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RESEARCH ARTICLE

Sesbania brown manuring improves soil health, productivity, and profitability of post-rice bread wheat and chickpea

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Summary

Continuous rotation of rice with wheat in rice–wheat system has resulted in stagnant yields and reduced profit margins while deteriorating the soil health. Legume incorporation in existing rice–wheat rotations might be a viable option to improve soil health and productivity. We investigated the influence of puddled transplanted flooded rice and direct-seeded rice on weed dynamics, soil health, productivity, and profitability of post-rice wheat and chickpea grown under zero tillage and conventional tillage. The previous direct-seeded rice crop was either sown alone or intercropped with sesbania as brown manure. The experiment comprised different rice–wheat and rice–chickpea systems which had been in place for two years: with and without rice residue retention. The initial soil analysis indicated that the plots with sesbania brown manuring in direct-seeded rice had the lowest soil bulk density (17.2%) and highest soil porosity (19.3%). Zero tillage in wheat or chickpea in the plots previously cultivated with co-culture of sesbania and direct-seeded rice increased total soil organic carbon by 13–22% in both years. The plots with sesbania brown manuring in direct-seeded rice followed by zero till or conventional till wheat and the plots with direct-seeded rice followed by zero till wheat with rice residue retention recorded the greater concentrations of total nitrogen, available phosphorus, and exchangeable potassium. Zero tillage in wheat and chickpea in post-rice sesbania brown manuring plots produced 41% and 43% more grain yield than those in the puddled transplanted flooded rice with conventional tillage and had the highest profitability. Overall, the rice–chickpea systems had better soil health and profitability than rice–wheat cropping systems. In conclusion, direct-seeded rice intercropped with sesbania followed by wheat and chickpea under zero tillage suppressed weed flora and improved soil physical properties, nutrient availability, productivity, and profitability.

Keywords: Brown manuring; Weed management; Soil properties; Legume incorporation; Conservation agriculture; Sustainability

Introduction

Cereal crops including bread wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) are grown in diverse crop rotations worldwide and play a vital role in ensuring food security. As leading food crops, rice and wheat supply 20% and 27% of the dietary energy and protein, respectively, in the developing world (Redona, 2004). In conventional rice–wheat rotations, rice seedlings are transplanted in puddled flooded soil to suppress weeds, reduce percolation losses, and improve the availability of certain micronutrients (Nawaz *et al.*, 2019). In contrast, wheat sowing requires well-drained soil of good tilth, which indicates a conflict in soil management practices for rice and the post-rice wheat crop (Farooq *et al.*, 2008). Indeed, puddling increases soil compaction by reducing total soil porosity and increasing soil bulk density (Farooq and Nawaz, 2014) and has a detrimental effect on successful wheat establishment due to restricted root growth and aeration stress (Nawaz *et al.*, 2019). In addition, puddling typically results in erratic crop stand establishment due to poor seed–soil contact (Nawaz *et al.*, 2016). Several studies on rice–wheat systems have reported lower wheat yield after puddled transplanted flooded rice than after direct-seeded aerobic rice (Nawaz *et al.*, 2016, 2017a, b).

Tillage practices affect the pattern of weed emergence, as the weed flora may differ between plow tillage and zero tillage (Nawaz and Farooq, 2016). Conventional tillage helps to suppress weeds during early growth, but late-season weed infestations can be stimulated in this tillage system, which can reduce crop yield and quality (Harker and Clayton, 2004). Tillage intensity can also affect soil moisture retention and then weed emergence, which has affected the yields of wheat and chickpea (Pradhan *et al.*, 2014). The use of resource conservation technologies including zero tillage in wheat and direct-seeded rice might enhance the productivity and profitability of rice–wheat rotations (Nawaz *et al.*, 2017a, b, 2019) by reducing soil degradation and increasing soil organic matter and soil fertility and finally improving the biological diversity in the rhizosphere (Farooq and Nawaz, 2014; Nawaz *et al.*, 2016, 2017a, b, 2021). For example, zero tillage in wheat reduces production costs (Hobbs and Gupta, 2003) and improves soil structure (Mohanty *et al.*, 2007), soil enzyme activity (Lupwayi *et al.*, 2007) and microbial biomass carbon by 7–36% (Soon and Arshad 2005).

Previous cultivation of direct-seeded rice improves the soil physical structure by improving soil porosity and reducing soil bulk density (Nawaz *et al.*, 2016), resulting in better root penetration by the wheat crop. In rice–wheat rotations, zero tillage suppresses some weeds due to less soil disturbance (Farooq and Nawaz, 2014). Various field experiments have concluded that direct-seeded rice is a better resource conservation technology than puddled transplanted flooded rice for improving soil health. For instance, zero tillage wheat grown after direct-seeded rice helped to sustain productivity in a rice–wheat cropping system (Farooq and Nawaz, 2014; Nawaz *et al.*, 2016, 2017a).

Legume incorporation into cropping systems enriches soil organic matter, improves soil nutrient availability (Cupina, 2014) and also soil physical conditions by reducing soil bulk density and enhancing soil aggregation (Mandal *et al.*, 2003). Previous studies have reported that growing sesbania (*Sesbania rostrata* Bremek. & Oberm) as an intercrop with direct-seeded rice and residue retention had a positive impact on soil properties and provided a favorable environment for the following crops (Nawaz *et al.*, 2017b; Iliger *et al.*, 2017). Moreover, legume incorporation as a break crop helps to suppress weeds, pests (Jensen *et al.*, 2010), and diseases (Cupina, 2014).

Some studies have compared conventional and conservation tillage systems (Shahzad *et al.*, 2016; Nawaz *et al.*, 2017a) and the inclusion of legumes (Lauren *et al.*, 2001) in rice–wheat systems for their impact on weed dynamics and productivity. However, to the best of our knowledge, there have been no studies on weed dynamics, soil health, productivity and profitability of wheat and chickpea in long-term rice-based conventional and conservation tillage systems. This study evaluated the effect of different rice-based cropping systems (conventional vs. conservation) and legume incorporation on soil physicochemical and biological properties, weed dynamics, productivity, and profitability of both chickpea and wheat grown in plow tillage and zero tillage systems.

Materials and methods

Experimental site

A field study was conducted at the Agronomic Research Area, University of Agriculture, Faisalabad (31°N, 73°E and 184.4 m a.s.l.), Pakistan in 2014/15 and 2015/16. The experimental plots (9.25 m × 15 m) were established in 2012/13. For soil analysis, soil samples were collected before the sowing of wheat and chickpea and after rice harvest from different points in the experimental field. The experimental soil (0–20 cm depth) was a sandy loam with pH 8.2, electrical conductivity (EC) 0.25 dS m^{-1}, and very low organic matter content (0.66%). Available P, total N, and exchangeable K were 7.0 ppm, 330 ppm, and 111 ppm, respectively, at the beginning of the experiment. Weather data during the course of investigation are shown in Supplementary Material Table S1.

Seed material

Seeds of chickpea (*Cicer arietinum* L.) cultivar 'Bakhar-2011' and the bread wheat (*Triticum aestivum* L.) cultivar 'Faisalabad-2008' were sourced from the Pulse Research Institute (Faisalabad, Pakistan) and the Wheat Research Institute (Faisalabad, Pakistan), respectively.

Experimental details and treatments

The experiment comprised the following eight rice–wheat and rice–chickpea systems in a randomized complete block design with 16 plots (with each plot designated as one cropping system); each plot was replicated three times: (1) direct-seeded rice followed by zero tillage wheat or zero tillage chickpea, with no rice residue retention (DR-ZT); (2) direct-seeded rice followed by conventional tillage wheat or conventional tillage chickpea, with no rice residue retention (DR-CT); (3) direct-seeded rice followed by zero tillage wheat or zero tillage chickpea, with rice residue retention (DR-ZTR); (4) direct-seeded rice followed by conventional tillage wheat or conventional tillage chickpea, with rice residue retention (DR-CTR); (5) puddled transplanted flooded rice followed by zero tillage wheat or zero tillage chickpea with no rice residue retention (TR-ZT); (6) puddled transplanted flooded rice followed by conventional tillage wheat or conventional tillage chickpea with no rice residue retention (TR-CT); (7) direct-seeded rice with sesbania brown manuring followed by zero tillage wheat or zero tillage chickpea, with no rice residue retention (DRS-ZT); (8) direct-seeded rice with sesbania brown manuring followed by conventional tillage wheat or conventional tillage chickpea, with no rice residue retention (DRS-CT).

The direct-seeded rice and puddled transplanted flooded rice systems had been maintained as per Nawaz *et al.* (2017b) for the previous 3 years.

Land preparation and crop husbandry for wheat and chickpea

For conventional tillage wheat and chickpea, the fields after direct-seeded rice were cultivated (up to 20 cm depth) twice with a cultivator followed by leveling while those after puddled transplanted flooded rice were cultivated four times using a cultivator followed by two plankings. In treatment 3 and 4, the rice residues (7 t ha^{-1}) of previous rice crop were retained in the wheat and chickpea plots. In both tillage systems, wheat and chickpea were seeded at 125 and 75 kg ha^{-1}, respectively.

The wheat was sown on 14 November 2014 and 18 November 2015 and chickpea sown on 15 October 2014 and 13 October 2015. The wheat and chickpea were sown using a manually operated single-row drill. For zero tillage wheat and chickpea, the seeds were sown directly into rice stubble. The row-to-row distance was 30 cm for chickpea and 22.5 cm for wheat.

Inorganic fertilizers were applied on the basis of the soil analysis report at 100/90 and 15/50 N/P kg ha^{-1} in the wheat and chickpea crops, respectively, using urea (46% N) and di-ammonium phosphate (18% N, 46% P). For wheat, the full amount of P and one-third of N was applied as a basal dose, and the remaining two-thirds of N was top dressed equally at the first and second irrigation (flooding method). For chickpea, the full amount of P and N was applied as a basal dose. Two (each of 76 mm) irrigations through flooding method were applied to chickpea, and four (each of 76 mm) to wheat in both tillage systems, in addition to the pre-sowing irrigation of 102 mm.

After recording the weed data at 30 days after sowing, the weed control in wheat fields was achieved through a selective post-emergence herbicide [Atlantas (iodo-mesosulfuron) at 14.4 g a.i. ha^{-1}]. Weeds in chickpea plots were controlled through the manual pulling of weeds at 30 days after sowing. There were no insect pest attacks or diseases in either crop or season. Both crops were harvested on 24 April 2015 and 29 April 2016.

Weed dynamics and soil health

Data on weed density (individual and total) were recorded 45 days after sowing from two random places (each measuring 1 m^2) in each plot through visual counting. To determine soil health, the soil was sampled at the harvest of each crop from different positions within the experimental plots using an auger. Soil pH and EC were measured using Thermo Scientific Orion 4-star plus pH/conductivity meter (Thermo Fisher Scientific, Inc., Beverly MA, USA) (Rhoades, 1996; Thomas, 1996). Exchangeable K (Richards, 1954), available P (Olsen *et al*., 1954), total N (Bremner and Mulvaney, 1982), soil bulk density (Blake and Hartge, 1986), total soil porosity (Vomocil, 1965), and total soil organic carbon (Walkley and Black, 1934) were estimated following standard protocols.

Morphological/yield parameters

At final harvest, from each plot, number of spike-bearing tillers were counted from three randomly selected three sampling sites (each of 1 m^2) to record the productive tillers. Ten spikes were randomly selected and threshed manually to separate the grains. The grains separated were counted to record number of grains per spike. A subsample of 1000 grains was taken from each plot and weighted to record 1000-grain weight. The crop was harvested, tied into bundles, and sun-dried for a week. Total above-ground wheat biomass of sun-dried samples from each plot were recorded with a spring balance (Kern 281, Inscale, Buckinghamshire, UK). The crop was threshed by a mini-thresher and grain yield for each treatment was recorded by a spring balance (Kern 281, Inscale, Buckinghamshire, UK) in kilograms and later expressed in tons per hectare (t ha^{-1}).

For chickpea, branch and pod number per plant were counted on five plants selected at random in each experimental plot and averaged. Twenty pods of chickpea from each experimental plot were threshed manually to determine the seed number per pod. One hundred seeds were weighed on an electronic balance to record 100-grain weight. To record total grain yield and total biomass of each crop, each plot was harvested in heaps and sun-dried for a week before being weighed on a spring balance (Kern 281, Inscale, Buckinghamshire, UK) to record total above-ground biomass. The bundles were then threshed, and grain yield recorded and expressed in tons per hectare. The harvest index of chickpea was expressed in percentage by dividing grain yield by total above-ground biomass.

Economic analysis

The net benefits for each treatment were calculated by subtracting total cost (fixed cost and variable cost) from the gross income (income from straw and grains) and was converted into (US$ ha^{-1}). The total fixed cost included land rent, seed cost, costs of fertilizer, plant protection, and irrigation. The variable cost included the cost of tillage/seedbed preparation, and harvesting/threshing charges (Table S2). The benefit:cost ratio was computed following CIMMYT (1998).

Statistical analysis

The experimental data were statistically analyzed by analysis of variance (Steel *et al*., 1997) using the software Statistics MSTAT-C (Crop and Soil Science Department, Michigan University, USA). The treatment means (cropping systems) were compared using the least significant difference at the 5% probability level.

Table 1. Influence of various rice production systems on soil physical properties before planting wheat or chickpea

	Soil bulk density (g cm^{-3})		Soil porosity (%)		Total soil organic carbon (g kg^{-1})	
Treatments	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16
DSR	1.20b	1.18b	54.88c	55.92c	3.26ab	3.43b
DSR + CR	1.16c	1.14c	56.12b	57.21b	3.29a	3.51a
DSR + SBM	1.14d	1.12b	57.11a	58.25a	3.35a	3.54a
PuTR	1.38a	1.35a	47.90d	48.83d	3.18b	3.18c
LSD ($p \le 0.05$)	0.01	0.02	0.39	0.41	0.08	0.07

Main effects sharing the same letter for a parameter during an experimental year do not differ significantly at $p \le 0.05$.
DSR = direct-seeded rice; DSR + CR = direct-seeded rice + crop residues; SBM = sesbania brown manuring; PuTR = puddled transplanted rice.

Results

Soil health

At rice harvest, the lowest total soil porosity and the maximum soil bulk density were recorded after harvesting the puddled transplanted flooded rice in both years. The DRS-ZT, DRS-CT, and DR-CR treatments caused the highest total SOC in both years (Table 1).

The rice–wheat and rice–chickpea cropping systems did not affect soil pH or EC in either year. In both years, the DRS-ZT and DR-ZTR in the rice–chickpea cropping system caused the highest SOC values (Table 2).

In both years, the direct-seeded rice treatments (except for DR-CT) in the rice–chickpea cropping system had the highest N concentrations (Table 2). In both years, the rice–wheat cropping system had the highest available P in the TR-CT and DRS-ZT treatments. The rice–chickpea cropping system had the highest available P in the transplanted rice treatments in both years. In 2014/15, the maximum exchangeable K was recorded in the rice–chickpea cropping system in the DRS-ZT treatment. In 2015/16, both cropping systems caused the highest exchangeable K in the DRS-ZT treatment (Table 2).

Weed dynamics

The weed flora in the different rice-based cropping systems consisted of toothed dock (*Rumex dentatus* L.), black medick (*Medicago lupulina* L.), blue pimpernel (*Anagallis arvensis* L.), common lambsquarter (*Chenopodium album* L.), swine cress (*Cronopus didymus* L.), field bindweed (*Convolvulus arvensis* L.), and littleseed canarygrass (*Phalaris minor* Retz.). In 2014/15, the wheat crop in the TR-ZT treatment had the highest density of toothed dock. In 2015/16, chickpea and wheat in the DR-ZTR treatment and wheat in the DRS-ZT treatment had the lowest densities of toothed dock. Wheat planted in the TR-ZT treatment had the lowest density of blue pimpernel in 2015/16 (Figure 1). The black medick and blue pimpernel density was highest in DR-CT treatment in both crops in both years (Figures 1 and 2).

The lowest density of common lambsquarter was recorded for both crops in the TR-ZT treatment in 2015/16 (Figure 2). Chickpea planted in the DR-ZT treatment had the lowest density of swine cress in 2015/16. In 2014/15, wheat planted in the DR-CT treatment and chickpea in the TR-CT treatment had the lowest densities of field bindweed (Figure 3). In 2015/16, no emergence of field bindweed was observed in the wheat planted in the DR-CT treatment (Figure 3).

In 2014/15, the DR-CTR and TR-CT treatments caused no emergence of littleseed canary grass in either crop (Figure 4). In 2015/16, chickpea grown in the DR-CT, DR-CTR, and DR-ZTR treatments had the lowest densities of littleseed canary grass (Figure 4). Wheat planted

Table 2. Influence of various rice–wheat and rice–chickpea cropping systems on different soil properties (ns = non-significant; DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea)Treatments sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$

	Soil Ph				Soil electrical conductivity (dS m^{-1})				Total soil organic carbon (g kg^{-1})			
	2014/15		2015/16		2014/15		2015/16		2014/15		2015/16	
Treatments	Wheat	Chickpea	Wheat	Chickpea	Wheat	Chickpea	Wheat	Chickpea	Wheat	Chickpea	Wheat	Chickpea
DR-ZT	8.0	8.0	8.1	8.1	0.28	0.35	0.29	0.34	3.44c	3.62ab	3.45c	3.69b
DR-CT	8.1	8.0	8.0	8.1	0.29	0.33	0.30	0.32	3.18f	3.35d	3.17f	3.42cd
DR-ZTR	8.0	8.4	8.1	8.2	0.33	0.30	0.34	0.39	3.60b	3.79a	3.64b	3.87a
DR-CTR	8.1	8.5	8.2	8.2	0.31	0.35	0.32	0.34	2.94h	3.09g	3.01g	3.15f
TR-ZT	8.0	8.4	8.1	8.1	0.27	0.31	0.28	0.30	3.10g	3.26e	3.07g	3.33e
TR-CT	8.2	8.3	8.2	8.2	0.22	0.29	0.26	0.28	2.95h	3.10g	2.92h	3.16f
DRS-ZT	8.1	8.5	8.0	8.3	0.39	0.40	0.40	0.42	3.65ab	3.84a	3.69b	3.92a
DRS-CT	8.1	8.3	8.1	8.2	0.37	0.34	0.38	0.41	3.27e	3.44c	3.28e	3.51c
LSD ($p \leq 0.05$)	Ns		ns		ns		ns		0.06		0.07	
	Total nitrogen (g kg^{-1})				Available phosphorus (ppm)				Extractable potassium (ppm)			
DR-ZT	0.35d	0.52ab	0.36d	0.54a	4.2b	3.5b	4.2bc	3.4c	160c	170bc	163b	173b
DR-CT	0.34de	0.45c	0.35d	0.46b	3.1bc	4.2b	3.1c	4.2bc	170bc	170bc	173b	173b
DR-ZTR	0.38d	0.55a	0.39d	0.56a	3.4b	3.5b	3.4c	3.5c	130e	180b	133c	184b
DR-CTR	0.37d	0.53a	0.38d	0.55a	5.2ab	4.3b	5.3ab	4.3bc	170bc	170bc	173b	173b
TR-ZT	0.28f	0.45c	0.29e	0.46b	5.3ab	6.2a	5.4ab	6.3a	170bc	150cd	173b	153bc
TR-CT	0.23g	0.44c	0.24e	0.45bc	7.0a	7.4a	7.1a	7.5a	180b	130e	184b	133c
DRS-ZT	0.49b	0.57a	0.50ab	0.58a	6.4a	5.2ab	6.5a	5.3ab	190b	210a	195a	214a
DRS-CT	0.44c	0.56a	0.45bc	0.57a	5.2ab	5.1b	5.3ab	5.4ab	170bc	190b	173b	196a
LSD ($p \leq 0.05$)	0.03		0.04		1.80		1.53		18.1		0.4	

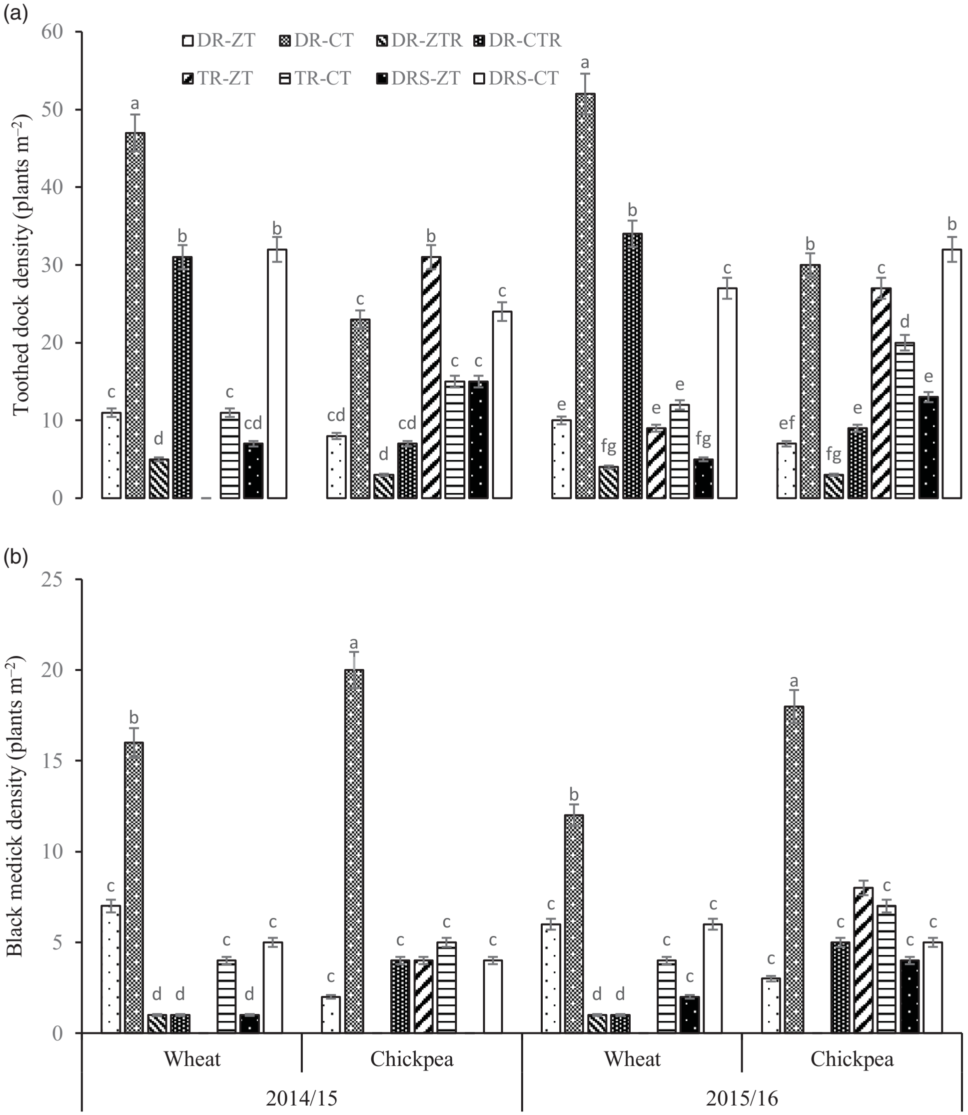

Figure 1. Influence of various rice–wheat cropping systems on the density of (a) toothed dock and (b) black medick in wheat and chickpea.

(DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; Bars are means ± standard error of means. The bars sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$)

in the TR-ZT treatment in both years and chickpea planted in the DR-ZTR treatment in 2014/15 and 2015/16 had the lowest total broad-leaved weeds (Figure 5). In 2014/15, wheat in the TR-ZT treatment and chickpea in the DR-ZTR and TR-CT treatments had the fewest total weeds (Figure 5). Similarly, in 2015/16, chickpea in the DR-ZTR treatment and wheat in the TR-ZT treatment had the fewest total weeds (Figure 5).

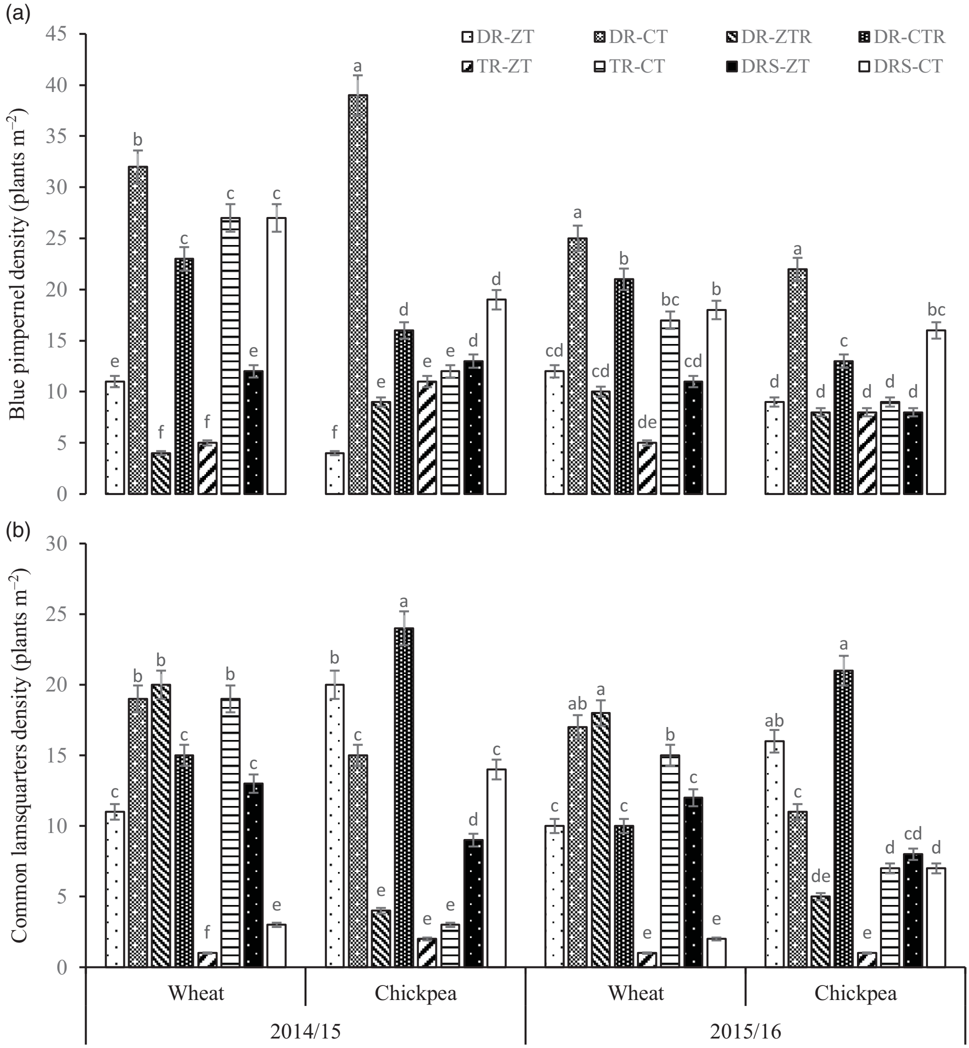

Figure 2. 720 Influence of various rice–wheat cropping systems on the density of blue pimpernel and common lambsquarters (m^{-2}) in wheat and chickpea.

(DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; Bars are means ± standard error of means. The bars sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$)

Wheat: morphological and yield parameters

The DRS-ZT treatment in both years produced the maximum productive tillers. In both years, the DRS-CT, DR-CTR, and DR-CT treatments had the most grains per spike in the wheat crop (Table 3). The DRS-ZT treatment produced the highest 1000-grain weight in both years (Table 3). The DRS-ZT and DR-ZTR treatments in 2014/15 and the DRS-ZT treatment in 2015/16 had the highest grain yields. In 2014/15, wheat planted in the DRS-CT and DR-ZTR

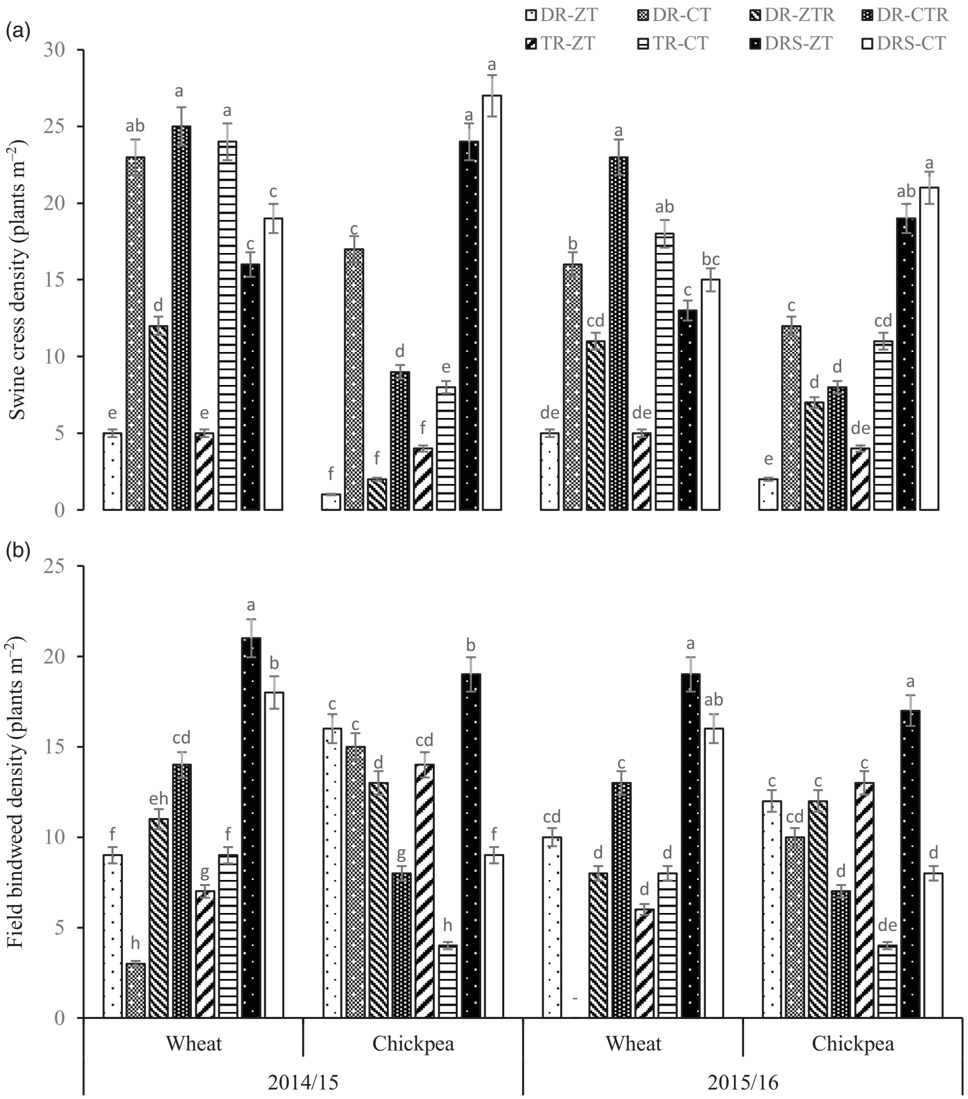

Figure 3. Influence of various rice–wheat cropping systems on (a) the density of swine cress and (b) field bindweed in wheat and chickpea.

(DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; Bars are means ± standard error of means. The bars sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$)

treatments produced the highest biological yields. In 2015/16, the DRS-ZT, DRS-CT, and DR-CTR treatments produced the maximum biological yields. Wheat grown in the DRS-ZT and DR-ZTR treatments in 2014/15 and the TR-CT and DR-ZTR treatments in 2015/16 had the highest harvest indices (Table 3).

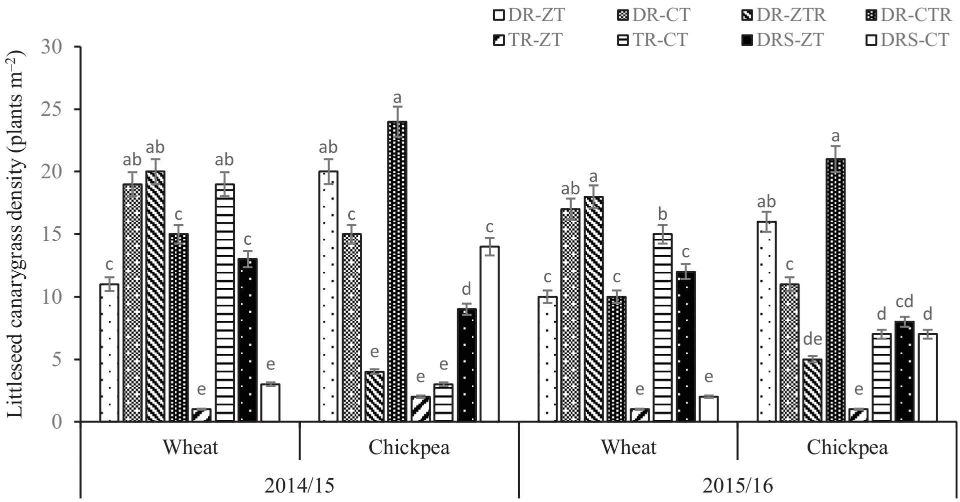

Figure 4. Influence of various rice–wheat cropping systems on the density of littleseed canarygrass in wheat and chickpea. (DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; bars are means ± standard error of means. The bars sharing the same letter during an experimental year do not differ significantly at $p \leq 0.05$)

Chickpea: morphological and yield parameters

In both years, the DRS-ZT and DR-ZTR treatments produced the most branches per chickpea plant. The DRS-ZT treatment produced the most pods per plant in both years and the DRS-ZT and DRS-CT treatments produced the most grains per pod (Table 4). In both years, the DRS-ZT and DR-ZT/CT treatments produced the highest 100-grain weights. In 2014/15, the DRS-ZT, DRS-CT, and DR-CTR treatments presented the highest grain yields. In 2015/16, the DRS-ZT and DRS-CT treatments had the highest grain yields (Table 4). In 2014/15, the DRS-CT, DRS-ZT, DR-CTR, and DR-ZTR treatments produced the most biological yield. In 2015/16, the DRS-CT and DRS-ZT treatments produced the highest biological yield. The DRS-ZT treatment had the highest harvest index in 2015/16 (Table 4).

Economics

For both wheat and chickpea, the DRS-ZT treatment produced the highest net benefits and benefit:cost ratio (averaged over 2 years), while crop growth after TR-CT had the lowest (Table 5).

Discussion

The rice-based cropping systems and different tillage practices used in this study for wheat and chickpea crops significantly affected weed dynamics, soil physio-chemical properties, grain yield, and profitability. Soil analysis after rice harvest indicated that the rice production systems (TR and DR) triggered a series of changes in soil quality (Table 1). Puddling enhanced soil bulk density and reduced soil porosity (Table 1). Indeed, puddling deteriorates soil physical properties (McDonald *et al.*, 2006) due to the formation of hardpan that causes subsurface compaction (Saharawat *et al.*, 2010) and increases soil bulk density (Farooq and Nawaz, 2014; Nawaz *et al.*, 2019). Puddling-induced compaction reduces soil porosity by changing pore size distribution and aggregate

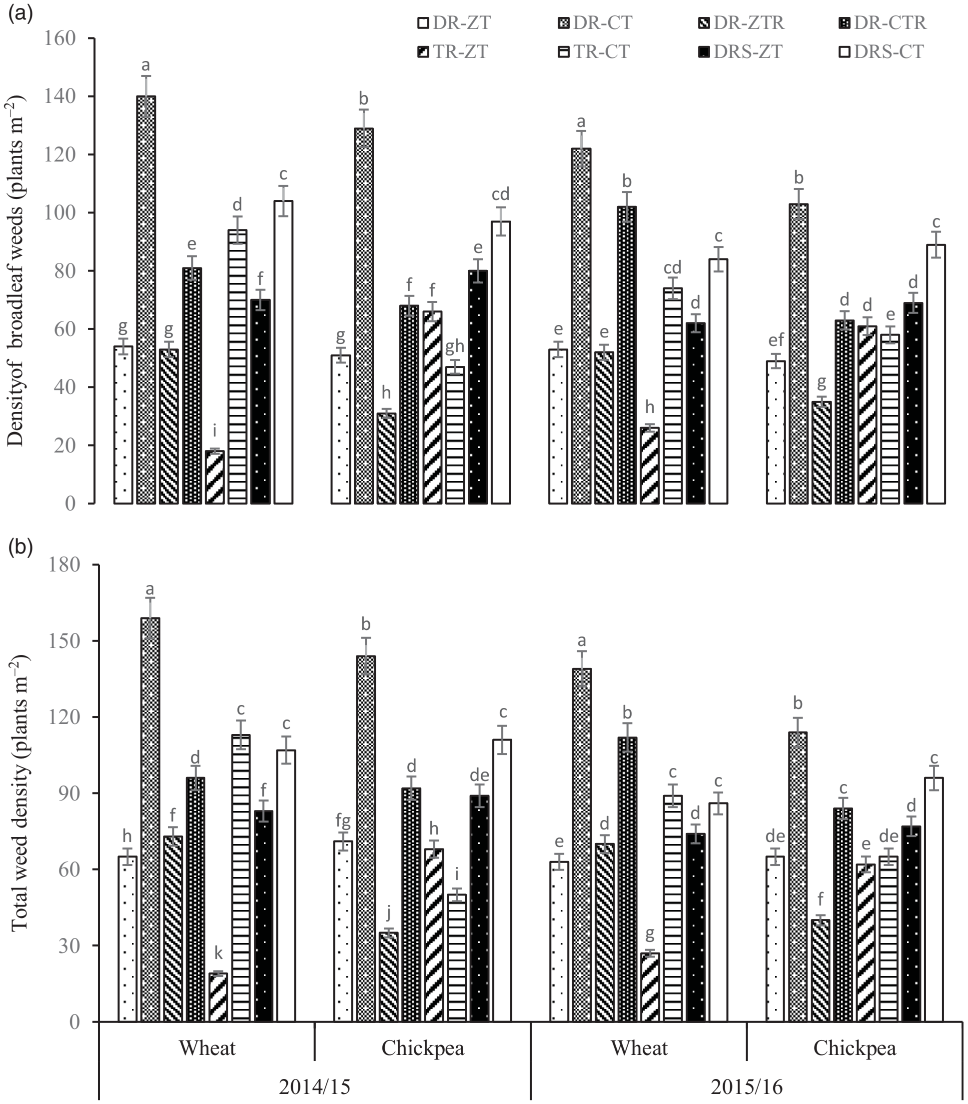

Figure 5. Influence of various rice–wheat cropping systems on the densities of (a) broadleaf weeds and (b) total weeds in wheat and chickpea.

(DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; bars are means ± standard error of means. The bars sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$)

stability (Behera *et al.*, 2009) and adversely affects the soil carbon stock (Ladha *et al.*, 2003), thus resulting in poor soil quality as observed in this study. In contrast, direct-seeded rice improves soil structure, which is attributed to low soil bulk density, increased soil porosity, and improved SOC (Prasad and Balanagoudar, 2017). Moreover, sesbania brown manuring in direct-seeded rice improves soil quality by enhancing SOC and improving soil physical properties (Tables 1 and 2; Maitra and Zaman, 2017; Nawaz *et al.*, 2017b).

Table 3. Influence of various rice–wheat cropping systems on grain yield and related parameters of wheat (DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea)

	Productive tillers (m^2)		Grains per spike		1000-grain weight (g)		Grain yield (t ha^{-1})		Biological yield (t ha^{-1})		Harvest index (%)	
Treatments	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16
DR-ZT	243e	248e	34.3cd	34.6cd	40.0b	38.8b	4.0bc	4.0bc	9.7bc	10.2b	38.4ab	41.2a
DR-CT	241f	238f	41.5a	41.9a	38.7b	37.5bc	3.5d	3.5d	11.1ab	11.2ab	28.7cd	33.0bc
DR-ZTR	276c	282c	37.3c	37.7c	39.3b	38.1b	4.9a	4.3b	10.9b	10.4b	41.5a	43.3a
DR-CTR	261d	266cd	42.3a	42.7a	37.3bc	36.2c	4.4b	4.0bc	12.3a	12.4a	33.4bc	33.9bc
TR-ZT	235f	239f	40.1ab	40.5ab	37.0bc	35.9c	2.9e	3.1e	8.1c	8.5c	32.3c	38.8ab
TR-CT	219g	225fg	36.4c	36.8c	36.0bc	34.9c	3.6cd	3.5d	8.9c	8.5c	37.3b	43.5a
DRS-ZT	361a	368a	37.0c	37.4c	43.5a	42.2a	5.2a	5.0a	11.0ab	13.2a	44.2a	39.3ab
DRS-CT	341b	348b	42.9a	43.3a	39.7b	38.5b	4.6ab	4.4b	13.1a	12.6a	33.3bc	36.6b
LSD ($p \leq 0.05$)	11.7		2.95		2.60		0.42		1.1		4.41	

Treatments sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$.

Table 4. Influence of various rice–wheat cropping systems on grain yield and related parameters of chickpea (DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea)Treatments sharing the same letter for a given variable during an experimental year do not differ significantly at $p \leq 0.05$

	Branch number per plant		Pod number per plant		Seed number per pod		100-grain weight (g)		Grain yield (t ha^{-1})		Biological yield (t ha^{-1})		Harvest index (%)	
Treatments	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16	2014/15	2015/16
DR-ZT	3.8b	4.1ab	36.3c	37.0c	1.47ab	1.46ab	25.53b	25.27b	2.48bc	2.55b	5.90ab	5.78b	42.0bc	44.1b
DR-CT	3.4bc	3.7b	31.2 d	31.8d	1.43ab	1.42b	23.50c	23.27c	2.33bc	2.40bc	6.10ab	5.98ab	38.2d	40.1c
DR-ZTR	4.6a	4.7a	40.6b	41.4b	1.50 ab	1.49ab	27.80a	27.52a	2.59b	2.67ab	6.22a	6.10ab	41.6c	43.8bc
DR-CTR	3.9b	4.2ab	37.2c	37.9c	1.47ab	1.46ab	24.33bc	24.09bc	2.51ab	2.59b	6.34a	6.21ab	39.6cd	41.7c
TR-ZT	3.7b	3.9b	29.3 de	29.9de	1.33bc	1.32bc	25.30b	25.05b	2.07d	2.13cd	5.70bc	5.59bc	36.3de	38.1d
TR-CT	3.6bc	3.7b	27.8e	28.4e	1.27c	1.26c	23.20c	22.97cd	2.04d	2.10cd	5.79bc	5.67bc	35.2e	37.0de
DRS-ZT	5.0a	5.1a	44.2a	45.1a	1.63a	1.61a	28.23a	27.95a	2.92a	3.01a	6.40a	6.27a	45.6b	48.0a
DRS-CT	4.1ab	4.3ab	39.8b	40.6b	1.57a	1.55a	25.98b	25.82b	2.74ab	2.82a	6.80a	6.66a	40.3c	42.3bc
LSD ($p \leq 0.05$)	0.63		2.29		0.12		1.34		0.22		0.54		2.31	

Table 5. Economic analysis of wheat and chickpea grown in different rice-based cropping systems (DR-ZT = direct-seeded rice followed by zero tillage wheat or chickpea; DR-CT = direct-seeded rice followed by conventional tillage wheat or chickpea; DR-ZTR = direct-seeded rice followed by zero tillage wheat or chickpea with residue mulch from previous rice crop; DR-CTR = direct-seeded rice followed by conventional tillage wheat or chickpea with residue mulch from previous rice crop; TR-ZT = puddled transplanted rice followed by zero tillage wheat or chickpea; TR-CT = puddled transplanted rice followed by conventional tillage wheat or chickpea; DRS-ZT = sesbania incorporation in direct-seeded rice followed by zero tillage wheat or chickpea; DRS-CT = sesbania incorporation in direct-seeded rice followed by conventional tillage wheat or chickpea; wheat grain = $12.38/40 kg; chickpea grain = $34.28/40 kg; wheat straw = $1.45/40 kg; chickpea straw = $0.57/40 kg; $ 1 = 105 PKR; For economic analysis, the grain and straw yields are reduced as recommended by CIMMYT. (1988)]

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Adjusted grain yield (kg ha^{-1})	Adjusted straw yield (kg ha^{-1})	Gross income ($ ha^{-1})	Total cost ($ ha^{-1})	Net benefits ($ ha^{-1})	Benefit:cost ratio
Wheat								
DR-ZT	4200	5750	3780	5175	1358	983	375	1.38
DR-CT	3700	7450	3330	6705	1274	1011	263	1.26
DR-ZTR	4800	5850	4320	5265	1528	998	530	1.53
DR-CTR	4400	7950	3960	7155	1485	1029	456	1.44
TR-ZT	3200	5100	2880	4590	1058	957	101	1.11
TR-CT	3750	4950	3375	4455	1206	1093	113	1.10
DRS-ZT	5300	6800	4770	6120	1698	1011	687	1.68
DRS-CT	4700	8150	4230	7335	1575	1010	565	1.56
Chickpea								
DR-ZT	2515	5840	2264	5256	2015	863	1152	2.33
DR-CT	2365	6040	2129	5436	1902	900	1002	2.11
DR-ZTR	2630	6160	2367	5544	2108	866	1242	2.43
DR-CTR	2550	6275	2295	5648	2048	905	1143	2.26
TR-ZT	2100	5645	1890	5081	1693	853	840	1.99
TR-CT	2070	5730	1863	5157	1671	974	697	1.72
DRS-ZT	2965	6335	2669	5702	2369	875	1494	2.71
DRS-CT	2780	6730	2502	6057	2231	884	1347	2.52

In this study, switching from a conventional tillage system to a zero tillage system in rice-based cropping affected total N, available P, exchangeable K, and total SOC. The DRS-ZT treatment had the highest SOC, total N, available P, and exchangeable K followed by the DRS-CT, DR-ZTR, DR-CTR, and DR-ZT treatments in the rice–wheat and rice–chickpea cropping systems (Table 2). Sesbania brown manuring in direct-seeded rice improved soil fertility, possibly due to the rapid decomposition of sesbania surface mulch which enhanced the available N, P, and K and substantially improved the SOC (Nawaz *et al.*, 2017b; Iliger *et al.*, 2017). Sesbania is the fast-growing legume that forms a symbiotic relationship with gram-negative bacteria to develop nitrogen-fixing nodules in the stem and roots (Capoen *et al.*, 2010) and thus increase the soil nutrient pool. Moreover, manuring with legume crops enhances soil porosity and improves soil aggregation and soil water holding capacity, thereby improving soil quality.

In this study, residue retention of the rice crop in post-rice wheat or chickpea improved the SOC in the wheat and chickpea crops, which is attributed to the accelerated activities of soil microbes that hasten residue decomposition (Das *et al.*, 2017). Increases in N, P, and K concentrations with zero tillage may be due to the release of nutrients as the residue decomposes. Less soil disturbance in zero tillage and the decomposition of surface-retained residues enhanced the nutrient pool in the rhizosphere (Bertol *et al.*, 2007), resulting in better root uptake of these nutrients. Further, zero tillage followed by sesbania brown manuring in direct-seeded rice increased the concentration of available N, P, and K nutrients (Table 2) in the root zone, and is known to improve SOC, and reduce soil bulk density to improve soil health (Maitra and Zaman, 2017). Soil fertility was improved more with chickpea than wheat in the DRS-ZT, DR-ZT, and DR-ZTR treatments (Table 2) because chickpea is a leguminous crop that can fix biological N to help restore the N balance, maintain soil fertility, and increase soil SOC (Mohammadi *et al.*, 2010).

Different tillage systems in rice-based cropping systems significantly affect weed dynamics. Overall, the TR-ZT, DR-ZTR, and DRS-ZT treatments had less weed flora. The DR-CT treatment had the highest densities of toothed dock and blue pimpernel, and the DR-CTR and DRS-ZT treatments had the highest densities of common lambsquarter, swine cress, and field bindweed (Figures 1 to 4). Surface residue retention in zero tillage acts as a physical barrier to the germination of weed seeds. Further, allelochemicals released from the residue of rice mulch may inhibit weed seed germination (Afridi *et al.*, 2014), which may explain the reduced weed infestation in the DR-ZTR treatment (Figures 1 to 5). Surface residue acts as a mulch and induces changes in the soil micro-environment that minimize soil temperature variations and prevent light stimulus (Franke *et al.*, 2007) and substantially reduce weed emergence and density, as observed in this study. Reduced weed infestations in zero tillage systems followed by transplanted rice may be due to a reduction in weed seed viability under flooding conditions, for example, common lambsquarter (Farooq and Nawaz, 2014). Seed viability of littleseed canarygrass and toothed dock declines when exposed to light and fluctuating temperature (Farooq and Nawaz, 2014), which may have reduced its germination in the wheat and chickpea crops, as observed in conventional tillage (Figure 4). Conventional tillage followed by direct-seeded rice enhanced the emergence of weed seeds as the plow tillage disturbs the soil and brings weed seeds to shallower depths, exposing them to temperature and sunlight (Figures 1 to 5; Singh *et al.*, 2012), which facilitates their germination.

The DRS-ZT and DRS-CT treatments had the highest grain yields for wheat and chickpea (Tables 3 and 4). Indeed, sesbania brown manuring in direct-seeded rice improved soil physical conditions, such as increased SOC, improved soil porosity, and reduced soil bulk density (Table 1) and N, P, and K concentrations in the rhizosphere (Table 2), which enhanced growth, yield-related traits, and ultimately grain yield. Sesbania reportedly improves the soil organic matter (SOM) pool and macro- and micro-nutrient uptake (N, P, K, Zn, and Cu) in the root zone (Iliger *et al.*, 2017), which may explain the improved performance of both wheat and chickpea in this study (Tables 3 and 4). Furthermore, zero tillage provides a favorable soil environment by increasing soil storage pores (0.5–50 mm; Pagliai *et al.*, 2004) and improving soil aggregation, soil organic carbon (SOC) (Jacobs *et al.*, 2009), and soil microbial activity (Singh and Kaur, 2012), which finally enhances soil productivity and grain yield. In this study, zero tillage after sesbania brown manuring reduced the frequency of soil disturbance and damage to the soil structure. As soil surface remained covered with straw, we noticed nutrient enrichment in the plow layer by decreasing nutrient losses and adding surface SOM. Crop residues are rich in high-carbon compounds such as lignin and cellulose, sources of SOM. Upon decomposition of these residues, carbon is released that promotes soil microbial immobilization and mineralizes inorganic nutrients (Devevre and Horwath, 2000), thus enhancing soil productivity and improving grain yield. The DRS-ZT treatment for both wheat and chickpea produced the maximum net benefit and benefit: cost ratio, due to high grain yields and cost-savings in terms of tillage in this treatment.

Conclusion

Puddling and flooding in rice deteriorate the soil structure by increasing soil bulk density and decreasing soil porosity and SOC contents. While the transplanted flooded rice systems had the lowest weed flora; sesbania brown manuring, and the retention of rice crop residues in zero tillage also helped to suppress weeds. Moreover, sesbania brown manuring in direct-seeded rice and rice straw mulch in zero tillage systems improved soil properties as evidenced by the increased total N, available P, exchangeable K, and SOC, reduced soil bulk density, and increased total soil porosity. Thus, weed suppression and the better soil environment with sesbania brown manuring and zero tillage improved crop productivity, profitability, and overall performance of wheat and chickpea grown in rice-based systems. Legume incorporation in existing rice–wheat systems will improve soil health and productivity in the long term.

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