Direct seeded rice in sequence with zero-tillage wheat in north-western India: addressing system-based sustainability issues

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Received: 24 November 2020 / Accepted: 4 October 2021

Published online:

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Abstract

Resource conserving and eco-friendly interventions through improved crop establishment are the need of time to produce more with less resources, and mitigating climatic vulnerabilities and protecting environmental quality in the rice–wheat cropping system (RWCS) of India. In this context, seven years (2010–2017) field experimentation at Karnal, Haryana, India revealed that the weed infestation was more intensified and diversified in direct seeded rice (DSR) than puddled transplanted rice (PTR), and even eliminating puddling in rice-induced more infestation of *Phalaris minor* in succeeding wheat crop. Residue retention in zero-till (ZT) DSR and rotating conventional till (CT) DSR with PTR reduced weed pressure compared to continuous DSR. Root knot and plant parasitic nematodes were less in DSR than PTR but reverse was true for saprozoic nematodes in DSR and ZT situations. CTDSR, ZTDSR (with or without residues), and ZT/CT machine-transplanted rice (MTR) produced grain yields at par ($P = 0.05$) with PTR. The grain yield of ZT wheat ($5.03\text{--}6.90\text{ t ha}^{-1}$) in sequence with CT/ZT rice establishment (DSR/MTR) was $0.3\text{--}0.6\text{ t ha}^{-1}$ higher than what it was attained after puddled rice systems. Net returns from DSR/MTR-based cropping systems were higher than PTR, with 22–31% saving of labor. Irrigation water productivity was also higher under DSR ($27.5\text{--}29.9\text{ kg ha-cm}^{-1}$) than PTR ($23.7\text{ kg ha-cm}^{-1}$), with 17.5–22.8% reduction in irrigation input. There was also improvement in soil health under ZTDSR/MTR (higher OC, N, P and K, and lower bulk density) compared to PTR. Overall, the resource conservation and soil health improvement through these planting methods signaled toward system stability over trade-offs in RWCS.

Keywords Direct seeded rice · Nematodes · Productivity · Sustainability · Weeds · Zero-tillage wheat

1 Introduction

Rice–wheat is the most prominent cropping system in south Asia occupying 13.5 million hectares' area in Indo-Gangetic Plains (IGP), out of which India has 10 m ha followed by Pakistan (2.2 m ha), Bangladesh (0.8 m ha) and Nepal (0.5 m ha) [1]. Rice in India is grown in 44 m ha area with 113 mt grain production (2017–18), and wheat in 30 m ha with 100 mt production [2]. But, the decline or stagnation in total factor productivity of rice–wheat cropping system (RWCS) along with depletion

of natural resources in north west (NW) India [3–5] along with increasing population have led to putting extra efforts for increasing the productivity and profitability of this important cropping system. It also challenges us to produce more with less cost on sustainable basis, increase labor and water productivity, besides conserving our natural resources and environmental safety.

Manual transplanting in puddled soil is the traditional method of rice crop establishment in north-western India. Puddling, however, results in disintegration of soil aggregates, disturbance of macro-pores and negative impact

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on soil physical properties, which result in compaction and poor aeration in soil [6–8]. It also leads to negative impact on the next crop. Soil puddling is a big hurdle for progression of conservation agriculture in rice crop-based systems [9]. Kumar et al. [7] reported lower (8%) yields of wheat grown after puddled transplanted rice (PTR) than direct seeded rice (DSR). Requirement of irrigation water for puddling has been reported to be 100 mm on the lower side (just to saturate the dry soil profile) [10] and 544 mm on the higher side (more soaking period due to water flow from field to field) [11]. Farmers are thus compelled/forced to think about adoption of labor-efficient methods of crop establishment due to labor scarcity, increased wages and high demand of labor for transplanting [12].

Dry direct seeded rice is one of the feasible alternatives to conventional method of manual transplanting, which results in lower irrigation water and other input costs [13]. The requirement of labor in DSR is about one-third of the transplanted rice [14]. Balasubramanian and Hill [15] have reported that DSR has higher resilience to water deficit and more profit in assured irrigation areas. DSR-based systems save (11–18%) irrigation water [16] and reduce the labor requirement (11–66%) compared to PTR, depending upon location, season and type of DSR [17, 18]. Easy planting, improved soil health, reduced methane emission and often higher net returns in assured irrigation areas are some of the other benefits of DSR [12, 19, 20]. In addition, rice matures 7–10 days earlier under direct seeding than puddled transplanting, which allows timely sowing of the succeeding wheat crop [21, 22].

Weeds are major problem in DSR which need to be managed effectively for good yields [23, 24]. In DSR, some of the weeds emerge along with the crop seedlings and grow faster in moist soil than in puddled soil of PTR [25], which results in severe competition with the crop for resources. Hence, weeds are the main biological constraint to the successful DSR [26], and failure in controlling weeds results in huge losses (50–90%) in grain yield [27, 28]. However, many pre- and post-emergence herbicides (for use as alone or in combination) are now available for effective weed management in DSR. Availability of precise and proper machinery in time and place would also favor DSR scaling. Layering of DSR with short/medium duration high-yielding rice varieties and improved agronomic practices will make this preposition more meaningful and viable. Modification in irrigation technology suitable for DSR is also required to improve water use efficiency further. Besides this, policy support and incentives would also help in faster upscaling of DSR in India.

Machine transplanting of rice (MTR) in non-puddled soil is less labor intensive and less water demanding and could be another alternative to PTR [29, 30]. Additionally, zero-tillage (ZT) in wheat can help reduce the turnaround time

between rice harvest and planting of the successive wheat crop. Compared to conventional till wheat (CTW), the multi-fold benefits of zero-till wheat (ZTW) in sequence with rice are already well documented [31, 32]. Malik and co-workers [33, 34] have also outlined long-term benefits and impacts of ZTW followed by different crop establishment methods in rice in the rice–wheat system.

Despite multiple benefits associated with these alternate crop establishment methods in rice–wheat system, their accelerated adoption at wider scale is yet to be achieved. For that, there is a need to bridge up some of the knowledge gaps to be addressed in a system approach. Evidences on medium to long-term impacts of CT/ZT rice in sequence with ZT wheat on system productivity, economics, weed dynamics, nematode infestation, irrigation water input etc. are lacking, particularly in north-west Indian conditions. However, scattered information from different ecologies on individual crops/ technologies is available, but authentic information based on well-planned experimentation on comparison of different establishment methods with a system approach in one ecology is scanty. In this context, evidence based on medium to long-term studies can help to eliminate some of the uncertainties and change the mindset of stakeholders for accelerated adoption and scaling of these alternative planting methods.

In context of the said identified knowledge gaps, we hypothesized that sequencing of DSR and MTR in CT/ZT situations with ZT wheat could be more productive, profitable and sustainable to replace PTR-CTW, which are already adopted at large scale in NW India. Residue retention in ZT rice in sequence with ZT wheat might simplify the complex problem of weeds to some extent besides improving system-based water and crop productivity. Rotating DSR with puddled rice after an interval could help in managing weeds along with harnessing the benefits of DSR. Keeping these points in view, the present investigation was proposed to study the impact of different crop establishment methods on weed infestation and diversity, nematodes infestation, labor and irrigation water input, along with productivity, profitability and sustainability of rice–wheat cropping systems.

2 Materials and methods

2.1 Site details

A seven years (2010–2017) field experiment was conducted at CCS Haryana Agricultural University, Regional Research Station, Karnal, India to evaluate the performance of different crop establishment methods in rice followed by ZT wheat. At the start of the experiment, the

soil (0–15 cm depth) was slightly alkaline (pH 8.30), low in organic carbon (0.32%), with moderate levels of available phosphorus (10.9 kg P ha⁻¹) and high in available potassium (298 kg K₂O ha⁻¹), and electrical conductivity 0.20 dS m⁻¹ (Table 1).

2.2 Experimental design/treatments

The experiment with treatment combinations of tillage x establishment methods x irrigation management (hereafter referred as rice system treatments) was laid out in a randomized complete block design with three replications. The plot size was 16.5 m × 8.8 m. The treatment details are given below.

- T1: ZTDSR(+ R)-ZTW (Zero-till DSR with 30% residue retention followed by ZT wheat)
- T2: ZTDSR-ZTW (Zero-till DSR without residue followed by ZT wheat)
- T3: ZTMTR-ZTW (Zero-till MTR followed by ZT wheat)
- T4: CTDSR-ZTW (Conventional till DSR followed by ZT wheat)
- T5: CTMTR-ZTW (Conventional till MTR followed by ZT wheat)
- T6: PMTR/CTDSR/PTR-ZTW (Puddled MTR up to 2013, CTDSR in 2014 and PTR in 2015 and 2016 followed by ZT wheat)
- T7: PTR-ZTW (PTR followed by ZT wheat)
- T8: PTR-ZTW/CTW (PTR followed by ZT wheat up to 2011–12 and CT wheat afterwards)

In T1, about 30% residues of manually harvested wheat crop were retained as anchored stubbles (about 10 cm height) along with some loose straw. PMTR-ZTW up to 2013 (T6) was changed to CTDSR-ZTW in 2014 and PTR-ZTW in 2015 to study the impact of CTDSR in rotation with puddled system of rice establishment on crop performance and weed infestation in comparison with continuous DSR- and PTR-based treatments. PTR-ZTW (T8) deployed during 2010 and 2011 was modified to PTR-CTW to represent/ accomplish farmers' practice being largely adopted in the domain area. These mid-course corrections in T6 and T8 were made only in rice and wheat phases, respectively. DSR included sowing of rice with drill under ZT/CT conditions. PTR includes manual transplanting in puddled plots which were under continuous flooding until about 2–3 weeks before harvest. MTR included transplanting of mat nursery with paddy transplanter. CT involved tillage and planking while the soil was dry/ moist, ZT meant no tillage and puddling included wet tillage followed by planking.

2.3 Crop management and monitoring

2.3.1 Rainy season

During the rainy season, a *basmati* (scented) rice cultivar CSR30 (PB1121 in 2013 only) was used for sowing/transplanting. Sowing of DSR was accomplished in the 2nd–3rd week of June (10–20 June; 20, 20, 15, 11, 10, 17 and 11 June during 2010, 2011, 2012, 2013, 2014, 2015 and 2016, respectively) using a seed rate of 20 kg ha⁻¹ with a

Table 1 Effect of different crop establishment methods on soil properties after seven years recorded after wheat harvest in rice–wheat system

Treatment	pH (1:2)	Electrical conductivity (dS m ⁻¹)	Organic carbon (%)	Available P (kg ha ⁻¹)	Available K ₂ O (kg ha ⁻¹)	Bulk density: 0–5 cm depth (g cc ⁻¹)	Bulk density: 5–10 cm depth (g cc ⁻¹)
Initial values	8.30	0.20	0.32	10.9	298	1.55	1.61
ZTDSR(+ R)-ZTW	8.27 ^{de}	0.11 ^a	0.45 ^a	13.0 ^b	320 ^{ab}	1.44 ^{bc}	1.59 ^a
ZTDSR-ZTW	8.29 ^{cd}	0.12 ^a	0.41 ^{ab}	12.3 ^{bc}	303 ^{bc}	1.43 ^{bc}	1.58 ^a
ZTMTR-ZTW	8.32 ^{cd}	0.12 ^a	0.43 ^a	12.8 ^b	298 ^{bc}	1.41 ^c	1.60 ^a
CTDSR-ZTW	8.20 ^e	0.15 ^a	0.36 ^{bc}	15.2 ^a	334 ^a	1.43 ^{bc}	1.60 ^a
CTMTR-ZTW	8.27 ^{de}	0.14 ^a	0.33 ^c	12.7 ^b	300 ^{bc}	1.44 ^{bc}	1.56 ^a
PMTR/CTDSR/PTR-ZTW*	8.37 ^{ac}	0.15 ^a	0.32 ^c	11.0 ^{cd}	298 ^{bc}	1.51 ^{ab}	1.60 ^a
PTR-ZTW	8.42 ^a	0.16 ^a	0.32 ^c	10.8 ^{cd}	292 ^{bc}	1.55 ^a	1.61 ^a
PTR-CTW	8.41 ^a	0.14 ^a	0.31 ^c	10.4 ^d	285 ^c	1.56 ^a	1.62 ^a
LSD (0.05)	0.09	NS	0.06	1.6	31	0.09	NS

(+ R), with residue; ZTDSR zero-till direct seeded rice; ZTMTR zero-till machine transplanted rice; CTMTR conventional till machine transplanted rice; PMTR puddled machine transplanted rice; PTR puddled transplanted rice; ZTW zero-till wheat; CTW conventional till wheat

*The figures in columns with similar letters did not differ statistically with each other

*PMTR up to 2013, CTDSR in 2014 and PTR in 2015 followed by ZT wheat

**PTR fb ZT wheat up to 2011–12 and CT wheat afterwards

ZT seed-cum-fertilizer drill having inverted T-type furrow openers (20 cm row spacing) and an inclined plate type seed metering mechanism. The seed used for sowing was dipped/soaked in fungicide solution (1 g carbendazim in 1 L water per kg seed) for 24 h, removed and spread out in the shade for two hours before sowing to make it free flowing in the seeding mechanism. The next day, mat-type nursery was sown on raised beds after initial sprouting of seeds, and the seedlings were mechanically transplanted after three weeks. Similarly, after two days, the nursery for conventional PTR was sown with fully sprouted seeds on a flat bed, and manual transplanting was done after 4–5 weeks.

Under ZT situations, the plots were kept undisturbed after wheat harvest, and glyphosate at 2.0 kg a.e. ha⁻¹ was sprayed for control of established weeds in the field before rice establishment. Under CT situations, the plots were well prepared at field capacity with three plowings followed by planking. Puddled conditions were achieved using a puddler in standing water followed by planking. Planking was also done immediately after sowing in DSR plots. Spacing was 21 cm × 14 cm for MTR (30 cm × 14 cm in 2013 only) and 20 cm × 15 cm in PTR. Changes in spacing under MTR during 2013 were due to availability of only different prototype in that year. Irrigation in DSR plots was applied at weekly intervals or as needed depending on rainfall to keep the soil moist. For PTR or MTR, irrigation was applied just before transplanting and then it was irrigated at weekly intervals or as needed depending on rainfall to maintain flooded conditions during initial 3–4 weeks, and flooded or saturated thereafter up to 2–3 weeks before harvest. Whereas in ZT/CTMTR, the plots were kept flooded during initial 1–2 weeks, and then under saturated conditions up to 2–3 weeks before harvest. However, during last 2–3 weeks before paddy harvest, the plots under PTR/ MTR were never dried rather remained below saturation. The said water status in different rice system treatments was maintained with need-based irrigation depending upon rainfall. Partial thinning and gap filling (removing some plants from densely populated areas and transplanting into sparsely populated pockets in order to create a uniform density of 22–25 plants per meter row length) in DSR was also done at 30 days after sowing (DAS).

Fertilizers were applied as per the recommendation of the state university. In transplanted rice (manual transplanted and machine transplanted), 30 kg P₂O₅, 25 kg ZnSO₄ and 60 kg N ha⁻¹ was applied; however, in variety PB 1121, N was applied at 90 kg ha⁻¹ as per its higher N requirement and recommendation. In all the rice system treatments, phosphorus (diammonium phosphate, DAP) and zinc sulfate were applied as basal fertilizers, and N (through urea) was broadcast as a post-emergence foliar fertilizer in two equal splits. DAP and zinc sulfate

were broadcast at the time of field preparation in transplanted rice (PTR or CTMTR), and just before transplanting in ZTMTR. In DSR, DAP was drilled through a seed-cum-fertilizer drill at the time of sowing, while zinc sulfate was broadcast at the time of field preparation in CTDSR and before the first irrigation in ZTDSR. DAP applied as basal also contributed N and the remaining N was applied in two equal splits at 3 and 6 weeks after transplanting. N was applied at 60 kg ha⁻¹ for the scented variety CSR-30. In DSR, a 25% higher N dose than transplanted rice (as per state recommendation) was applied in two equal splits at 15 and 50 DAS as per findings/ recommendations of State University. Potassium was not used in rice and wheat as well due to its already rich status in soil.

The plot size was 16.5 m × 8.8 m and all the plots were kept weed-free using recommended herbicides. In DSR, pendimethalin 1000 g ha⁻¹ was applied pre-emergence, followed by bispyribac-sodium 25 g ha⁻¹ plus pyrazosulfuron 25 g ha⁻¹, using a knapsack sprayer fitted with a flat fan nozzle at 300–500 L water ha⁻¹, and integrated with need-based manual weeding. In transplanted rice, pretilachlor 1000 g ha⁻¹ or pretilachlor plus pyrazosulfuron 615 g ha⁻¹ were broadcast pre-emergence in standing water.

For recording data on weeds, random patches of 2 m × 2 m were kept unweeded in all the plots. Data on weed density were recorded at 90 DAS from DSR plots, and at 60 days after transplanting in transplanted plots, at two places using a quadrat of 0.5 m × 0.5 m. The crop was harvested in November (5–16 November during different years). The DSR crop matured about a week earlier than the transplanted rice crop; however, for uniformity harvesting was done when the crop had reached maturity in all the plots. Grain yield was recorded from a harvested area of 5.0 m × 5.0 m at two places in each plot. Threshing was accomplished by beating bundles of harvested crop plants with intact panicles on a drum. Grain weight was recorded at 14% moisture after threshing, cleaning and drying. The grains were cleaned by winnowing, and grain yield was expressed as t ha⁻¹.

2.3.2 Winter season

During winter, wheat was grown in ZT situations in all plots (treatment T1–T7) except in T8 in the last five years. This mid-course correction/modification was made to align this treatment with the existing farmers' practice (PTR-CTW) in the domain area. For CT wheat (T8), the field was prepared under *Vattar* conditions (moist field conditions) with three plowings followed by planking. To maintain uniformity, the sowing dates were kept the same for all treatments. Wheat was sown during 12–24 November (24, 24, 23, 12, 22, 22 and 20 November in 2010, 2011, 2012, 2013, 2014, 2015, 2016, respectively) with a ZT seed-cum-fertilizer drill using

a seed rate of 100–125 kg ha⁻¹ at a row spacing of 20 cm. Wheat varieties PBW550 (2010–11), WH711 (2011–12), DPW621-50 (2012–13), WH1105 (2013–14), HD2967 (2014–15 to 2016–17) were used for sowing. Weed-free conditions were maintained by applying recommended herbicides (sulfosulfuron plus metsulfuron 32 g ha⁻¹ or clodinafop plus metsulfuron 64 g ha⁻¹) with need-based hand weeding. Irrigation was first applied at 21 DAS, with follow-up irrigations at critical stages depending upon rainfall. The irrigation schedule followed in ZT and CT was same. Flood irrigation was applied in bunded beds/plots, and irrigation was stopped when 75% of the plot length was filled with water. Irrigation water use computed/estimated based upon the time taken for irrigation, which was around 10% less in ZT wheat compared to CT wheat. Fertilizers were applied as per state university recommendations (150 kg N ha⁻¹ and 60 kg P₂O₅ ha⁻¹). The full dose of phosphorus was applied as basal, and N was applied in three equal splits at sowing, 21 and 42 DAS.

For recording data on weeds, random patches of 2 m × 2 m were kept unweeded in all the plots. Data on the weed population were recorded at 75 DAS by placing two quadrats of 0.5 m × 0.5 m size/plot. ZT wheat stayed bit greener and it reached maturity 2–3 days later than CT wheat. However, for uniformity harvesting was done at the same time, when the crop was mature in all the plots. The crop was harvested in April (15–28 April). Grain yield was recorded from a harvested area of 5.0 m × 5.0 m at two places in each plot. Threshing was done with a plot thresher, followed by cleaning. Wheat grain weight was recorded at 14% moisture after threshing, cleaning and drying. The grain yield was expressed as t ha⁻¹.

Relative yields of rice, wheat and rice–wheat cropping system under ZTDSR (+R)-ZTW and CTDSR-ZTW were computed in comparison to PTR-ZTW by dividing their grain yields by yields of PTR-ZTW over the years.

2.4 Soil studies

Sampling of soil from 0 to 15 cm depth was done from different plots at the end of the experiment (after harvest of winter season wheat crop) in 2017, and these soil samples were analyzed for pH, electrical conductivity (EC), organic carbon, available phosphorus and potassium. To estimate soil pH, 5 g of soil was mixed with 10 ml of distilled water and it was shaken for 30 min and the pH (1:2) of soil suspension was measured at 25 °C with glass electrode pH meter [35]. EC was measured at 25 °C with conductivity bridge method [36]. Organic carbon was estimated with Walkley and Black's rapid titration method [37]. Available phosphorus was estimated using the Olsen's method [38] and potassium with flame photometer method [36]. Sampling of soil from 0–5 cm to 5–10 depths using a core

sampler of 4.1 cm diameter was also done with two samples from each plot to record data on bulk density. The soil samples for bulk density were dried in oven at 60 °C temperature for 48 h before computing the bulk density (g cc⁻¹).

2.5 Economic evaluation

For economic evaluation of different crop establishment treatments, the net return per hectare for rice and wheat was computed by deducting the respective variable cost of cultivation (cost of preparatory tillage, seed/nursery and treatment, sowing/transplanting, fertilizer, irrigation, weed management, crop protection, harvesting, threshing, transport and interest charges, which also included cost of labor use) from the gross return under different treatments, and converting the value in Indian Rupees (INR) to \$ by a conversion factor (1 \$ = 67 INR).

2.6 Irrigation water input

During 2010–11, 2011–12 and 2012–13 (three years only), the number of times the rice and wheat crops irrigated was recorded under different rice–wheat system treatments, and data on irrigation depths were computed based on the effective discharge of the tube-well (38.4 L second⁻¹) and the time taken for each irrigation. Reduction in irrigation input was also computed for different treatments in comparison with PTR followed by ZT wheat.

2.7 Nematode studies

Nematode studies were also undertaken in the last rice season (2016–17) of the experiment. For recording nematode populations, soil samples were drawn from different treatment plots in October 2016 with two samples from each plot, which were then mixed to make representative samples. The nematode population was recorded from 200 cc representative soil sample by adopting the standard procedure of sieving and counting under microscope. Also bio-assay studies were undertaken using these soil samples by growing rice cultivar PB1121 in pots.

2.8 Statistical analysis

Before statistical analysis, the data on weed density were subjected to square root transformation ($\sqrt{X+1}$) to improve homogeneity of variance. Data were subjected to analysis of variance (ANOVA) [39], and treatment effects assessed using the 'F' test at a 5% significance level. The 'OPSTAT' software of CCS Haryana Agricultural University, Hisar, India, was used for statistical analysis [40]. The data were analyzed separately for each year. The data on cost of

cultivation, net returns and irrigation water input (only for initial three years) were aggregated over the years to get the overall mean under different rice system treatments.

3 Results

3.1 Effect on soil properties

The soil properties recorded at the termination of the experiment, i.e., after wheat harvest (2017) indicated that the soil pH decreased under ZTW sequenced with non-puddled or zero-till DSR/ MTR (8.20–8.32) than in sequence with PTR (8.41–8.42) (Table 1). The electric conductivity of soil did not differ among different crop establishment treatments. Organic carbon was improved under ZTW-ZTDSR/MTR (0.41–0.45%) and it was higher than ZTW/CTW-PTR (0.31–0.32%). Available phosphorus was also higher under ZTW-zero-till/non-puddled methods of rice establishment (12.3–15.2 kg ha⁻¹) than ZTW/CTW-PTR (10.4–10.8 kg ha⁻¹). Similarly, available potassium was also higher under ZTW-zero-till/non-puddled methods of rice establishment (298–334 kg ha⁻¹) than ZTW/CTW-PTR (285–292 kg ha⁻¹); however, the differences were not always significant. Bulk density of soil at 0–5 cm depth was lower under ZTW-zero-till or

non-puddled rice (1.41–1.44 g cc⁻¹) than ZTW/CTW-puddled rice (1.55–1.56 g cc⁻¹), whereas bulk density of soil at 5–10 cm depth was not influenced by different treatments (1.58–1.62 g cc⁻¹).

3.2 Effect on weeds

3.2.1 Effect on weeds in rice

In rice, *Echinochloa crus-galli*, *Leptochloa chinensis*, *Eragrostis tenella*, *Dactyloctenium aegyptium*, and *Brachiaria reptans* dominated among grassy weeds; *Ammannia baccifera*, *Euphorbia hirta*, and *Eclipta prostrata* among broadleaf weeds, and *Cyperus rotundus* among sedges. Differences in weed infestation under different establishment methods were visible even in the first year (2010) of experimentation, with the exception of *Echinochloa crus-galli* (Fig. 1). Infestation of weeds, in general, was higher under ZT or CT systems of rice establishment (both direct seeded and machine transplanted), compared to puddled manual or machine transplanted rice, and infestation levels continued to build up year after year.

There was no or negligible infestation by other grass weeds (*Leptochloa chinensis*, *Eragrostis tenella*, *Dactyloctenium aegyptium* and *Brachiaria reptans*) under PTR over the years (Fig. 1). In the first season (2010), infestation of these

Fig. 1 Effect of different crop establishment methods on density of weeds in rice under the rice–wheat cropping system (alternate years). The bars of a season with similar letters did not differ statisti-

cally with each other; treatment details (T1–T8) are given in Materials and Methods

grasses was significantly higher under CT/ZT rice (8.7–24.7 plants m^{-2}) and it further built up with time (15.3–70.3 plants m^{-2}) compared with puddled transplanting (0.0–3.3 plants m^{-2}). In 2016, density of these grasses was higher under ZT conditions (49.0–70.3 plants m^{-2}) relative to CT methods (15.3–40.7 plants m^{-2}) of rice establishment. CTDSR in rotation with puddled rice (T6) did not exaggerated infestation of other grass weeds compared to continuous CT/ZT rice. Infestation of these weeds was higher under DSR than MTR, and it further reduced with residue retention.

Similar to grassy weeds, there were more broadleaf weeds under CT or ZT rice (61.0–101.3 plants m^{-2}) than PTR (50.0–55.3 plants m^{-2}) during rainy season of 2010. These did not increase with time under PTR; however, increased under CT or ZT rice (76.0–209.7 plants m^{-2}), and such differences with PTR (45.3–61.7 plants m^{-2}) became wider and wider over the years (Fig. 1).

In 2016–17, infestation by broadleaf weeds in CT or ZT situations was invariably higher under machine transplanting (195.0–209.7 plants m^{-2}) than direct seeding (76.0–198.3 plants m^{-2}). Within direct seeding, the density of broadleaf weeds was higher under ZTDSR (118.7–198.3 plants m^{-2}) compared to CTDSR (76.0 plants m^{-2}); however, residue retention in ZTDSR further lowered infestation of broadleaf weeds (118.7 plants m^{-2} versus 198.3 plants m^{-2} without residues). CTDSR in rotation with PMTR (T6) just for one year also reflected lower density of broadleaf weeds compared to continuous CT/ZT rice and it was as good as PTR.

Throughout the experimentation, there was no or little infestation by sedges (0.0–2.7 plants m^{-2}) under puddled conditions (Fig. 1). Infestation by sedges became higher under non-puddled or ZT conditions (12.7–37.3 plants m^{-2}) in the first season of the experiment itself, which further increased with time (32.3–76.7 plants m^{-2}). Under ZT/CT conditions in 2016, sedge infestation (*Cyperus rotundus*) was highest in DSR (42.7–76.7 plants m^{-2}), followed by MTR (28.7–36.3 plants m^{-2}) and puddled rice (0.0–2.3 plants m^{-2}). CTDSR in rotation with puddled rice (T6) also reflected lower density of sedges compared to continuous CT/ZT rice.

After seven years of experimentation (i.e., by the rainy season of 2016), infestation by *E. crus-galli* was higher under CT or ZT (5.0–9.3 plants m^{-2}) compared to puddled conditions (2.3–5.0 plants m^{-2}) (Fig. 1). Residue retention in ZTDSR resulted in the lowest density of *E. crus-galli* among all the non-puddled or ZT systems of rice establishment; however, the differences were not always significant. Inclusion of CTDSR in rotation with PMTR after four years (T6) did not allow buildup of *E. crus-galli* population compared to continuous CT/ZTDSR. Infestation with *E. crus-galli* in rice was 54% less in PTR-ZTW than PTR-CTW

system; however, its infestation under both was very less (2.3–5.0 plants m^{-2}).

3.2.2 Effect on weeds in wheat

Infestation of *Phalaris minor* and *Poa annua* among grassy weeds; and *Coronopus didymus*, *Anagallis arvensis*, *Melilotus indica*, and *Malva parviflora* among broadleaf weeds were recorded across different plots. In 2010–11, *P. minor* infestation in ZT wheat was lower in sequence with ZT rice (2.7–4.0 plants m^{-2}) than after non-puddled/puddled rice (6.0–8.7 plants m^{-2}) (Fig. 2). During 2010–11, the infestation of *P. minor* in wheat was significantly less in ZTW grown in sequence with ZT-DSR along with residue. Infestation of this weed increased in ZTW when it was grown either in sequence with non-puddled DSR, MTR or PTR. In subsequent years, almost identical trend was found in case of *P. minor* population; however, its density increased compared to 2010–11 more particularly in the plots under ZTW grown in sequence with non-puddled DSR/MTR, and it was also still higher in CTW sequenced with PTR.

The difference became more pronounced with time, and in 2016–17, *P. minor* infestation was significantly higher in wheat plots which were in sequence with non-puddled MTR/DSR (20.3–32.7 plants m^{-2}), followed by puddled rice (7.3–13.3 plants m^{-2}) and ZT rice (2.0–2.24 plants m^{-2}). CTDSR in rotation (just for a year) with puddled rice (T6) continued reflecting lower density of *P. minor* compared to continuous CT/ZT rice. ZT wheat had significantly lower *P. minor* infestation from the beginning itself and during 2016–17, ZTW had 3.0–7.3 plants m^{-2} compared to 12.7 plants m^{-2} in CT wheat.

Density of *Poa annua* was similar in ZTW grown in sequence with ZT-DSR (+ or – residue), ZT/non-puddled-MTR but it was significantly higher in ZTW grown in sequence with PTR (manual or MTR) and non-puddled DSR in 2010–11 (Fig. 2). During 2012–13, 2014–15 and 2016–17, the population of *P. annua* increased compared to 2010–11. Infestation of *P. annua* was more in ZTW or CTW grown in sequence with PTR, non-puddled MTR/DSR compared to ZT-DSR with or without residue. In 2010–11, emergence of *Poa annua* in wheat was significantly higher after puddled rice (46.0–51.3 plants m^{-2}) than ZT/CT rice (11.3–31.3 plants m^{-2}). The difference became more pronounced with time. In 2016–17, emergence of *Poa annua* in wheat was highest in plots following PTR (176.3–201.7 plants m^{-2}), closely followed by CT rice (57.7–98.3 plants m^{-2}) and ZT rice (11.3–20.3 plants m^{-2}). *Poa annua* infestation in wheat was also lower following ZTDSR (11.3–13.0 plants m^{-2}) relative to ZTMTR (36.7 plants m^{-2}). In wheat following DSR, *Poa annua* was more abundant after CTDSR than ZTDSR.

Fig. 2 Effect of different crop establishment methods on density of weeds in wheat under the rice–wheat cropping system (alternate years). The bars of a season with similar letters did not differ statisti-

cally with each other; Treatment details (T1–T8) are given in Materials and Methods

Population of broadleaf weeds was not affected much by different CE methods during 2010–11. But their infestation increased in ZTW in sequence with PTR, non-puddled DSR/MTR, ZT-DSR without residue, and it was statistically lower in ZTW after ZT-DSR with residues, and CTW-PTR over the years. At the start of the experiment (2010–11), infestation by broadleaf weeds was similar across all establishment methods (Fig. 2). In 2016–17, there were more broadleaf weeds in wheat following MTR (74.0–117.3 plants m⁻²) than DSR (47.7–103.0 plants m⁻²). The lowest number of broadleaf weeds in wheat was recorded in sequence with PTR (6.19–8.66 plants m⁻²) and ZTDSR plus residues (6.98 plants m⁻²). In general, avoidance of puddling resulted in greater infestation by *Phalaris minor* and broadleaf weeds; while the reverse was true for *Poa annua*. ZT in wheat also encountered lower weed infestation than CT wheat. However, infestation of broadleaf weeds under PTR-ZTW was similar to PTR-CTW. CTDSR in rotation with puddled rice (T6) still reflected lower density of broadleaf weeds compared to continuous CT/ZT rice.

3.3 Effect on crops

3.3.1 Effect on rice crop

Over the years and in general, the differences in grain yield of rice under CTDSR (2.39–3.94 t ha⁻¹) were non-significant

compared to PTR (2.60–4.07 t ha⁻¹) indicating its medium-term sustainability (Table 2). ZTDSR with or without residues also had at par grain yield to PTR, except minor variations in 2013 and 2015. ZTMTR or CTMTR (2.48–4.31 t ha⁻¹) too had yields statistically similar (non-significant) to PTR; except that ZTMTR in 2011 and CTMTR in 2013 had lower yields than PTR. Relative yield difference of rice in ZTDSR with residue was non-significant to ZTDSR without residue. ZTDSR gave non-significantly/ similar yield to CTDSR except higher yield under CTDSR in 2011. The grain yield of rice in ZTMTR was also non-significant to CTMTR with minor variations. However, the yield trends under ZTMTR/CTMTR and PMTR were inconsistent.

3.3.2 Effect on wheat crop

Grain yields of wheat (5.03–6.90 t ha⁻¹) following CT/ZT rice establishment were higher than puddled systems (4.52–6.37 t ha⁻¹) over the years (Table 2). During 2012–13 to 2014–15, the grain yield of ZTW was higher or similar CTW each in sequence with PTR. Wheat yield increased by 0.4–0.6 t ha⁻¹ when it was grown after CT or ZT rice as compared to PTR. Thus, the productivity of the RWCS was higher under non-puddled or ZT crop establishment methods compared with conventional PTR or CT wheat. It indicated the sustainability in terms of higher productivity

Table 2 Effect of different crop establishment methods on grain yield of rice and wheat rice–wheat cropping system

Treatment [@]	Grain yield of rice (t ha ⁻¹)							Grain yield of wheat (t ha ⁻¹)						
	2010	2011	2012	2013	2014	2015	2016	10–11	11–12	12–13	13–14	14–15	15–16	16–17
ZTDSR(+ R)-ZTW	2.87 ^{ab}	2.86 ^{ab}	3.22 ^a	3.88 ^{bc}	2.36 ^b	2.81 ^c	2.87 ^a	5.46 ^a	5.07 ^{bc}	6.49 ^{ab}	5.67 ^a	5.45 ^a	5.30 ^a	6.76 ^a
ZTDSR-ZTW	2.99 ^a	2.78 ^b	3.24 ^a	3.73 ^{cd}	2.34 ^b	2.79 ^c	2.83 ^a	5.34 ^a	5.03 ^c	6.48 ^{ab}	5.68 ^a	5.30 ^a	5.27 ^a	6.75 ^a
ZTMTR-ZTW	2.93 ^{ab}	2.48 ^c	3.11 ^a	4.31 ^a	2.80 ^a	2.87 ^{bc}	2.83 ^a	5.42 ^a	5.15 ^a	6.43 ^b	5.68 ^a	5.28 ^a	5.04 ^a	6.82 ^a
CTDSR-ZTW	2.88 ^{ab}	3.03 ^a	3.18 ^a	3.94 ^{bc}	2.39 ^b	2.91 ^{abc}	2.82 ^a	5.35 ^a	5.12 ^{ab}	6.55 ^a	5.68 ^a	5.40 ^a	5.11 ^a	6.74 ^a
CTMTR-ZTW	2.86 ^{ab}	2.75 ^b	3.30 ^a	3.41 ^e	2.85 ^a	2.93 ^{abc}	2.81 ^a	5.18 ^a	5.14 ^a	6.46 ^{ab}	5.57 ^a	5.35 ^a	5.04 ^a	6.90 ^a
PMTR/CTDSR/PTR-ZTW*	2.44 ^c	3.07 ^a	3.29 ^a	3.65 ^d	2.40 ^b	2.98 ^{ab}	2.99 ^a	4.87 ^b	4.74 ^d	6.01 ^c	5.18 ^b	5.06 ^b	4.63 ^b	6.33 ^b
PTR-ZTW	2.80 ^b	3.01 ^a	3.15 ^a	4.07 ^b	2.60 ^{ab}	3.03 ^a	3.06 ^a	4.79 ^b	4.69 ^d	5.98 ^c	5.20 ^b	4.83 ^c	4.66 ^b	6.37 ^b
PTR-ZTW/CTW**	–	–	3.14 ^a	4.06 ^b	2.60 ^{ab}	3.05 ^a	3.00 ^a	–	–	5.86 ^d	5.17 ^b	4.71 ^c	4.52 ^b	6.26 ^b
LSD (0.05)	0.19	0.23	NS	0.22	0.27	0.15	NS	0.29	0.06	0.12	0.16	0.22	0.33	0.33

(+ R), with residue; ZTDSR zero-till direct seeded rice; ZTMTR zero-till machine transplanted rice; CTMTR conventional till machine transplanted rice; PMTR puddled machine transplanted rice; PTR puddled transplanted rice; ZTW zero-till wheat; CTW conventional till wheat; NS non-significant

[@]The figures in columns with similar letters did not differ statistically with each other

*PMTR up to 2013, CTDSR in 2014 and PTR in 2015 and 2016 followed by ZT wheat

**PTR fb ZT wheat up to 2011–12 and CT wheat afterwards

of wheat grown after ZT/CT rice (DSR/MTR) vis-à-vis PTR, and also sustainable productivity of ZT wheat vis-à-vis CT wheat on a medium-term basis. Stop gap intervention of CTDSR in rotation with puddled rice (T6) for a year also improved grain yield of wheat compared to what was realized after PTR.

3.3.3 Relative yields

Relative yields of ZT wheat in sequence with ZTDSR (with or without residues) or ZTMTR were similar to ZT wheat after CTDSR/CTMTR, with few exceptions of lower yields after ZT rice in 2011–12 and 2012–13. The graphs plotted for relative yield of rice and wheat under ZTDSR(+ R)-ZTW and CTDSR-ZTW in comparison with PTR-ZTW indicated that relative yield of rice under ZT/CTDSR-ZTW system was initially similar to PTR-ZTW but then it showed slight declining trend with time (Fig. 3). However, relative yield of wheat remained higher under ZT/CTDSR-ZTW than PTR-ZTW over the years, which ultimately resulted in higher system yields.

3.3.4 Economics

3.3.4.1 Cost of cultivation In rice, the average variable cost of cultivation under ZT/CT establishment methods (\$ 417–491 ha⁻¹) was lower than PTR (\$ 555 ha⁻¹) (Table 3). Cost of cultivation was lower under ZT (\$ 417–471 ha⁻¹) compared with CT rice (\$ 448–491 ha⁻¹) and DSR (\$ 417–448 ha⁻¹) compared with MTR (\$ 471–491 ha⁻¹). The major contributing factors to the higher cost of cultivation under PTR were preparatory tillage, seed/nursery and establish-

ment, and irrigation compared to ZT/CTDSR or MTR. The cost of fertilizer was slightly higher under DSR than transplanted rice, and the cost of weed management was also higher under DSR (\$53–65 ha⁻¹) than PTR (\$ 15 ha⁻¹), and likewise ZT rice (\$ 45–65 ha⁻¹) than CT rice (\$ 30–53 ha⁻¹). Manual labor, a major factor to escalate cost of cultivation, was less in ZT/CTDSR (30–31%) and MTR (22%) than PTR.

In wheat, the average variable cost of cultivation under different rice system treatments was similar, except the cost was higher under CT wheat (\$ 414 ha⁻¹) than ZT wheat (\$ 354 ha⁻¹) mainly due to the cost incurred on preparatory tillage (\$ 54 ha⁻¹ vs. \$ 0 ha⁻¹), and interest accrued (\$ 18 ha⁻¹ vs. \$ 15 ha⁻¹). The other costs incurred on seed/ establishment (\$ 57 ha⁻¹), fertilizer (\$ 70 ha⁻¹), irrigation (\$ 61 ha⁻¹), weed management (26 ha⁻¹), harvesting and threshing (\$ 129 ha⁻¹) were similar under different establishment methods.

3.3.4.2 Net returns For rice, the net economic returns were invariably higher or statistically similar under ZT/CT rice establishment methods in comparison to PTR, with few exceptions (Table 4). This was primarily due to decreased cost of production as elaborated above (Table 3). The net returns from ZTDSR were also invariably similar to CTDSR (Table 4). The overall mean of net returns was also higher under ZTDSR/ZTMTR/CTDSR than PTR. PMTR was the least remunerative of all the establishment methods. Overall, ZT/CT rice system treatments particularly DSR were more remunerative.

The net returns in ZT wheat in sequence with ZT or CT rice were more than when it was grown in sequence with PTR or PMTR (Table 4). Further, ZT wheat was more

Fig. 3 Relative yield of rice (top), wheat (middle) and rice–wheat system (lower) under ZTDSR (+ Residue)-ZTW (left) and CTDSR-ZTW (right) as compared to PTR-ZTW

remunerative than CT wheat. Economic viability of ZT wheat after ZT/CT rice, particularly after DSR, was clearly visible on medium-term basis.

3.4 Irrigation water input

On an average of three rainy seasons (2010 to 2012), the maximum irrigation water input was under puddled rice (132–135 cm) (Table 5). ZTDSR with residues had the lowest irrigation water input (102 cm) followed by ZTDSR without residue and CTDSR. There was 23% reduction in irrigation input under ZTDSR with residue and 18% under ZTDSR without residue or CTDSR as compared to PTR. The irrigation water productivity ($27.5\text{--}29.9 \text{ kg ha cm}^{-1}$) of

ZTDSR with or without residue and CTDSR was also higher than that of PTR ($23.7 \text{ kg ha cm}^{-1}$).

Based on average of three winter seasons (2010–11 to 2012–13), the irrigation water input in wheat was similar under all the methods of crop establishment (38–41 cm) (Table 5). The irrigation water productivity of ZTW after ZT rice (DSR/MTR) ($144.1\text{--}145.4 \text{ kg ha cm}^{-1}$) was higher than after conventional till or puddled transplanted rice (PTR/MTR) ($135.6\text{--}138.3 \text{ kg ha cm}^{-1}$).

3.5 Effect on nematodes

Number of plant parasitic nematodes was lower under ZT/CTDSR (192–292 per 200 cc soil) as compared to PTR (414–456) (Table 6). Rice root knot nematodes were present only under PTR (96–104) and CTMTR (52), but no

Table 3 Details of variable cost of cultivation (\$ ha⁻¹) and labor use (No. ha⁻¹) in rice under different establishment methods in the rice–wheat cropping system (average of 2010–2016)

Treatment ^a	Preparatory tillage	Seed/nursery/establishment	Fertilizer	Irrigation	Weed management	Plant protection	Harvesting & threshing	Interest	Total variable cost	Labor use (No. ha ⁻¹)
ZTDSR(+R)-ZTW	0 ^c	49 ^c	41 ^a	96 ^c	65 ^a	38 ^a	111 ^a	18 ^f	417 ^f	57
ZTDSR-ZTW	0 ^c	49 ^c	41 ^a	96 ^c	65 ^a	38 ^a	111 ^a	18 ^f	417 ^f	57
ZTMTR-ZTW	0 ^c	102 ^{ab}	38 ^b	116 ^b	45 ^c	38 ^a	111 ^a	20 ^d	471 ^d	63
CTDSR-ZTW	36 ^c	55 ^c	41 ^a	96 ^c	53 ^b	38 ^a	111 ^a	19 ^e	448 ^e	56
CTMTR-ZTW	36 ^c	102 ^{ab}	38 ^b	116 ^b	30 ^d	38 ^a	111 ^a	21 ^b	491 ^c	63
PMTR/CTDSR/PTR-ZTW*	83 ^b	98 ^b	38 ^b	122 ^a	21 ^e	38 ^a	111 ^a	23 ^b	534 ^b	68
PTR-ZTW	91 ^a	113 ^a	38 ^b	125 ^a	15 ^f	38 ^a	111 ^a	24 ^a	555 ^a	81
PTR-ZTW/CTW**	91 ^a	113 ^a	38 ^b	125 ^a	15 ^f	38 ^a	111 ^a	24 ^a	555 ^a	81
LSD (0.05)	9	12	0.4	6	6	NS	NS	1	19	-

(+R), with residue; ZTDSR zero-till direct seeded rice; ZTMTR zero-till machine transplanted rice; CTMTR conventional till machine transplanted rice; PMTR puddled machine transplanted rice; PTR puddled transplanted rice; ZTW zero-till wheat; CTW conventional till wheat; NS non-significant

^aThe figures in columns with similar letters did not differ statistically with each other

*PMTR up to 2013, CTDSR in 2014 and PTR in 2015 followed by ZT wheat

**PTR fb ZT wheat up to 2011–12 and CT wheat afterwards

infestation of this pathogen was found under ZT/CTDSR systems. Whereas, saprozoic nematode population was more under ZT/CTDSR (904–1156) than PTR (492–666). These were higher under ZT systems and/ or with crop residues. Maximum infestation of root knot nematode in bio-assay studies was recorded under PTR (21–24 galls plant⁻¹) than CTMTR (9) and ZT/CTDSR (0).

4 Discussion

4.1 Impact of planting methods on weed dynamics and nematodes

4.1.1 Rice

Weed intensity and diversity was higher under continuous ZT/CT rice compared to PTR on medium-term basis (7 years' study). The findings reaffirm earlier reports largely based on short-term studies [23, 41–48]. This could be because weeds emerge simultaneously with crop seedlings in DSR, and grow more quickly in moist soil than in PTR [25], and there is no seedling size/heading advantage. Lower weed emergence under PTR could be due to combined effect of puddling and stagnating water. Intervention of CTDSR in rotation with puddled rice (T6) also did not allow build up of weeds compared to continuous CT/ZTDSR. An option for effective weed management could be through retention of wheat crop residue in ZTDSR as evidenced from this study. The benefits of residue retention for weed management have been well documented for various crops [32, 42, 49]. But, the availability of wheat residues and its economic cost could be a constraint in some situations (fodder scarcity areas), and therefore inclusion of herbicides as integrated weed management tool would be imperative. A wide range of pre- and post-emergence herbicides are currently available and can be used alone or in combination to effectively control weed emergence [41, 44, 45, 47, 50–53]. Besides this, integration of herbicides with manual or mechanical weeding in DSR and MTR, particularly under non-puddled situations, would provide long-term solutions for managing complex weed flora. However, the availability of new molecules, awareness about their proper use, and the development and inclusion of herbicide-tolerant rice cultivars could be more viable and integral strategies for achieving higher weed control efficacy through integrated weed management in DSR and could lead to its faster adoption.

Number of plant parasitic and root knot nematodes were lower under ZT/CTDSR as compared to PTR. Rice root knot nematode was recorded only under PTR and CTMTR, but no infestation under ZT/CTDSR systems. Whereas, saprozoic (favorable/ friendly) nematode

Table 4 Net economic returns over variable cost from rice and wheat crops under different crop establishment methods in the rice–wheat cropping system

Treatment [@]	Net returns from rice (\$ ha ⁻¹)							Net returns from wheat (\$ ha ⁻¹)						
	2010	2011	2012	2013	2014	2015	2016	10–11	11–12	12–13	13–14	14–15	15–16	16–17
ZTDSR(+ R)-ZTW	982 ^{ab}	482 ^{ab}	1204 ^a	2209 ^b	1246 ^{ab}	799 ^a	985 ^a	861 ^a	862 ^{bc}	1269 ^a	1147 ^a	1104 ^a	1130 ^a	1482 ^a
ZTDSR-ZTW	1035 ^a	460 ^{abc}	1212 ^a	2113 ^b	1185 ^{bc}	787 ^a	967 ^a	841 ^a	856 ^c	1267 ^a	1150 ^a	1072 ^a	1123 ^a	1481 ^a
ZTMTR-ZTW	966 ^{ab}	323 ^e	1095 ^{bc}	2437 ^a	1371 ^a	762 ^{ab}	910 ^a	854 ^a	879 ^a	1256 ^a	1150 ^a	1066 ^a	1069 ^a	1496 ^a
CTDSR-ZTW	974 ^{ab}	511 ^a	1168 ^{ab}	2224 ^b	1245 ^{ab}	803 ^a	876 ^a	842 ^a	873 ^{ab}	1280 ^a	1150 ^a	1093 ^a	1085 ^a	1478 ^a
CTMTR-ZTW	920 ^{bc}	382 ^{de}	1169 ^{ab}	1816 ^c	965 ^d	763 ^{ab}	873 ^a	813 ^a	876 ^a	1262 ^a	1126 ^a	1082 ^a	1070 ^a	1514 ^a
PMTR/CTDSR/PTR-ZTW*	680 ^d	427 ^{bcd}	1108 ^{bc}	1926 ^c	1060 ^{cd}	718 ^b	887 ^a	758 ^b	801 ^d	1171 ^b	1046 ^b	1019 ^b	977 ^b	1382 ^b
PTR-ZTW	841 ^c	402 ^{cd}	1038 ^c	2190 ^b	1176 ^{bc}	739 ^{ab}	922 ^a	745 ^b	790 ^d	1167 ^b	1049 ^b	969 ^c	984 ^b	1392 ^b
PTR-ZTW/CTW**	–	–	1032 ^c	2184 ^b	1172 ^{bc}	744 ^{ab}	893 ^a	–	–	1067 ^c	965 ^c	866 ^d	872 ^b	1280 ^b
LSD (0.05)	83	66	86	148	131	65	NS	50	12	25	33	47	74	77

(+ R), with residue; *ZTDSR* zero-till direct seeded rice; *ZTMTR* zero-till machine transplanted rice; *CTMTR* conventional till machine transplanted rice; *PMTR* puddled machine transplanted rice; *PTR* puddled transplanted rice; *ZTW* zero-till wheat; *CTW* conventional till wheat

[@]The figures in columns with similar letters did not differ statistically with each other

*PMTR up to 2013, CTDSR in 2014 and PTR in 2015 and 2016 followed by ZT wheat

**PTR fb ZT wheat up to 2011–12 and CT wheat afterwards

Table 5 Irrigation water input, reduction in irrigation input and irrigation water productivity in rice under different crop establishment methods continued since 2010–11 in the rice–wheat system (Average of 2010–11 to 2012–13)

Treatment [@]	Rice			Wheat		
	Irrigation water input (cm)	Reduction in irrigation input (%)	Irrigation water productivity (kg ha-cm ⁻¹)	Irrigation water input (cm)	Reduction in irrigation input (%)	Irrigation water productivity (kg ha-cm ⁻¹)
ZTDSR(+ R)-ZTW	102 ^c	22.8	29.9 ^a	39 ^a	–2.6	145.4 ^a
ZTDSR-ZTW	109 ^c	17.5	27.5 ^{ab}	39 ^a	–2.6	144.1 ^a
ZTMTR-ZTW	121 ^a	7.3	22.2 ^c	39 ^a	–2.6	145.3 ^a
CTDSR-ZTW	110 ^{bc}	17.5	29.9 ^a	41 ^a	–7.9	138.3 ^b
CTMTR-ZTW	125 ^{ab}	5.7	24.0 ^{bc}	41 ^a	–7.9	136.4 ^b
PMTR-ZTW	135 ^a	–2.2	23.9 ^{bc}	38 ^a	0.0	137.0 ^b
PTR-ZTW	132 ^a	0.0	23.7 ^{bc}	38 ^a	0.0	135.6 ^b
LSD (0.05)	16	–	4.8	NS	–	5.3

(+ R), with residue; *ZTDSR* zero-till direct seeded rice; *ZTMTR* zero-till machine transplanted rice; *CTMTR* conventional till machine transplanted rice; *PMTR* puddled machine transplanted rice; *PTR* puddled transplanted rice; *ZTW* zero-till wheat; *CTW* conventional till wheat

[@]The figures in columns with similar letters did not differ statistically with each other

population was more under ZT/CTDSR than PTR. These were higher under ZT systems and or with crop residues, probably due to presence of some or more crop residues under ZT systems. Maximum infestation of root knot nematode in bio-assay studies was also found under PTR compared to CT/ZT rice establishment methods, indicating DSR to be safe from nematodes even after seven years. This study ruled out the speculation that the nematode infestation increases under DSR systems or continuous ZT-RWCS. Contrarily, root-knot nematodes

have also been reported to pose severe constrain when PTR was shifted with DSR in Philippines [54, 55].

4.1.2 Wheat

Broadleaf weed infestation of wheat was lowest in sequence with PTR and ZTDSR (with wheat residues) (as we also hypothesized in the present study). Avoidance of puddling resulted in higher infestation by *Phalaris minor* and broadleaf weeds in wheat; while, the reverse was true

Table 6 Effect of different crop establishment methods on nematodes in rice crop after seven years in the rice–wheat cropping system

Treatments	No of plant parasitic Nematodes/ 200 cc soil	Rice root-knot nematode infestation/200 cc soil	No of saprozoic nematodes/200 cc soil	Rice root-knot nematode infestation in rice cv PB-1121 under bio-assay
ZTDSR(+ R)-ZTW	192	0	1156	Nil
ZTDSR-ZTW	288	0	904	Nil
ZTMTR-ZTW	387	0	935	Nil
CTDSR-ZTW	292	0	935	Nil
CTMTR-ZTW	311	52	895	Mild infestation (9 galls/plants)
PMTR/CTDSR/PTR-ZTW*	380	0	841	Mild infestation(3 galls/plants)
PTR-ZTW	414	96	666	Infestation (21 galls/plants)
PTR-ZTW/CTW**	456	104	492	Infestation (24 galls/plants)

(+ R), with residue; *ZTDSR* zero-till direct seeded rice; *ZTMTR* zero-till machine transplanted rice; *CTMTR* conventional till machine transplanted rice; *PMTR* puddled machine transplanted rice; *PTR* puddled transplanted rice; *ZTW* zero-till wheat; *CTW* conventional till wheat; *NS* non-significant

*PMTR up to 2013, CTDSR in 2014 and PTR in 2015 and 2016 followed by ZT wheat

** PTR fb ZT wheat up to 2011–12 and CT wheat afterwards

for *Poa annua*. This could be a cause of concern, as *Phalaris minor* infestation in wheat following rice is already a serious threat to wheat production in north western India. Therefore, rotating DSR with PTR intermittently could be important to keep a check on flaring up of this weed menace. Puddling facilitates water stagnation in the rice phase and this might be more detrimental to *Phalaris minor* seed longevity compared with the aerobic conditions in DSR, which could have resulted in its comparatively higher infestation in wheat grown in sequence with DSR than PTR. Infestation of *P. minor* in wheat was lower in ZTW than CTW in present study, which reaffirms the earlier reports [42, 56–59]. This might be because ZT in wheat could create unfavorable conditions for the emergence of *P. minor*. To mitigate this weed in future, there is a need to adopt ZT in wheat as part of an integrated weed management strategy. Reduced infestation of *Poa annua* in non-puddled rice situations realized in present study appeared favorable/advantageous; however, this weed otherwise is comparatively less damaging than *Phalaris minor*.

4.2 Impact of planting methods on productivity and profitability

The grain yield of rice under non-puddled situations (DSR or MTR with and without residues) was statistically similar to PTR, with a few exceptions and minor variation over the years. A higher number of panicles in DSR relative to PTR might have compensated for lower 1000-grain weight and grains per panicle (data not given). Wheat yield increased by 0.4–0.6 t ha⁻¹ when it was grown after CT/ZT rice than PTR. This was due to improved number of spikes, 1000-grain weight and grains per panicle. Higher spike density in wheat after CT/ZT rice systems could be due to higher

tiller production (data not given). PTR has already been widely reported to have negative impacts (soil compaction) on subsequent crops like wheat in rotation [7, 8]. Increase in ZT wheat as compared to CT wheat, and wheat yield after DSR as compared to PTR is due to their positive impact on yield attributing characters due to favourable conditions [60].

Reduction in *P. minor* infestation, improved fertilizer utilization through better seed to soil contact, and congenial soil conditions in the root zone through residue retention in ZT could have favored the ZT wheat crop compared with the CT crop. An increase in the productivity of wheat in ZT compared to CT, from 1–15% in northwest to 9–36% in northeast India, has already been reported [61, 62]. Irrigation water productivity of DSR on an average of three years was also higher than PTR during 2010–12. While comparing direct seeding and transplanting methods on loamy sand soil at Ludhiana, it was found that water productivity varied from 0.36 to 0.46, i.e., 25% by adopting DSR with about 18% less irrigation water consumption and with comparable yield as compared to transplanted rice [63].

Relative yields of ZT wheat in sequence with ZTDSR (with or without residues) or ZTMTR were similar to ZT wheat after CTDSR/CTMTR, with few exceptions of lower yields after ZT rice in 2011–12 and 2012–13. The graphs plotted for relative yield of rice and wheat under ZTDSR (+ R)-ZTW and CTDSR-ZTW in comparison with PTR-ZTW, indicated that relative yield of rice under ZT/CTDSR-ZTW was initially similar to PTR-ZTW which showed slight declining trend with time. However, relative yield of wheat remained higher under ZT/CTDSR-ZTW than PTR-ZTW over the years, which overall resulted in higher system yields.

Compared with the traditional method of manual transplanting in puddled fields (PTR), the cost of cultivation in

DSR was found to be reduced through input (irrigation water and cultivation) and labor savings (lack of nursery raising, puddling and transplanting), and likewise it reduced in non-puddled MTR (absence of puddling and manual transplanting). There was a 30–31% saving of labor in ZT/CTDSR and 22% in ZT/CTMTR as compared with PTR, in spite of labor being required for manual weeding in DSR. A reduction in total labor requirement under DSR compared to PTR has been reported elsewhere [17, 18]. The net returns from ZT/CT rice-based systems were also invariably higher than PTR, which is in conformity with earlier findings in Haryana, India [41, 44–46, 64, 65]. Present study reaffirmed that ZT wheat further added to the overall net returns over CT wheat. ZT wheat in the rice–wheat system has already been reported to be more productive, profitable and sustainable than CT Wheat [31, 33, 34, 49, 59, 66]. The present study clearly indicated that the productivity and profitability of ZT wheat was higher than that of CT wheat, and it was further improved when ZTW was grown in sequence with CT/ZT rice than PTR. It can therefore even help compensate for higher yields often reported in PTR than DSR.

4.3 System-based stability

The sustainability of the rice–wheat cropping system in India is in question, particularly in the northwest, due to reduction in the organic matter content of soil, depletion of water resources and deteriorating water quality (including ground water reservoirs), burning of residue, reduced productivity, unsatisfactory product quality, and environmental pollution. The results of the present investigation indicate that savings of water and labor could be achieved by switching over from traditional PTR to CT/ZTDSR. There was improvement in organic carbon under ZTW-ZTDSR/MTR (0.41–0.45%) than ZTW- PTR (0.31–0.32%), and available phosphorus and potassium were also higher under ZTW-zero-till/ non-puddled methods of rice establishment than ZTW/CTW-puddled systems. Bulk density of soil at 0–5 cm depth was lower under ZTW-zero-till or non-puddled rice (1.41–1.44 g cc⁻¹) than ZTW/CTW-puddled rice (1.55–1.56 g cc⁻¹). DSR provides reduction in irrigation input due to avoidance of continuous flooding [37, 67]. Overall, ZT wheat in sequence with ZT/CT rice vis-à-vis PTR were realized more sustainable along with improved productivity and profitability of the system. Additionally, adverse environmental impacts are also reduced [7, 8]. Residue retention in ZTDSR improved water and crop productivity besides reducing weed pressure. Reduction in greenhouse gases and global warming potential leading to overall environmental protection and system sustainability has also been well documented from same ecology earlier also [68]. Similarly, retention of rice residues in

wheat may also add to the benefits, which needs to be further confirmed in long-term studies on ZT-ZT rice–wheat system. Long-term studies are also required to optimize the periodicity of rotating PTR with DSR, if need be, for combating weeds (particularly expected problematic aerobic weeds weedy rice, and even wild rice), harnessing the envisaged full benefits of DSR and overall sustainability issues. However, based on present 7-year medium-term study and by taking relevant support from similar learnings from elsewhere, we can anticipate multifold benefits by adopting these system-based resource conserving technologies/ establishment methods at scale.

5 Conclusions

In India, the mindset of farmers is fast switching over from traditional, intensive wet tillage/puddling and resource inefficient crop establishment methods (PTR/CTW), to alternate resource conserving crop establishment methods (DSR/MTR/ZTW). In this context, the present medium-term (7 years) system-based study enables to draw important inferences with all positive notes regarding the impact of alternate planting methods on the productivity, profitability and stability of rice–wheat cropping system. ZT in wheat was reaffirmed to address many ongoing concerns with respect to weed dynamics, nematodes, soil health, productivity and profitability. In rice also, yield was maintained or improved simply by switching over from PTR to DSR/MTR in ZT/CT soil conditions besides attaining higher system productivity and farm income. The relative yields of ZT-wheat and DSR in RWCS were consistently higher during the study, which appear quite helpful in addressing the sustainability-related issues/concerns of the RWCS. These alternative establishment methods also significantly reduced the cost of cultivation resulting into higher profitability. Additionally, there was significant saving in labor, reduction in irrigation water input in DSR/MTR and also improvement in soil properties under CT/ZT situations compared to PTR, and these are important keys to address long-term sustainability of rice–wheat cropping system. However, the weed flora changed rapidly, becoming very complex in rice and also in wheat to some extent, once rice cultivation was switched from PTR to ZT/CT methods. Therefore, very effective integrated weed management strategies (including herbicides, herbicide tolerant competitive varieties and manual/mechanical methods) are pre-requisites for the success of non-puddled rice particularly in ecologies where exacerbated weed problems could jeopardize its long-term adoption. Other easy and possible option would be to retain residues in ZT systems and rotate DSR with PTR periodically to reverse the shift in weed flora along with harnessing the benefits of DSR in

rice–wheat system; however, further research is required to optimize the scheduling of such rotation. On a positive note, the infestation of root knot nematode and plant parasitic nematodes in rice was lower under DSR than PTR. These findings will help bridge up some of the existing knowledge gaps and change mindset of researchers, policy makers and farmers for accelerated adoption of alternate planting methods in rice–wheat cropping system at scale. Further research efforts are required to coin/layer the potential benefits of short/medium high yielding rice varieties/hybrids and long duration high yielding wheat varieties along with improved planting methods and agro-nomic practices and generate evidence-based recommendations suited to different landscapes/agro-ecologies.

Acknowledgements This work was supported by the funding from Australian Centre for International Agricultural Research (Project number SMCN/2004/033, later on renumbered CSE/2004/033) through the University of Adelaide, Adelaide, Australia to the CCS Haryana Agricultural University, Hisar, India, which is thankfully acknowledged.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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