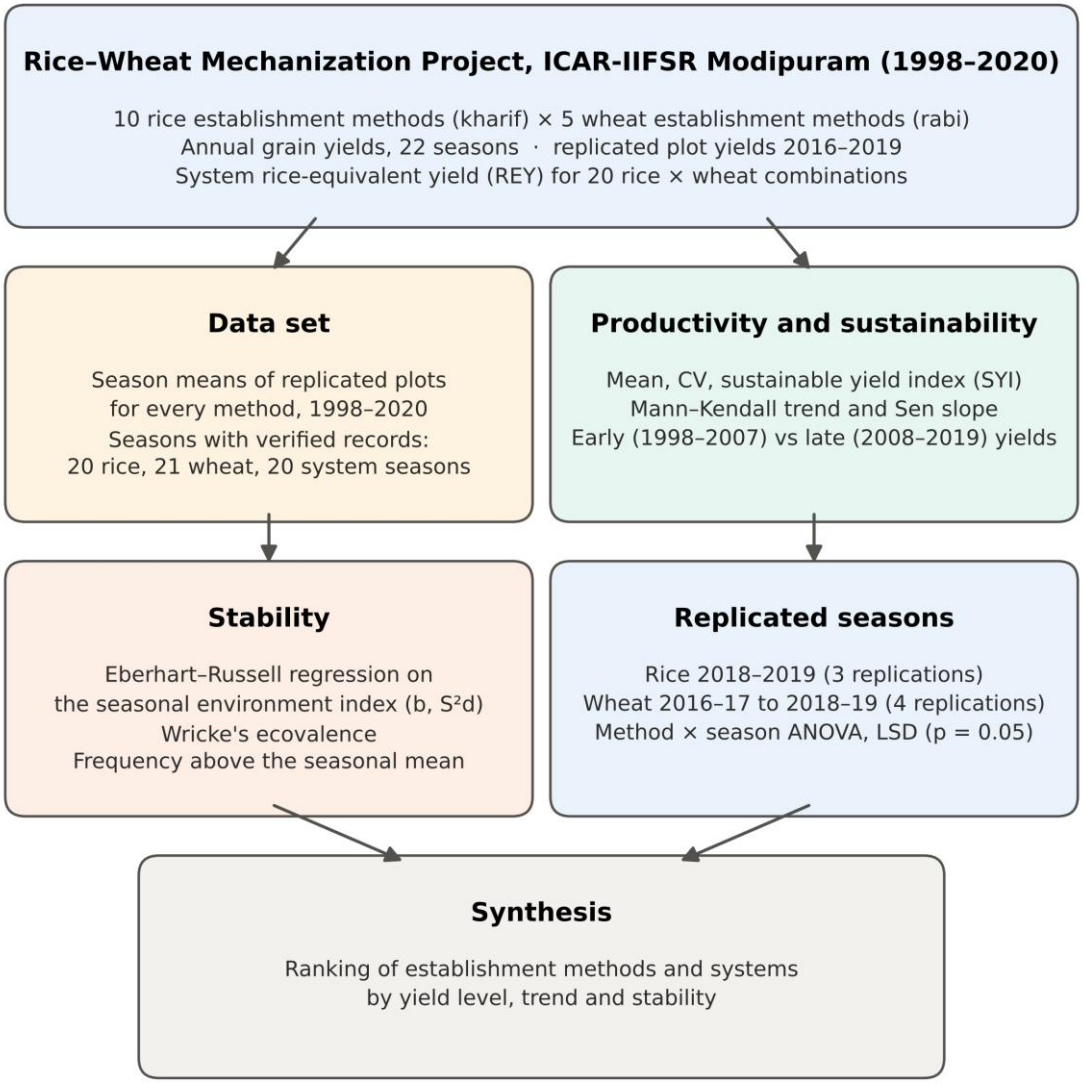


Fig. 2 Data set and analysis workflow

2.4 System productivity

Wheat yield was converted to rice-equivalent yield (REY) with the wheat:rice price ratio, and system REY was obtained by adding rice yield and wheat REY for the same crop year using Eqs. (1) and (2):

$$\mathrm{REY}_{w,j} = \mathrm{Y}_{w,j} \times (\mathrm{P}_{w,j} / \mathrm{P}_{r,j}) \quad (1)$$

$$\mathrm{REY}_{s,j} = \mathrm{Y}_{r,j} + \mathrm{REY}_{w,j} \quad (2)$$

where Y is grain yield (t ha^{-1}), P is price, the subscripts w and r denote wheat and rice, and j denotes the season. The project database used the price ratio of each season, calculated from the minimum support prices of paddy and wheat declared by the Government of India for that season, which fell from 1.25 in 1998–99 to 1.01 in 2019–20. Because a changing price ratio alters REY even when grain yields do not change, the trend and stability analyses for systems used a fixed ratio equal to the mean of the kept seasons (1.160); results with season-specific ratios are given for comparison. System REY was calculated for the 20 combinations of the split-plot trial, that is, four rice methods (ZT, DS, MaT and FPT) each followed by the five wheat methods. For the seasons before 2004, system values were formed by adding the rice and wheat yields of the corresponding methods in the same season.

2.5 Yield variability, sustainability and trend

For each method and system we calculated the mean, standard deviation (σ) and coefficient of variation (CV) across seasons (Eq. 3), and the sustainable yield index (Eq. 4) [14]:

$$\mathrm{CV}\ (\%) = 100 \times \sigma / \bar{\mathrm{Y}} \quad (3)$$

$$\mathrm{SYI} = (\bar{\mathrm{Y}} - \sigma) / \mathrm{Y}_{max} \quad (4)$$

where $\bar{\mathrm{Y}}$ is the mean yield of the method and Ymax is the highest yield recorded for that crop, or system, by any method in any kept season (6.92 t ha^{-1} for rice, 6.57 t ha^{-1} for wheat and 13.72 t ha^{-1} for system REY at the fixed price ratio). Using a common Ymax allows SYI values to be compared across methods. Monotonic trends were tested with the Mann–Kendall test [23, 24], and their size was estimated with the Sen slope [25], the median of all pairwise slopes (Eq. 5):

$$\beta = \mathrm{median}\ [(\mathrm{Y}_k - \mathrm{Y}_i) / (t_k - t_i)],\ \text{for all } i < k \quad (5)$$

with its 95% confidence interval. Slopes are reported in t ha^{-1} per decade. Mean yields in the first (1998–2007) and second (2008–2019) decades of the experiment were also compared.

2.6 Yield stability

Stability across seasons was assessed with the regression approach of Finlay and Wilkinson [26] as extended by Eberhart and Russell [27]. The yield of method i in season j was regressed on an environmental index Ij, the mean yield of all methods of that crop in season j minus the grand mean (Eqs. 6 and 7):

$$Y_{ij} = \mu_i + b_i I_j + \delta_{ij} \tag{6}$$

$$S^2d_i = \Sigma_j \delta^2_{ij} / (n - 2) \tag{7}$$

A regression coefficient b close to 1 indicates average responsiveness to good and poor seasons; $b < 1$ indicates a method that changes less than the average, and $b > 1$ one that responds more. A small deviation variance S^2d indicates that the response is predictable. Wricke's ecovalence [28], the contribution of each method to the method × season interaction, and the percentage of seasons in which a method yielded at or above the season mean were calculated as additional measures (Eq. 8):

$$W_i = \Sigma_j (Y_{ij} - \bar{Y}_i - \bar{Y}_j + \bar{Y})^2 \tag{8}$$

2.7 Replicated seasons

Replicated rice yields (2018 and 2019) and wheat yields (2016–17 to 2018–19) were analysed as a combined analysis of variance with season, replication within season, establishment method and season × method. The season effect was tested against replication within season and the method and interaction effects against the pooled error [29]. Means were separated by the least significant difference (LSD) at $p = 0.05$. All analyses were done in Python 3 with NumPy and SciPy (version 1.18). The season-wise data set and calculations are provided as Supplementary Data S1.

3 Results

3.1 Seasonal variation

Yields varied considerably between seasons (Fig. 3). The mean rice yield of all methods ranged from 4.33 t ha^{-1} in 2007 to 5.80 t ha^{-1} in 2004, and the mean wheat yield from 5.10 t ha^{-1} in 2006–07 to 6.08 t ha^{-1} in 2000–01. Poor and good seasons affected all methods in the same direction, but the ranking of methods was largely preserved: in rice, the three transplanted methods were above the season mean in 80–100% of seasons, whereas conventional sowing and broadcasting never were, and in wheat, strip tillage was above the season mean in every season and conventional sowing in none.

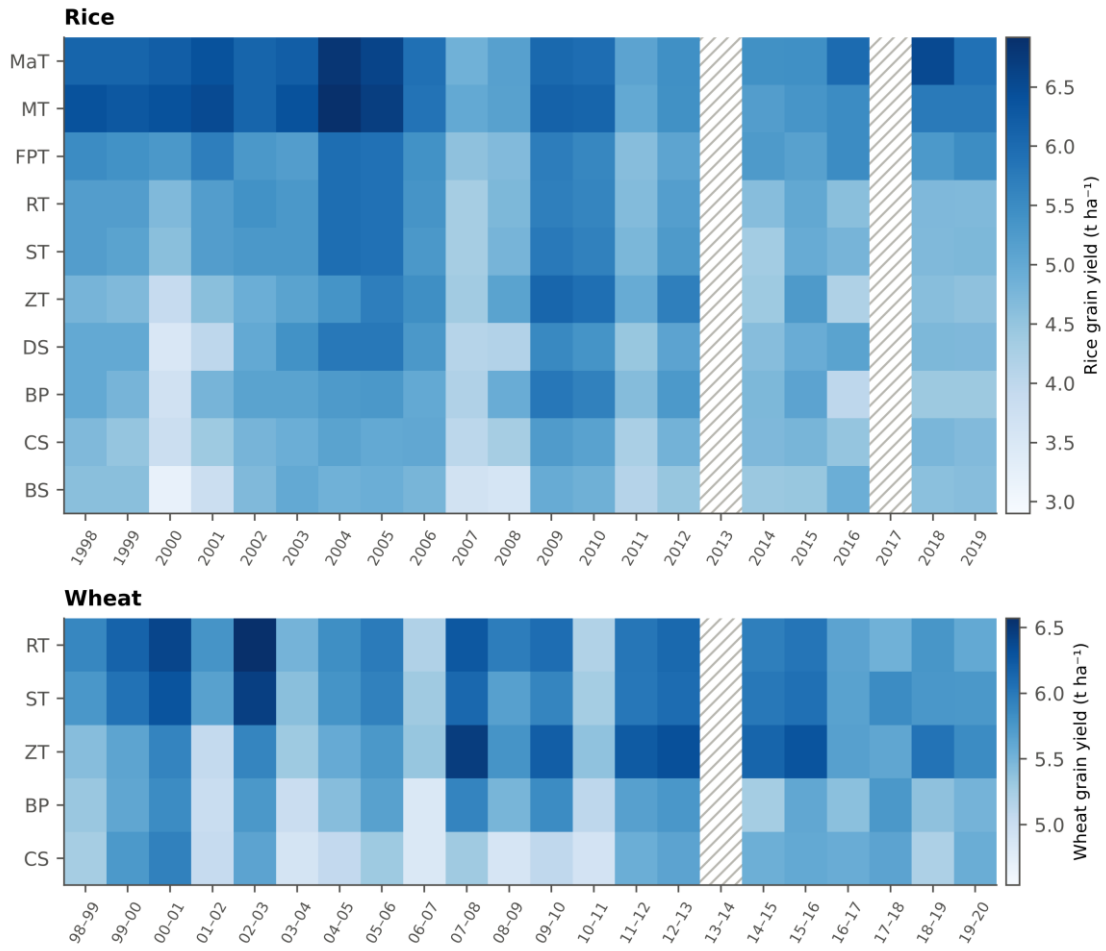


Fig. 3 Grain yield of ten rice (upper panel) and five wheat (lower panel) establishment methods in each season, 1998–2020. Hatched columns are seasons not included in the analysis (Section 2.3). Treatment codes as in Table 1

3.2 Rice

Puddled transplanted rice gave the highest yields over the 20 seasons (Table 2). The mechanical transplanter (MaT, 5.91 t ha^{-1}) and the manual transplanter (MT, 5.90 t ha^{-1}) were followed by manual transplanting (FPT, 5.33 t ha^{-1}). Taken together, the three transplanted methods averaged 5.71 t ha^{-1}, 17% more than the mean of the seven direct-sown methods (4.86 t ha^{-1}). Dry-seeded rice in unpuddled soil (ZT, ST, BP, RT and CS) averaged 4.94 t ha^{-1} and sprouted-seed rice on puddled soil (DS and BS) 4.67 t ha^{-1}. Among the direct-seeded methods, reduced tillage and strip tillage gave the highest yields (5.10 t ha^{-1} each) and broadcasting the lowest (4.46 t ha^{-1}). The SYI followed the same order, from 0.778 under MaT to 0.569 under broadcasting. Variability was lowest under FPT (CV 7.2%) and conventional sowing (8.0%) and highest under direct sowing (12.5%) and zero tillage (11.9%).

Table 2 Yield level, variability, trend and stability of rice establishment methods over 20 seasons (1998–2019)

Method	Mean (t ha⁻¹)	SD	CV (%)	SYI	Sen slope (95% CI) (t ha⁻¹ decade⁻¹)	p (MK)	b	S²d	1998–2007	2008–2019
MaT	5.91	0.53	8.9	0.778	−0.19 (−0.61, +0.12)	0.104	0.86	0.161	6.13	5.69
MT	5.90	0.59	9.9	0.768	−0.49 (−0.86, −0.16)	0.019	1.00	0.183	6.26	5.54
FPT	5.33	0.38	7.2	0.715	−0.11 (−0.46, +0.18)	0.363	0.73	0.061	5.42	5.23
RT	5.10	0.46	9.1	0.670	−0.25 (−0.60, +0.04)	0.091	1.08	0.020	5.25	4.95
ST	5.10	0.48	9.5	0.667	−0.24 (−0.56, +0.13)	0.173	1.11	0.025	5.21	4.98
ZT	4.98	0.59	11.9	0.634	+0.10 (−0.50, +0.71)	0.820	1.09	0.160	4.89	5.08
DS	4.88	0.61	12.5	0.617	0.00 (−0.49, +0.55)	1.000	1.31	0.086	4.89	4.88
BP	4.86	0.53	10.8	0.626	−0.14 (−0.49, +0.37)	0.537	1.02	0.109	4.83	4.90
CS	4.67	0.37	8.0	0.621	+0.06 (−0.22, +0.46)	0.721	0.81	0.031	4.63	4.72
BS	4.46	0.51	11.6	0.569	+0.08 (−0.22, +0.46)	0.721	0.99	0.107	4.41	4.50

Note: SYI, sustainable yield index (Ymax = 6.92 t ha⁻¹); MK, Mann–Kendall test; b and S²d, Eberhart–Russell regression coefficient and deviation variance. The last two columns are period means (t ha⁻¹). Treatment codes as in Table 1.

Only one rice method showed a significant trend (Fig. 4a). Yield under the manual transplanter fell by 0.49 t ha⁻¹ per decade (95% CI −0.86 to −0.16; p = 0.019), from 6.26 t ha⁻¹ in 1998–2007 to 5.54 t ha⁻¹ in 2008–2019. The mechanical transplanter, reduced tillage and strip tillage also had negative slopes of 0.19–0.25 t ha⁻¹ per decade, but these were not significant (p = 0.09–0.17). The zero-till, conventionally sown and broadcast crops had small positive slopes, and direct sowing had none. As a result, the advantage of transplanted over direct-sown rice became smaller over time: the gap between MaT and ZT rice narrowed from 1.24 t ha⁻¹ in the first decade to 0.61 t ha⁻¹ in the second.

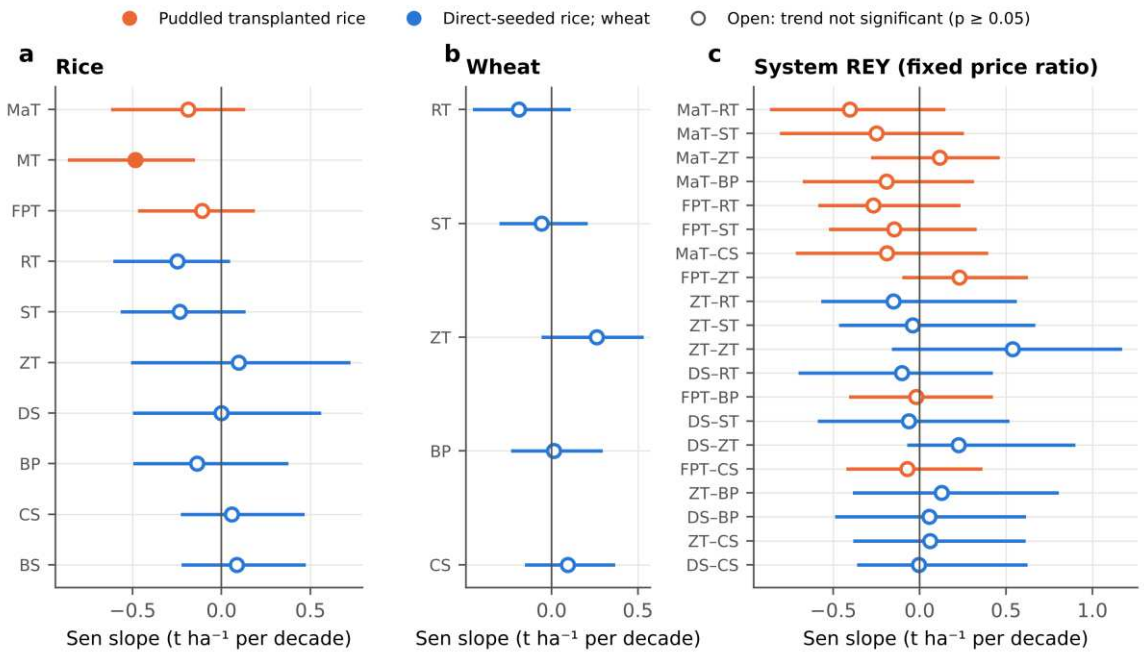


Fig. 4 Sen slope of yield with 95% confidence interval for (a) rice, (b) wheat and (c) rice–wheat system rice-equivalent yield at a fixed price ratio. Filled markers indicate a significant Mann–Kendall trend ($p < 0.05$). Treatment codes as in Table 1

The stability analysis separated the transplanted methods from the rest (Fig. 5a). MaT and FPT had regression coefficients below 1 (0.86 and 0.73), so their yields changed less than the average from good to poor seasons, but their deviations from regression were relatively large (S^2d 0.161 and 0.061), largely because of the downward drift in later seasons. MT had average responsiveness (b = 1.00) and the largest ecovalence (3.30). Reduced tillage and strip tillage had b slightly above 1 (1.08 and 1.11) and the smallest deviations (S^2d 0.020 and 0.025), with the season index explaining about 90% of their yield variation; they were therefore the most predictable rice methods. Direct sowing was the most responsive method (b = 1.31), gaining most in good seasons and losing most in poor ones. Zero-till rice combined above-average responsiveness (b = 1.09) with a large deviation (S^2d 0.160).

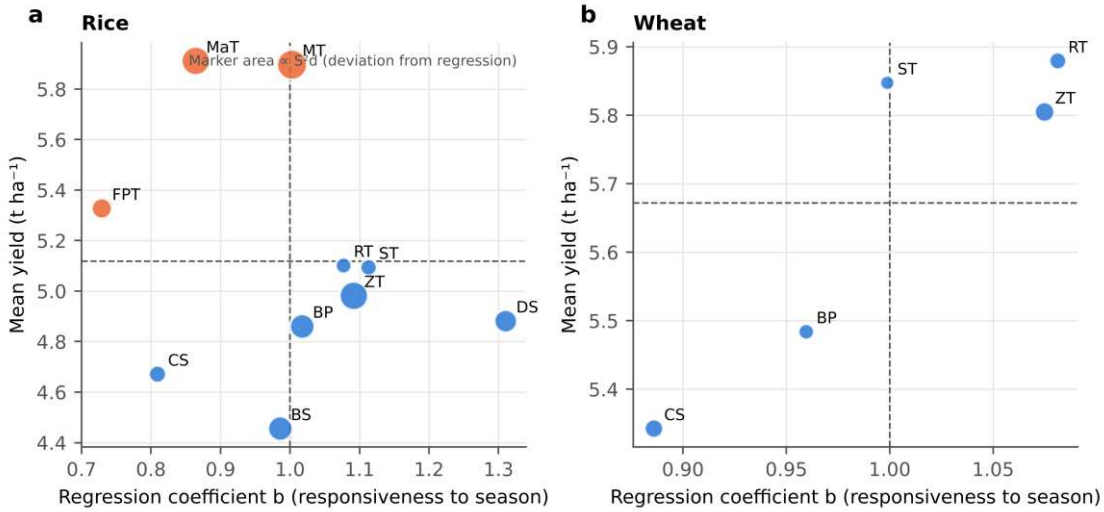


Fig. 5 Mean yield against the Eberhart–Russell regression coefficient (b) for (a) rice and (b) wheat establishment methods. Marker area is proportional to the deviation variance (S^2d). Dashed lines show b = 1 and the grand mean. Orange, puddled transplanted rice; blue, other methods

3.3 Wheat

The three conservation methods with the least soil disturbance produced the most wheat (Table 3). Reduced tillage (5.88 t ha^{-1}), strip tillage (5.85 t ha^{-1}) and zero tillage (5.80 t ha^{-1}) out-yielded conventional sowing (5.34 t ha^{-1}) by 0.46–0.54 t ha^{-1}, or 9–10%, and bed planting was intermediate (5.48 t ha^{-1}). Wheat yields were more stable than rice yields under every method (CV 5.2–6.6%). Strip tillage was the most stable wheat method by all measures: it had the lowest CV (5.2%), the highest SYI (0.844), *b* = 1.00, the smallest deviation variance (S^2d 0.008) and the smallest ecovalence (0.14), and it yielded at or above the season mean in all 21 seasons. No wheat method showed a significant trend (Fig. 4b). Zero-till wheat came closest, rising by 0.26 t ha^{-1} per decade (p = 0.097), from 5.64 to 5.96 t ha^{-1} between the two decades, so that in the second decade it yielded more than reduced and strip tillage. Reduced tillage showed a slight, non-significant decline (−0.19 t ha^{-1} per decade).

Table 3 Yield level, variability, trend and stability of wheat establishment methods over 21 seasons (1998–99 to 2019–20)

Method	Mean (t ha^{-1})	SD	CV (%)	SYI	Sen slope (95% CI) (t ha^{-1} decade^{-1})	p (MK)	b	S^2d	1998–2007	2008–2019
RT	5.88	0.36	6.0	0.841	−0.19 (−0.45, +0.10)	0.158	1.08	0.029	5.96	5.81
ST	5.85	0.30	5.2	0.844	−0.06 (−0.29, +0.20)	0.531	1.00	0.008	5.88	5.82
ZT	5.80	0.39	6.6	0.825	+0.26 (−0.05, +0.52)	0.097	1.07	0.053	5.64	5.96
BP	5.48	0.31	5.6	0.788	+0.01 (−0.22, +0.29)	0.880	0.96	0.018	5.44	5.53
CS	5.34	0.33	6.1	0.763	+0.09 (−0.14, +0.36)	0.566	0.89	0.043	5.30	5.38

Note: SYI calculated with Ymax = 6.57 t ha^{-1}. Period means refer to the year in which the wheat season began. Abbreviations and treatment codes as in Tables 1 and 2.

3.4 Rice–wheat systems

System REY at the fixed price ratio ranged from 11.06 t ha^{-1} for direct sowing–conventional sowing (DS–CS) to 12.75 t ha^{-1} for MaT–RT (Table 4). The rice method set the level of system productivity: all ten systems with transplanted rice (MaT or FPT) yielded more than any system with direct-sown rice of the same wheat method, and the eight most productive systems all had transplanted rice. The wheat method mattered less, but within each rice method the systems with RT, ST or ZT wheat yielded 0.6–0.7 t ha^{-1} more than those with conventionally sown wheat. Systems with transplanted rice were also generally less variable than those with direct-sown rice (CV 3.4–5.0% vs 4.7–6.2%) and had higher SYI (0.80–0.89 vs 0.76–0.82). MaT–ZT combined a high mean (12.65 t ha^{-1}) with the lowest CV of the MaT systems (3.5%) and the highest SYI (0.890).

Table 4 System rice-equivalent yield (REY) of 20 rice–wheat establishment combinations, 1998–2019

System (rice–wheat)	Mean REY (t ha^{-1})	CV (%)	SYI	Sen slope, fixed ratio	p (MK)	Sen slope, season prices	p (MK)	1998–2007	2008–2019
MaT–RT	12.75	4.7	0.886	−0.40	0.113	−0.89	<0.001	13.04	12.46
MaT–ST	12.69	4.5	0.883	−0.25	0.319	−0.78	0.001	12.94	12.44
MaT–ZT	12.65	3.5	0.890	+0.12	0.725	−0.37	0.024	12.66	12.64
MaT–BP	12.26	4.4	0.854	−0.19	0.386	−0.69	0.002	12.44	12.07
FPT–RT	12.17	3.9	0.852	−0.27	0.165	−0.76	<0.001	12.33	12.00
FPT–ST	12.11	3.8	0.850	−0.15	0.260	−0.61	0.002	12.23	11.98
MaT–CS	12.09	5.0	0.838	−0.19	0.386	−0.67	0.004	12.28	11.90
FPT–ZT	12.07	3.4	0.850	+0.23	0.146	−0.29	0.064	11.96	12.18
ZT–RT	11.82	5.2	0.817	−0.15	0.631	−0.62	0.086	11.79	11.85
ZT–ST	11.76	5.0	0.815	−0.04	0.873	−0.48	0.186	11.70	11.82
ZT–ZT	11.72	6.2	0.802	+0.54	0.098	−0.01	0.974	11.42	12.03
DS–RT	11.72	5.1	0.811	−0.10	0.773	−0.78	0.024	11.80	11.64
FPT–BP	11.67	3.8	0.818	−0.02	0.924	−0.55	0.007	11.73	11.62
DS–ST	11.66	5.1	0.807	−0.06	0.631	−0.56	0.034	11.70	11.62
DS–ZT	11.62	5.9	0.797	+0.22	0.113	−0.25	0.501	11.42	11.82
FPT–CS	11.50	4.3	0.802	−0.07	0.823	−0.53	0.007	11.57	11.44
ZT–BP	11.33	5.9	0.777	+0.13	0.677	−0.36	0.461	11.19	11.46
DS–BP	11.23	5.7	0.771	+0.06	0.873	−0.53	0.098	11.20	11.26
ZT–CS	11.16	4.7	0.775	+0.06	0.773	−0.26	0.351	11.03	11.29
DS–CS	11.06	5.5	0.762	0.00	1.000	−0.38	0.146	11.04	11.08

Note: Mean, CV, SYI and period means are for REY at the fixed wheat:rice price ratio of 1.160 (Ymax = 13.72 t ha^{-1}). Sen slopes are in t ha^{-1} per decade; season prices, REY computed with the price ratio of each season as recorded in the project database. Systems are ordered by mean REY. Treatment codes as in Table 1.

Comparing the first and second decades of the experiment at the fixed price ratio shows where the changes occurred (Fig. 6). Systems with MaT or FPT rice lost 0.1–0.6 t ha^{-1} of REY between the two periods, apart from FPT–ZT, which gained 0.2 t ha^{-1} and MaT–ZT, which was unchanged. Systems with zero-till or direct-sown rice followed by zero-till wheat gained 0.4–0.6 t ha^{-1}. As a result, the gap between the most productive system (MaT–RT) and ZT–ZT narrowed from 1.62 t ha^{-1} in 1998–2007 to 0.43 t ha^{-1} in 2008–2019.

How the trend in system productivity was judged depended on the price ratio used (Fig. 7). With season-specific prices, REY declined significantly in 11 of the 20 systems, by 0.37–0.89 t ha^{-1} per decade, and every system had a negative slope. The price ratio itself, however, fell significantly over the experiment (Sen slope −0.078 per decade; $p = 0.005$; Fig. 7a), so part of each decline came from wheat being valued less relative to rice rather than from lower grain output. At the fixed price ratio none of the system trends was significant (Table 4). Slopes ranged from −0.40 t ha^{-1} per decade for MaT–RT to +0.54 t ha^{-1} per decade for zero-till rice followed by zero-till wheat (ZT–ZT; $p = 0.098$).

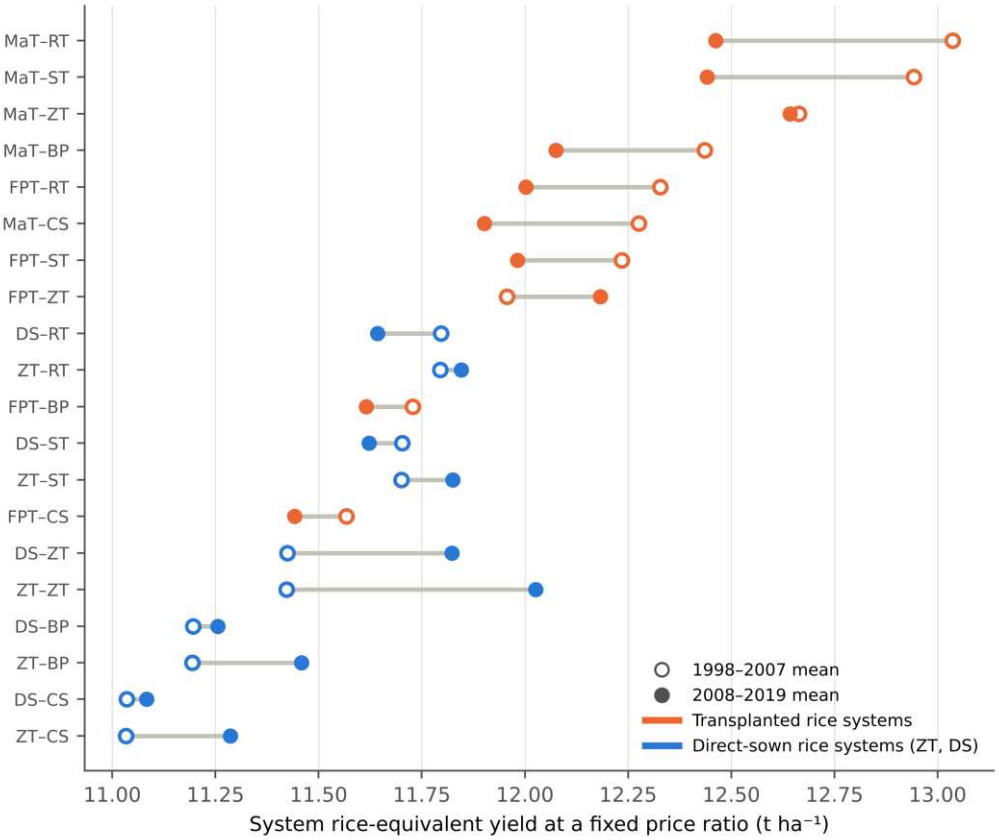


Fig. 6 System rice-equivalent yield at a fixed price ratio in the first (1998–2007, open markers) and second (2008–2019, filled markers) decades of the experiment for 20 rice–wheat establishment combinations

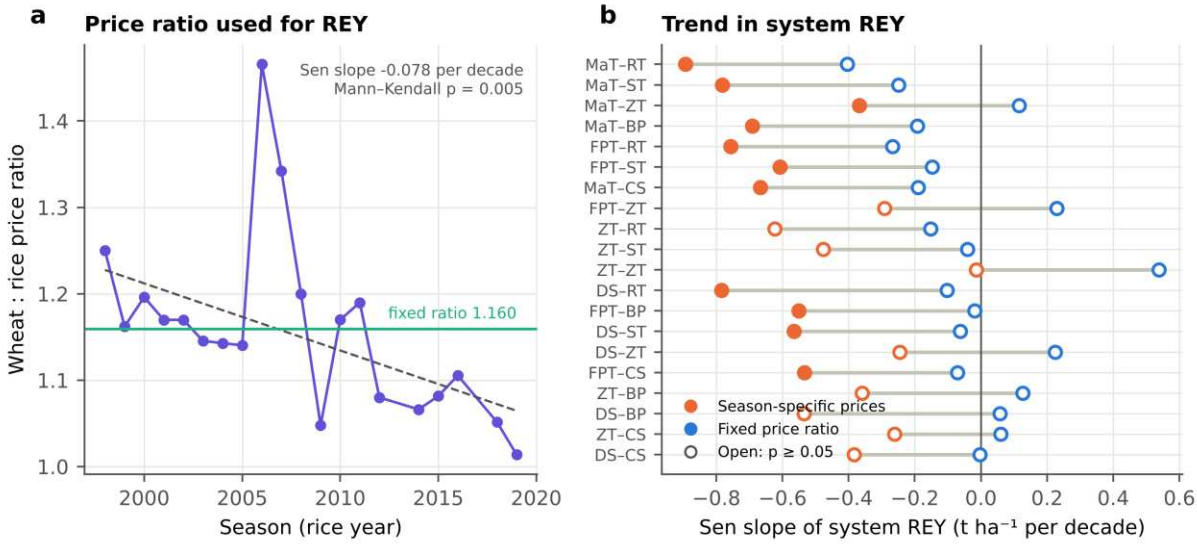


Fig. 7 Effect of the price ratio on the trend in system productivity: (a) wheat:rice price ratio used for rice-equivalent yield in the project database, with Sen trend line (dashed) and the fixed ratio used in this study; (b) Sen slope of system REY computed with season-specific prices and with the fixed ratio. Filled markers indicate a significant Mann–Kendall trend ($p < 0.05$)

3.5 Replicated seasons

The replicated data from the most recent seasons confirmed the main differences in rice but were less conclusive for wheat (Table 5; Fig. 8). In rice, establishment method had a large effect ($p < 0.001$) and the season × method interaction was also significant, while the 2018 and 2019 season means were similar. MaT gave the highest yield (6.21 t ha^{-1}), followed by MT (5.77 t ha^{-1}) and FPT (5.38 t ha^{-1}), and the three were significantly different from each other and from all direct-sown methods. Among the direct-sown methods, direct sowing, conventional sowing, strip tillage and reduced tillage were similar (4.71–4.73 t ha^{-1}), while broadcasting (4.61 t ha^{-1}), zero tillage (4.58 t ha^{-1}) and bed planting (4.42 t ha^{-1}) were lower. In wheat, the method effect was marginal ($p = 0.053$). Zero tillage (5.78 t ha^{-1}) and strip tillage (5.76 t ha^{-1}) out-yielded conventional sowing (5.47 t ha^{-1}) by more than the LSD, consistent with the long-term means in Table 3.

Table 5 Combined analysis of variance of replicated rice (2018–2019) and wheat (2016–17 to 2018–19) yields

Source of variation	df	F	p
Rice (2 seasons × 10 methods × 3 replications)			
Season	1	0.22	0.665
Establishment method	9	259.28	<0.001
Season × method	9	8.35	<0.001
LSD ($p = 0.05$), t ha^{-1}		0.11	
CV (%)		1.8	
Wheat (3 seasons × 5 methods × 4 replications)			
Season	2	0.13	0.882
Establishment method	4	2.58	0.053
Season × method	8	1.82	0.104
LSD ($p = 0.05$), t ha^{-1}		0.25	
CV (%)		5.4	

Note: Season was tested against replication within season (rice df = 4; wheat df = 9); method and season × method against the pooled error (rice df = 36; wheat df = 36).

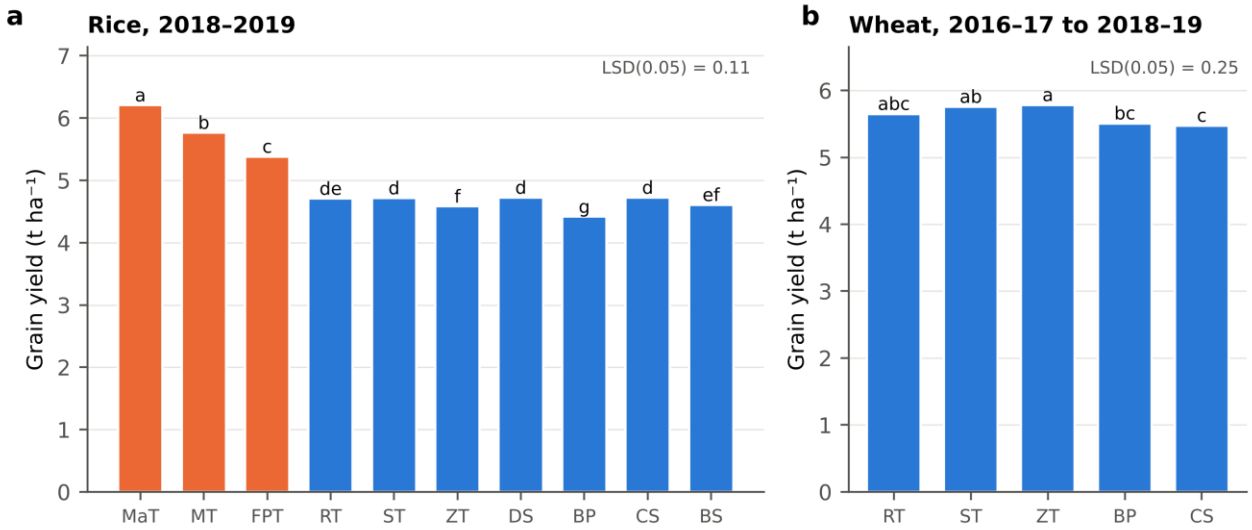


Fig. 8 Mean grain yield of (a) rice establishment methods in 2018–2019 and (b) wheat establishment methods in 2016–17 to 2018–19. Means with a common letter do not differ at p = 0.05 (LSD). Treatment codes as in Table 1

4 Discussion

4.1 Transplanted rice: a high but eroding advantage

Puddled transplanted rice out-yielded direct-sown rice throughout the experiment, which agrees with most comparisons in the IGP [5, 8] and with the early results from this experiment [15, 16]. Puddling suppresses weeds, reduces percolation losses and gives the transplanted seedling a head start over weeds, and these advantages are hard to match in unpuddled direct-sown rice, particularly on light-textured soils such as the sandy loam at Modipuram [8]. A recent meta-analysis put the average yield penalty of direct-seeded rice at about 11% [30], close to the 15% found here on a light soil. The two transplanters were at least as productive as manual transplanting and, in the replicated seasons, clearly more so, presumably because they set a uniform plant population at the planned spacing. Mechanical transplanting was also the highest-yielding rice method in the first three seasons of this experiment [16], and the 16-year record showed it out-yielding the direct-seeded methods by 14–26% [17].

The long record shows that this advantage is not fixed. Yield under the manual transplanter declined significantly, and the mechanical transplanter, though not significant, moved in the same direction. This matches the yield declines reported for many long-term rice–wheat experiments in Asia, in which rice was usually the more affected crop [2]. Ladha et al. [2] attributed such declines to falling soil fertility, nutrient imbalance and changes in climate, and repeated puddling is known to degrade soil structure and leave a compacted layer [1, 5]. We

did not measure soil properties, so the cause cannot be identified from these data. Whatever the cause, the narrowing of the gap between MaT and zero-till rice, from 1.24 to 0.61 t ha^{-1}, means that the yield penalty for giving up puddling was half as large in the second decade as in the first.

4.2 Direct-sown rice: lower but steady

None of the seven direct-sown rice methods showed a significant decline. Their yields were lower than those of transplanted rice but held steady over two decades, which is the property the sustainable yield index and trend tests are designed to capture. The SYI of the best systems here (0.80–0.89) is similar to the 0.81–0.82 reported for conservation agriculture scenarios after a decade in Haryana [12]. Reduced tillage and strip tillage were the most predictable rice methods, with the smallest deviations from regression, and direct sowing was the most responsive to season. Gathala et al. [5] found that zero-till direct-seeded rice yielded less than puddled transplanted rice in the first years of a trial in the western IGP but caught up later, as soil conditions under zero tillage improved. The small positive slope for zero-till rice in our record points the same way, although it was not significant. The lower SYI of direct-sown rice reflects mainly its lower mean yield, and better weed control and crop establishment are the most likely ways to raise it [8].

4.3 Wheat responds to less tillage

In wheat the situation was reversed: the methods with the least soil disturbance yielded most and were also the most stable. Strip tillage with the Turbo Seeder stood out, giving a high mean together with the lowest variability and an above-average yield in every season. This fits the experience with the Turbo Happy Seeder in north-west India, where sowing into standing rice residue allowed timely wheat establishment without burning [9]. Earlier sowing is the main reason zero-till wheat often matches or exceeds conventionally sown wheat in the IGP [7], and surface residue can buffer the crop against terminal heat. The upward trend in zero-till wheat, which by the second decade had overtaken the other methods, is consistent with gradual improvement of the soil under continuous zero tillage [10, 13]. In an 18-year rice–wheat experiment in the IGP, zero tillage with residue retention kept more carbon in soil aggregates and supported higher glomalin and β-glucosidase activity than conventional tillage with residue burning [6], which is one route by which such gains could build up. Conservation agriculture systems in the western IGP have likewise raised surface soil organic carbon and improved soil structure and infiltration within eight years [31]. Weed pressure is another. Project records

show that zero-, strip- and rotary-till drilling and bed planting reduced the density of *Phalaris minor*, the main grass weed of wheat in the region, by 57–82% compared with conventional sowing (unpublished data). Conventional sowing was the lowest-yielding and least stable wheat method in both the long-term and replicated data.

4.4 System productivity and the price ratio

At the system level the choice of rice method set the yield level, while the wheat method fine-tuned it. The highest REY came from transplanted rice followed by reduced-, strip- or zero-till wheat, which combines the strengths of the two crops. In the north-western IGP, Gathala et al. [32] likewise found that rice–wheat systems built on conservation agriculture saved irrigation water, labour and energy while remaining at least as productive as the conventional puddled system. MaT–ZT is worth noting because it was nearly as productive as the best system but with the lowest variability and highest SYI in that group. Zero-till rice followed by zero-till wheat was less productive on average, but it was the only system that gained substantially between the two decades and its gap to the best system shrank to 0.43 t ha^{-1}.

The price-ratio analysis carries a wider lesson. Rice-equivalent yield is the usual way of comparing cropping systems [11], but when it is computed with the prices of each season, any trend in relative prices becomes part of the yield trend. In this experiment the wheat:rice price ratio fell by about a fifth over 22 seasons, and with season-specific prices 11 systems appeared to decline significantly. With a fixed ratio none did. A reader shown only the first set of results would conclude that every system was losing productivity, which the grain yields of the individual crops do not support. We suggest that long-term system trends be tested either on grain yield of each crop or on REY at a fixed price ratio, with season-specific prices kept for economic comparisons.

4.5 Resource use and sustainability

Yield is only one side of sustainability. The energy use and greenhouse gas emissions of the same ten rice methods have already been measured in this experiment [17]. Input energy ranged from 25.7 GJ ha^{-1} under strip tillage with the Turbo Seeder to 38.9 GJ ha^{-1} under manual transplanting, and the three transplanted methods needed 38.0–38.9 GJ ha^{-1}, about 40–50% more than ST, BP and ZT, mainly because of puddling and pumping irrigation water. Grain energy-use efficiency was 2.70 under ST and 2.55 under ZT, against 1.98–2.09 for the transplanted methods. Estimated emissions were 9.6 t CO_2-eq ha^{-1} for the transplanted methods and 3.5–4.0 t CO_2-eq ha^{-1} for the direct-seeded ones, chiefly because flooded rice emits more

methane. Weed control is the one input that costs more energy in direct-seeded rice, because of the herbicides and extra weeding involved [17, 18]. At the same location, conservation tillage also cut the energy use and carbon footprint of wheat [21], and long-term zero tillage with residue retention improved energy efficiency and lowered emissions in the rice–wheat system [22]. On smallholder farms of the Eastern Gangetic Plains, zero-tillage-based establishment has likewise cut energy use and raised energy productivity [33].

Taken together with these results, the yield record changes the trade-off in favour of direct seeding. The 15% lower yield of direct-seeded rice is its main cost, and this cost fell over the two decades while its yield stayed stable. In exchange, direct seeding saves 29–49% of the irrigation water (Table 1), a fifth to a third of the input energy and roughly 60% of the emissions of puddled transplanting. For areas where groundwater is falling [4], dry direct seeding with zero-till or strip-till wheat offers stable productivity at much lower water, energy and emission costs. Where the highest output is the priority, mechanical transplanting followed by zero-till or strip-till wheat gives most of the yield of the best system with greater stability, as already suggested from the early seasons of this experiment [16].

4.6 Limitations

Several limitations apply. The data come from a single site on a sandy loam soil, and the ranking of methods may differ on heavier soils, where direct-sown rice often performs better. Three crop seasons could not be included in the trend analysis. System values for the seasons before the split-plot layout of 2004 were assembled from method means of the same season and may not fully capture carry-over effects of rice establishment on the following wheat crop. Soil properties and weed counts were not available for every season, so the causes of the trends could not be identified. Finally, trend tests on 20–21 seasons have limited power, and slopes of 0.2–0.3 t ha^{-1} per decade could be missed.

5 Conclusions

Over 22 seasons at Modipuram, puddled transplanted rice gave 17% more grain than direct-sown rice, and the mechanical transplanter was the most productive and sustainable rice method. The advantage was eroding, however: yield under the manual transplanter fell significantly, and the gap between mechanical transplanting and zero-till rice halved between the two decades. None of the direct-sown rice methods declined. In wheat, reduced tillage, strip tillage with the Turbo Seeder and zero tillage gave 9–10% more grain than conventional sowing, and strip tillage was the most stable method. At the system level, transplanted rice

450 followed by conservation-tilled wheat gave the highest rice-equivalent yield, while zero-till
451 rice followed by zero-till wheat steadily closed the gap. Apparent declines in system
452 productivity were largely caused by a falling wheat:rice price ratio, and long-term system
453 trends should therefore be assessed at fixed prices. Combined with the lower energy use,
454 emissions and irrigation water of the conservation methods reported earlier, these results
455 support machine-based conservation establishment, with zero-till or strip-till wheat in every
456 system, as a sustainable option for the rice–wheat system of the IGP.

457 ## Declarations

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462 ***Author contributions***

463 Ved Prakash Chaudhary: conceptualisation, field experimentation, data curation, formal
464 analysis, writing – original draft, writing – review and editing. Kanchan Kumar Singh:
465 conceptualisation, supervision, resources, writing – review and editing. Rahul Chaudhary:
466 investigation, data curation, resources. All authors read and approved the final manuscript.

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471 ***Data availability***

472 The data supporting the findings of this study are included in this article and its supplementary
473 information. Further data are available from the corresponding author on reasonable request.

474 ***Ethics approval and consent to participate***

475 The study did not involve human participants as research subjects or any animals. The plant
476 material consisted solely of cultivated crops, rice (*Oryza sativa* L.) and wheat (*Triticum*
477 *aestivum* L., cv. PBW-343), grown from seed of publicly released cultivars on the research
478 farm of the ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, under
479 the institute's approved research programme. No wild plants, protected or endangered species,

or plant material from private or protected land were collected. The cultivation of the crops and all field experimentation complied with relevant institutional, national and international guidelines and legislation, including the Biological Diversity Act, 2002 of India, the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora. Because only released, cultivated crop varieties were grown on the institute's own research farm with the permission of the institute, no additional permissions or licences were required for the collection of plant material. Informed consent to participate was obtained from all individuals who appear in the photographs in Fig. 1 and the graphical abstract. All of them were adults aged 18 years or older, so consent from a parent or legal guardian was not required.

Consent to publish

Informed consent to publish was obtained from all individuals whose identifiable images appear in Fig. 1 and the graphical abstract, including consent to the publication of these images in an open access journal. All of them were adults aged 18 years or older, so consent from a parent or legal guardian was not required.

Clinical trial number

Not applicable.

Competing interests

The authors declare no competing interests.

Use of AI-assisted technologies

During preparation of this manuscript, generative AI-assisted tools were used to support language editing and code drafting. The authors reviewed and edited all content and take full responsibility for the publication.

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