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Effect of Cropping System and Rice Residue Retention on Crop Productivity and Soil Physical Properties in Rice Based Cropping System of Bangladesh

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Abstract

Cropping systems of Bangladesh are highly diverse and cultivation costs of puddled transplanted rice (PTR) are high. Therefore, an improved system is needed to address the issues, a field experiment was conducted during 2011-2013 to evaluate system intensification with varying degrees of cropping systems and residue retention. Four cropping systems (CSE) namely CSE1: T. *boro* rice-T. *aman* rice (control), CSE2: wheat-mungbean-T. *aman* rice (wheat and mungbean sown using a power tiller-operated seeder (PTOS) with full tillage in a single pass; puddled transplanted *aman*), CSE3: wheat-mungbean-dry seeded DS *aman* rice (DSR), and CSE4: wheat-mungbean-DS *aman* rice (all sown by PTOS with strip tillage) were compared. Two levels of *aman* rice residue retention (removed; partial retention i.e. 40 cm of standing stubble) were compared in sub plots. Grain yield was significantly higher (by 11%) when wheat was grown after DSR than PTR. Similarly, PTR and DSR (*aman* rice) produced statistically similar crop yields. Rice residue retention resulted a significantly higher (by 10%) wheat yield and a slightly increased (by 6%) mungbean yield than that of residues removed. The system productivity of CSE4 was significantly higher (by 10%) than CSE1 when averaged of the two years data. Partial *aman* residue retention gave significantly higher system yield than residue removal (by 0.6 t ha^{-1}). After two years, no effect of CSE or partial *aman* residue retention was found on soil physical property (bulk density) of the top soil. Therefore, CSE4 along with residue retention would be more effective for sustainable crop production.

Keywords: Cropping system, rice residue retention, crop intensification, system productivity, soil physical properties

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1. Introduction

Rice is the staple food in Bangladesh that contributes 95% of the total food grain consumption (BBS, 2011), about two-thirds of the total calorie supply and half of the total protein intake per person (Begum and Luc D'Haese, 2010). Wheat is the second most important cereal crop that contributes 7% of the total output of food cereals (Hossain and Teixeira, 2013), with low average yield of rice and wheat compared to other countries (Bhowmik *et al.*, 2012). Although rice production has increased more than three folds in the last few decades, the country still could not attain sustainable self-sufficiency in food. The population of Bangladesh is projected to be 172 million by 2020, with rice and wheat requirements of 36.9 and 1.3 Mt, respectively, but with no scope of increasing the area under rice and wheat production (IFPRI, 2012). Therefore, there is a need to increase rice and wheat production by increasing yield and cropping system intensification.

In addition to calorific food security, malnutrition is a major problem in Bangladesh; children and women in general, and 95% of lactating mothers, are the worst affected (Kabir *et al*., 2005). From a nutritional standpoint, mungbean is a rich protein source (24.5%), two to three folds higher than the protein content of wheat and rice, contains some essential micronutrients, especially Zn, Fe, and some essential amino acids (especially lysine) that are lacking in rice and wheat (Alam *et al.*, 2017).

The major agricultural crop production systems in Bangladesh are: 1) Transplanted (T.) *boro* rice (winter)–T. *aman* rice (monsoon) and 2) wheat–T. *aman* rice cropping systems, which occupies 2.4 and 0.5 Mha, respectively (Ladha *et al*., 2003; Dawe *et al*., 2004). Over 85% of the wheat produced in Bangladesh is grown in sequence with puddled transplanted (T. *aman*) rice (Timsina and Connor, 2001). The current T. *boro* rice-T. *aman* rice and wheat-T. *aman* rice cropping systems are not sustainable because of decreasing profitability due to increasing labor and tillage costs, increasing labor scarcity, groundwater depletion, and declining soil fertility.

Agricultural soils in Bangladesh are generally poor in organic matter content due to intensive tillage, removal of crop residues, low use of organic materials and imbalanced fertilizer practices (BARC, 2012). Continuous cultivation of puddled transplanted rice in sequence with upland crops such as wheat led to declining soil organic matter and increasing deficiencies of major nutrients (N, P, K, and S) and micronutrients (Zn, Fe, and Mn) due to over mining from soils (Ladha *et al*., 2000; Tiwari, 2002). So, alternative practices for rice-based cropping systems are needed which would increase the productivity, and reduce adverse environmental effects. One potential way of achieving this is to switch to conservation agriculture (CA) practices with reduced tillage, inclusion of legume in the rotation, residue retention and crop diversification (Hobbs *et al.*, 2008).

Considering the above facts, a two year rice-based cropping system experiment was conducted in a calcerous soil of Bangladesh to evaluate the effects of reduced tillage, increased cropping intensity, the inclusion of a legume, and rice residue retention on crop growth, yield performance and soil properties.

2. Materials and Methods

2.1. Site description

The experiment was conducted during 2011-13 at the experimental farm of the Regional Agricultural Research Station (RARS) of Bangladesh Agricultural Research Institute (BARI), Jessore (23°11' N, 89°14' E and 16 m above sea level). The climate at the experimental site is subtropical monsoon with high rainfall during May to October and scanty rainfall during November to April. Annual average rainfall is 1590 mm, 90% of the total rainfall occurs from May to October and the distribution of the rainfall is uneven and unpredictable. Monthly average temperature ranges from 20 °C in January to 35 °C in April, with maximum and minimum daily values of 42 °C and 5 °C in April-May and January, respectively. Monthly mean solar radiation ranges from 13 $MJm^{-2}d^{-1}$ in December to 22 $MJm^{-2}d^{-1}$ in May. The soil at the experimental site is a calcareous brown clay loam of the High Ganges River Floodplain (BARC, 2012). Soil texture is clay loam to a depth of at least 120 cm, but clay content declines from 38% in the topsoil to 26-28% at 60-120 cm. The topsoil is slightly alkaline (pH 7.7-7.8) and with low soil organic C content of 1.0% (Alam *et al.*, 2017; 2018).

2.2. Experimental design

The experiment was laid out in a split plot design with three replications. Four cropping system/establishment method treatments (CSE) were considered as main plots as follows:

CSE1: T. *boro*-T. *aman* (control)
- both crops transplanted into puddled soil

CSE2: CT wheat-CT mungbean-T. *aman*
- conventional tillage (CT) for wheat and mungbean which were sown using a power tiller-operated seeder (PTOS) in a single pass with full tillage; *aman* transplanted into puddled soil

CSE3: CT wheat-CT mungbean-CTDS *aman*
- conventional tillage (CT) for all crops including dry seeded (DS) *aman*, using a PTOS in a single pass with full tillage

CSE4: ST wheat-ST mungbean-STDS *aman*
- as for CSE3 but using strip tillage (ST) for all crops

Two levels of *aman* residue retention such as removed at ground level (-R), and partial retention (+R, 40 cm of standing stubble)-were compared as sub-plot treatments.

2.3. Crop management

All the crops were well managed following recommended management practices. Further details on management of the wheat, mungbean and T. *boro* was provided as described by Alam *et al*. (2017), while management of the dry seeded and puddled transplanted *aman* rice was outlined by Alam *et al*. (2018).

2.4. Crop monitoring

2.4.1. Crop growth

Tiller density and biomass were determined at the start of tillering, mid-tillering (MT), panicle initiation (PI) (only for rice), anthesis and physiological maturity (PM) stages on plants collected from 2 × 0.5 m rows in two locations in each sub plot (for wheat and DSR) and from 2 × 0.6 m rows in two locations for transplanted rice. The total number of tillers in each sample was counted. The plants were dried in an oven at 70 °C for 3-5 days until the weight was constant and weighed. Tiller density (no. m^{-2}) and dry biomass (t ha^{-1}) were calculated by dividing the total number of tillers and total biomass by the sample area (0.4 m^2 for wheat and DSR, 0.48 m^2 for transplanted rice).

2.4.2. Yield

Grain yield was determined by harvesting a 16 m^2 (for rice and wheat) and 15.6 m^2 (mungbean) area in the centre of each sub-plot. The grain was manually threshed and fresh grain and straw weights were determined. Grain moisture content was determined on 3 × 100 grain sub-samples using a grain moisture meter (Model: GMK-303RS) at the time of weighing. Fresh grain yield was converted to grain yield (t ha^{-1}) at 12% moisture content (for wheat), 14% (for rice) and 10% (for mungbean) using the following formula:

Grain yield (t ha^{-1}) at x% moisture content =

$$\frac{(100 - \text{moisture}\%) \times \text{Fresh grain weight (kg)} \times 10000}{(100 - x) \times 16 \text{ or } 15.6 \times 1000}$$

Where, x is adjusted moisture (for rice, wheat and mungbean @ 14, 12 and 10%, respectively)

2.5. System rice equivalent yield

Rice equivalent yield (REY) of wheat and mungbean was calculated from the grain yield and price of each crop using the formula:

REY (crop $_\chi$) = $Y_\chi \, (P_\chi / P_r)$

where, Y_χ is the yield of crop 'x'(t grain ha^{-1}at the above moisture content for that crop), P_χ is the price of crop 'x' (USD t^{-1}) andP_r is the price of rice (Biswas *et al.*, 2006).

2.6. System energy output

Total system energy output was estimated using energy equivalents as suggested by many scientists (Khan and Hossain, 2007; Shahin *et al*., 2008). The energy output was calculated by totalling the energy value of both the main product and by-products.

2.7. Soil properties

2.7.1. Soil water tension

Soil water tension (SWT, kPa) was determined daily at 9 am at depths of 7.5, 22.5, 37.5, 52.5 and 75 cm for wheat and mungbean, and 7.5, 22.5, 37.5 cm for DSR *aman* rice, throughout the season, using vacuum gauge tensiometers (IRROMETER). Soil tension was determined after correcting for the head of water in the tensiometer as follows (Alam, 2016):

soil tension (kPa) =

$$\frac{\text{Tensiometer reading (kPa)} - \rho hg}{100}$$

Where, ρ = the density of water (1 g cm^{-3})
h = height of tensiometer (m)
g = acceleration due to gravity (9.8 ms^{-2}).

2.7.2. Bulk density

Bulk density of the soil profile was determined by digging a pit in buffer areas during the first wheat crop. Soil samples were collected at depths of 0-15, 15-30, 30-60, 60-90 and 90-120 cm using steel cylinders (diameter 5.5 cm, length 4.3 cm). The rings were hammered into the sides of the pits. The cores were carefully trimmed, cleaned, weighed, oven-dried at 105 °C, then reweighed. Bulk density was calculated using the formula:

Bulk density (g cm^{-3}) =

$$\frac{\text{Weight of oven dried soil (g)}}{\text{Volume of core (cm}^3\text{)}}$$

2.8. Weather data

Daily maximum and minimum temperature, rainfall and sunshine hours during the experimental period were collected from the weather station, Bangladesh Meteorological Department (Jessore) located about 5 km from the experimental site. Long term weather records (1948 to 2010) were also acquired from the same weather station. Solar radiation was calculated from daily sunshine hours using the Angstrom Formula (Sys *et al*,. 1991).

2.9. Statistical analysis

Data were analyzed by ANOVA (using Crop Stat 7.2) to evaluate differences between treatments, and the means were separated using least significant difference (LSD) at the 5% level of significance ($p<0.05$).

3. Results

3.1. Crop environment

Monthly mean rainfall, temperature, sunshine hour and solar radiation for the crops wheat, T. *boro*, mungbean and *aman* rice are presented in Figs 1a, b and 2a-d. The total amount of rainfall in both the year were also lower than the long term average (Figs. 1a, b; 2a). Monthly mean daily maximum and minimum temperatures in both seasons were usually lower than the longterm averages, and the second season was generally cooler than the first season (by 3-5 °C in November and January, with several frost days in January) (Fig. 2b). Mean monthly daily sunshine hours were much low compared to that of the long term average (by 30-50% in November-January), and lower in 2011-2012 than in 2012-2013 in November-January (Fig. 2c). Each season, solar radiation during the grain filling period (Feb-Mar/April in wheat and T. *boro*) was much high than that during the vegetative stage. Sunshine hours and solar radiation during 2012 and 2013 *aman* crops were lower than the long term average throughout the season (Fig. 2d).

3.2. Crop performance

3.2.1. Wheat

3.2.1.1. Tiller density

There was no significant effect of crop establishment method on tiller density at any stage, but rice residue retention had significant but variable effects on tiller density (Figs. 3a-d). In 2011-2012, tiller density increased to 584 tillers m^{-2} at 35 DAS, and then declined to 421 tillers m^{-2} at anthesis (28% tiller mortality), with little further change thereafter. On the other hand, in 2012-2013, tiller density was lower (16%) with rice residues retained than removed, and this was also the case at mid tillering (MT). However, from MT to anthesis tiller mortality was higher with residues (19%) than without residues (7%) which resulted in significantly higher tiller density in the residue retained treatments at anthesis and maturity. Tiller density was always lower in 2012-2013 than in the previous year, with final tiller densities at PM of 317 and 404 m^{-2} in 2012-2013 and 2011-2012, respectively.

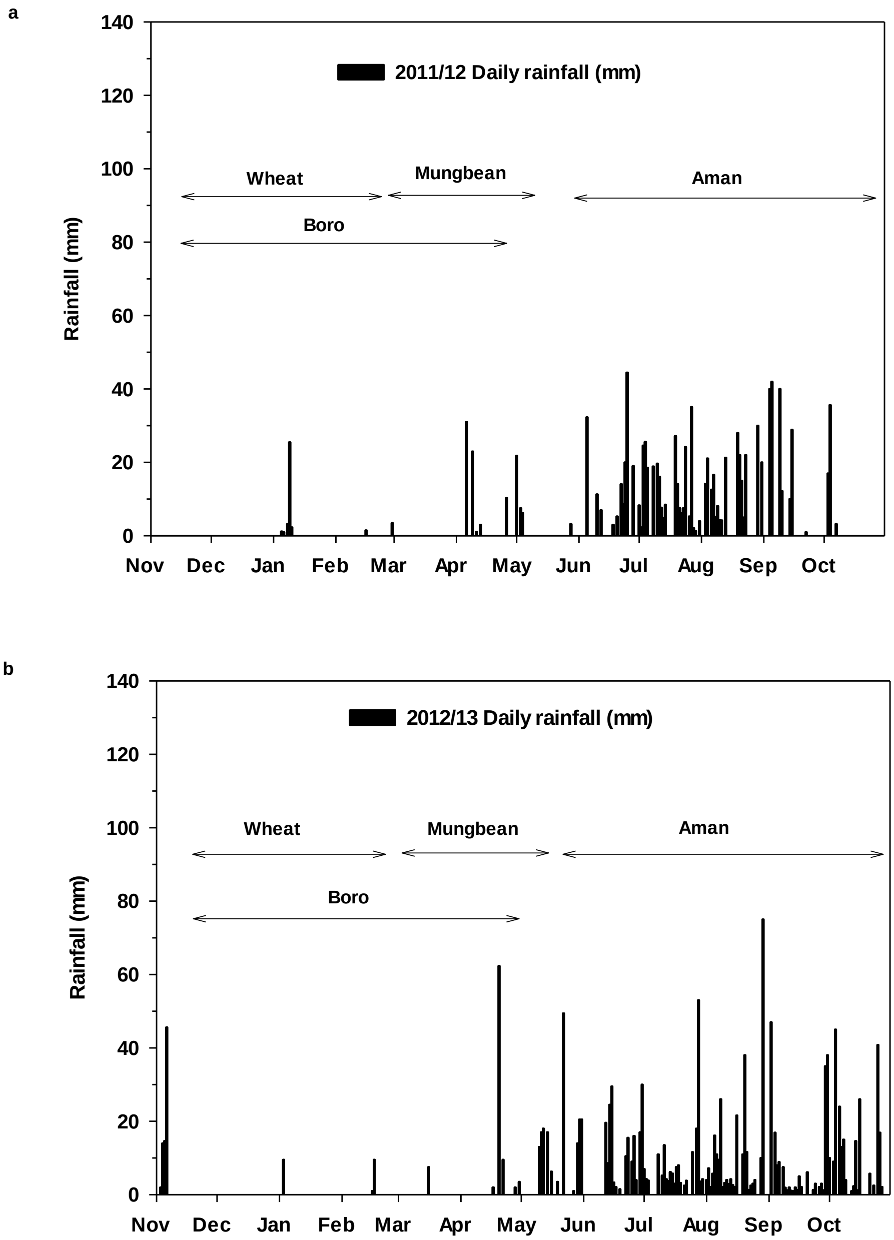

Figure 1. Distribution of rainfall at the experimental site in (a) 2011-2012 and (b) 2012-2013.

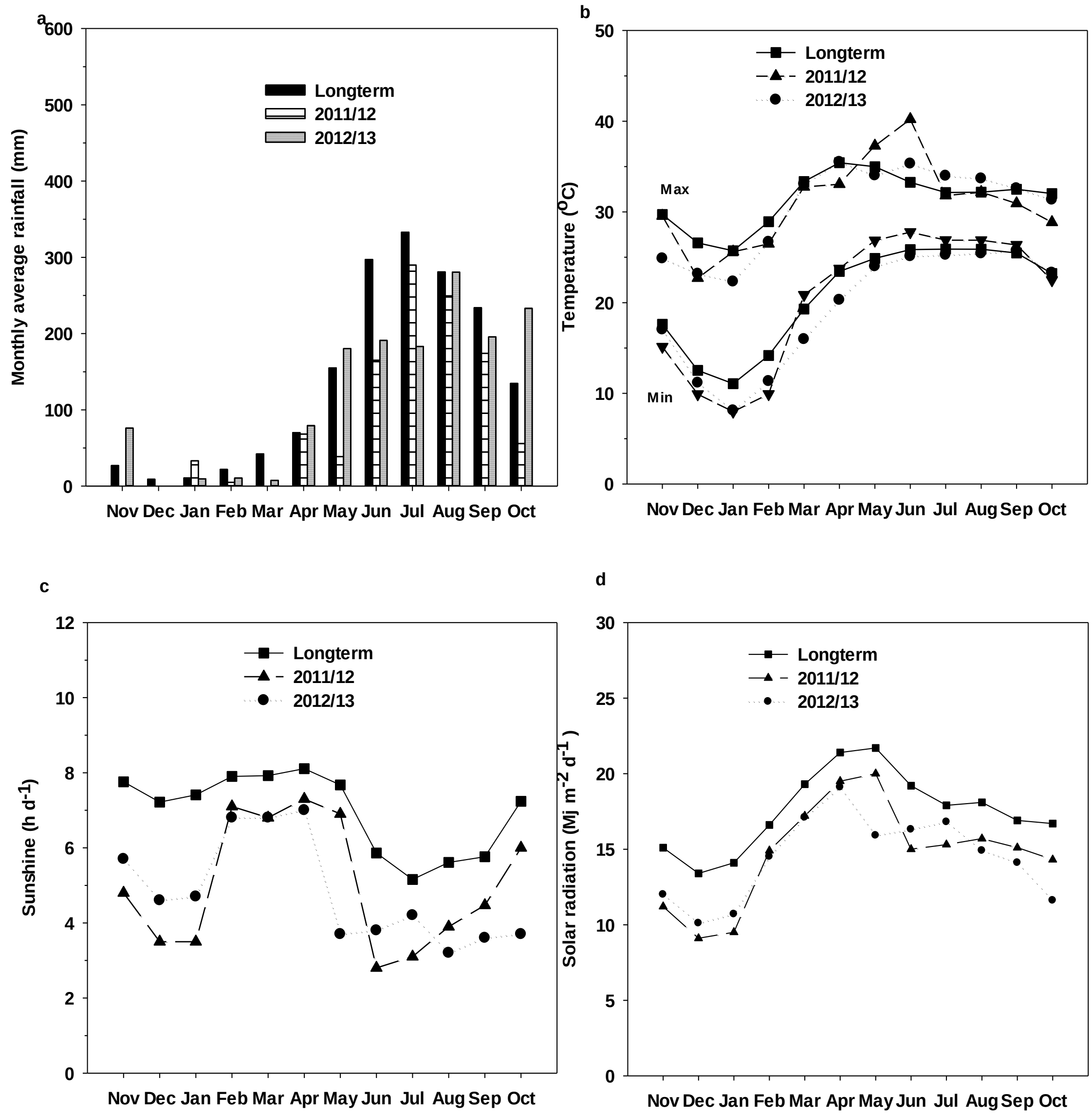

Figure 2. (a) Monthly rainfall (mm), (b) monthly mean maximum and minimum temperature,(c) monthly mean daily sunshine hours, (d) monthly mean solar radiation during the 2011-2012 and 2012-2013 crop seasons in comparison to the long term (1948-2010) at the Bangladesh Meteorological Department station at Jessore.

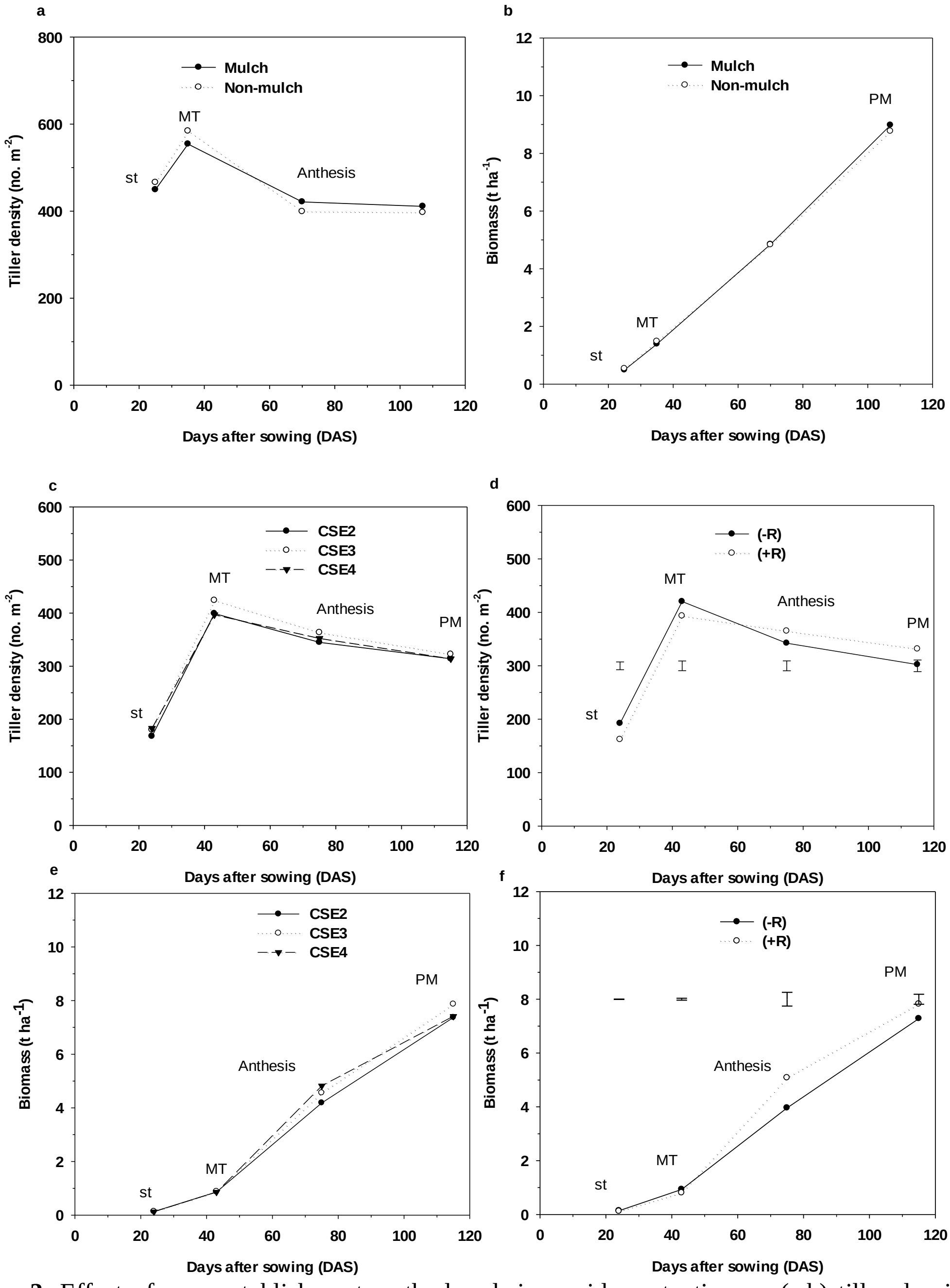

Figure 3. Effect of crop establishment method and rice residue retention on (a,b) tiller density and biomass production in 2011-2012, (c,d) tiller density in 2012-2013, and (e,f) biomass production in 2012-2013 during wheat season (vertical bars are LSD (p=0.05) for comparing treatment means within sampling date).

3.2.1.2. Biomass

As for tiller production, there was no significant effect on above ground biomass (Figs. 3e, f). In 2011-2012, the average rate of biomass production was 69 kg $ha^{-1}d^{-1}$ between sowing and anthesis, and 109 kg ha^{-1} d^{-1} between anthesis and PM. In 2012-2013, the rate of biomass accumulation was significantly higher without straw (23 kg ha^{-1} d^{-1}) from establishment to MT than with straw (20 kg ha^{-1} d^{-1}). From MT to anthesis, the biomass accumulation rate was significantly higher with residues retained (146 kg ha^{-1} d^{-1}) to than without (110 kg ha^{-1} d^{-1}), while rates were similar in both treatments from anthesis to PM stage (73 kg ha^{-1} d^{-1}). The net result was significantly higher in final total biomass (7.8 t ha^{-1}) with residues retained than with residues removed (7.3 t ha^{-1}). Total biomass at anthesis (5.1 t ha^{-1}) with residue retention was similar to total biomass in both treatments in 2011-2012 (4.8 t ha^{-1}). At PM, total biomass with residue retention was also higher in 2011-12 (8.9 t ha^{-1}) than in both treatments in 2012-2013 (7.8 t ha^{-1}).

3.2.2. Aman rice

3.3.2.1. Tiller density

Tiller density of DSR was significantly higher than that of PTR at the vegetative stage in both the years, with the maximum observed difference at MT (~836 tillers m^{-2} in 2012 and ~919 tillers m^{-2} in 2013, respectively) (Fig. 4a, b). The rate of tiller mortality in DSR was very high (~47% in 2012 and ~59% in 2013) between MT and anthesis, compared with mortality in PTR (~31% in 2012 and ~39% in 2013) between PI and anthesis. Tiller mortality with both establishment methods was higher in 2013 than in 2012 (49 and 39% in DSR and PTR, respectively). At PM, tiller density averaged 246 and 347 m^{-2} in PTR and DSR, compared with 241 and 403 m^{-2} in 2012, respectively. Tillage method had no effect on tiller density of DSR in the wheat-mung-rice system, and cropping system had no effect on tiller density of PTR. There were no effects of *aman* residue management on tiller density.

3.3.2.2. Biomass

As in 2012, early biomass accumulation was greater in DSR (73 kg ha^{-1} d^{-1} in 2012 and 83 kg ha^{-1} d^{-1} in 2013) than that in PTR (57 kg ha^{-1} d^{-1} in 2012 and 64 kg ha^{-1} d^{-1} in 2013), resulting in significantly higher biomass at MT in DSR (Figs. 4 c,d). However, between MT and anthesis, growth rate was greater in PTR (315 kg $ha^{-1}d^{-1}$ in 2012 and 327 kg ha^{-1} d^{-1}in 2013) than DSR (99 kg $ha^{-1}d^{-1}$ in 2012 and 92 kg ha^{-1} d^{-1} in 2013), resulting in similar biomass at anthesis. The net result was similar for final biomass in PTR and DSR (mean 10.3 t ha^{-1} in 2013) compared with 9.7 t ha^{-1} in 2012. Tillage method had no effect on biomass of DSR at any stage in the wheat-mungbean-rice system, and cropping system had no effect on biomass of PTR. There were no effects of residue management on biomass in any of the year.

3.3. Rice equivalent system yield

There were no significant interactions between cropping system/establishment method on rice equivalent system yield each year (Table 1). Furthermore, there were no significant CSE x R x year interactions, therefore, it is valid to compare the treatment means averaged over the 2 years. There was a consistent trend for higher rice equivalent system yield of the three wheat-mungbean-*aman* systems (CSE 2, 3, 4) than that of the *boro*-*aman* system (CSE1), with significant differences in the first year and when the data were pooled over the two years (means of 14.6-15.0 t ha^{-1} in CSE 2, 3, 4 compared with 13.4 t ha^{-1} in CSE 1). There was also a trend for higher system yield with *aman* rice residue retention with significant differences in the second year and when averaged over the two years (14.1 vs 14.7 t ha^{-1} for residues removed or retained, respectively).

3.4. Energy output (grain, harvested straw)

There was no interactions between CSE and *aman* residue management on energy output of any crop each year, not on the total system, and there was no significant CSE x R x year interaction (Table 2). Energy output of the *boro*-*aman* system (mean 354 GJ ha^{-1} over the 2 years) was significantly higher (by an average of around 20%) than of the wheat-mungbean-*aman* systems each year. Removal of *aman* rice residues also resulted in higher energy output each year (by about 10%) due to the fact that the energy value of the retained residues was not included as an energy output.

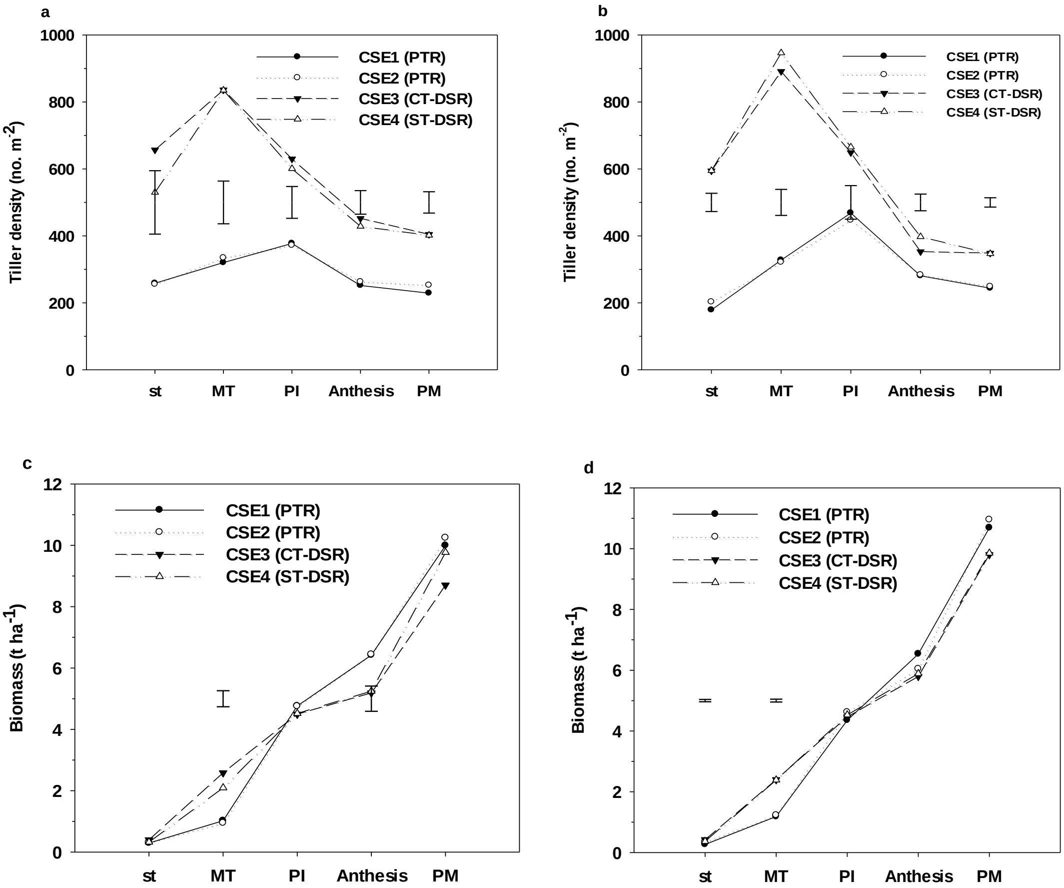

Figure 4. Effect of crop establishment method on (a) tiller density 2012 (b) tiller density 2013, (c) biomass production 2012, and (d) biomass production 2013 of *aman* rice (vertical bars are $LSD_{0.05}$ for comparing main treatment effects at each stage).

3.5. Soil properties change

3.5.1. Soil water tension

3.5.1.1. Wheat

There were significant interactions between CSE, residue treatment and soil depth on soil water tension (SWT) at different dates of with very small lsd (0.8 kPa). For simplicity, the data for the residue retained and removed treatments are presented in two separate figures for CSE3 (Figs. 5a-d). As in 2011-12, the soil dried fastest nearest the surface and the rate of soil drying decreased as depth increased. Throughout the wheat season, the degree of soil drying at 52.5-75 cm was small, with soil tension never exceeding 25 kPa. There was a trend for faster soil drying with residues removed, more so in the top soil, but the differences were never significant. The degree of soil drying at 22.5 cm was less in 2012-2013 than in 2011-2012.

Table 1. Effect of CSE and rice residue retention on yield of individual crops and on annual cropping system rice equivalent yield (t ha^{-1}) during 2011-12 and 2012-13, and averaged over the 2 years.

Crop/ system[1]		Wheat (2011/2)[1]	*Boro* (2011/2)	Mung (2012)[2]	*Aman* (2012)[3]	System rice equiv. yield[4]	Wheat (2012/3)[1]	*Boro* rice (2012/3)	Mung (2013)[2]	*Aman* (2013)[3]	System rice equiv. yield[4]	Mean
Mean												
	CSE1	NA	8.49	NA	5.24	13.7	NA	7.95	NA	5.18	13.1	13.4
	CSE2	4.29	NA	1.41	5.28	15.7	3.59	NA	1.29	5.22	14.3	15.0
	CSE3	4.26	NA	1.24	5.01	14.8	4.03	NA	1.24	4.91	14.4	14.6
	CSE4	4.26	NA	1.27	5.07	15.0	3.93	NA	1.24	4.94	14.3	14.7
	(-R)	4.19	8.29	1.32	5.09	14.7	3.67	7.51	1.22	5.03	13.6	14.1
	(+R)	4.35	8.70	1.29	5.21	15.0	4.03	8.38	1.29	5.10	14.5	14.7
CSE1 -R	PT *boro*-PT a*man*	-	8.29	-	5.10	13.4	-	7.51	-	5.12	12.6	13.0
CSE1 +R	PT *boro*-PT *aman*	-	8.70	-	5.38	14.1	-	8.38	-	5.24	13.6	13.9
CSE2-R	CTwheat-CTmung-PT *aman*	4.17		1.40	5.20	15.4	3.41		1.24	5.15	13.8	14.6
CSE2+R	CTwheat-CTmung-PT *aman*	4.40		1.41	5.37	16.0	3.77		1.33	5.29	14.8	15.4
CSE3-R	CTwheat-CTmung-DS *aman*	4.14		1.27	5.00	14.8	3.82		1.21	4.90	14.0	14.4
CSE3+R	CTwheat-CTmung-DS *aman*	4.37		1.21	5.02	14.9	4.24		1.28	4.92	14.8	14.9
CSE4-R	STwheat-STmung-ST *aman*	4.26		1.30	5.05	15.0	3.79		1.2	4.93	14.0	14.5
CSE4+R	STwheat-STmung-ST *aman*	4.27		1.25	5.08	14.9	4.07		1.27	4.95	14.6	14.8
$LSD_{0.05}$	CSE	NA[1]	NA	NS	NS	1.3	0.3	NA	NS	NS	NS	0.9
	R	NS	NS	NS	NS	NS	0.2	NS	0.1	NS	0.5	0.3
	CSE x R	NA[1]	NA	NS	NS	NS	NS	NA	NS	NS	NS	NS

**NA=Not applicable; NS=Non significant*

Table 2. Effect of CSE and rice residue management on individual crop and annual cropping system energy output (GJ ha^{-1}) during 2011-12 and 2012-13 and averaged over both years.

Crop/system[1]		Wheat (2011/2) [1]	*Boro* (2011/2)	Mung (2012)[2]	*Aman* (2012)[3]	System energy output[4]	Wheat (2012/3)[1]	*Boro* (2012/3)	Mung (2013)[2]	*Aman* (2013)[3]	System energy output[4]	Mean
Means												
	CSE1	NA	238	NA	142	380	NA	185	NA	143	329	354
	CSE2	133	NA	18	144	296	113	NA	17	146	276	286
	CSE3	140	NA	16	131	287	124	NA	15	131	270	279
	CSE4	134	NA	17	136	287	113	NA	15	132	260	274
	(-R)	134	232	17	159	331	111	176	16	156	295	313
	(+R)	137	244	17	117	293	122	195	16	120	273	283
CSE1 -R	PT *Boro*-PT *Aman*	-	232	-	162	394	-	176	-	163	339	367
CSE1 +R	PT *Boro*-PT *Aman*	-	244	-	121	365	-	195	-	124	319	342
CSE2-R	CTwheat-CTmung-PT *aman*	126		18	170	314	108		17	165	289	302
CSE2+R	CTwheat-CTmung-PT *aman*	140		18	119	277	118		17	128	263	270
CSE3-R	CTwheat-CTmung-DS *aman*	138		17	150	304	118		15	147	280	292
CSE3+R	CTwheat-CTmung-DS *aman*	143		16	112	270	131		15	116	261	266
CSE4-R	STwheat-STmung-ST *aman*	139		17	156	312	109		15	150	273	293
CSE4+R	STwheat-STmung-ST *aman*	130		16	116	262	118		15	115	248	255
$LSD_{0.05}$	CSE	NA[1]	NA	2.8	NS	28.3	6.2	NA	1.7	NS	28.1	25.1
	R	NS	NS	NS	6.3	10.1	4.1	NS	NS	4.7	9.9	6.7
	CSE x R	NA[1]	NA	NS	NS	NS	NS	NA	NS	NS	NS	NS

**NA=Not applicable ; NS=Non significant*

1 kg rice grain, wheat grain, mungbean grain, rice straw, wheat straw and mungbean biomass produced energy of 14.7, 14.7, 15.5, 15.6, 15.8 and 12.5 MJ (adopted from Khan and Hossain, 2007 and Shahin et al., 2008).

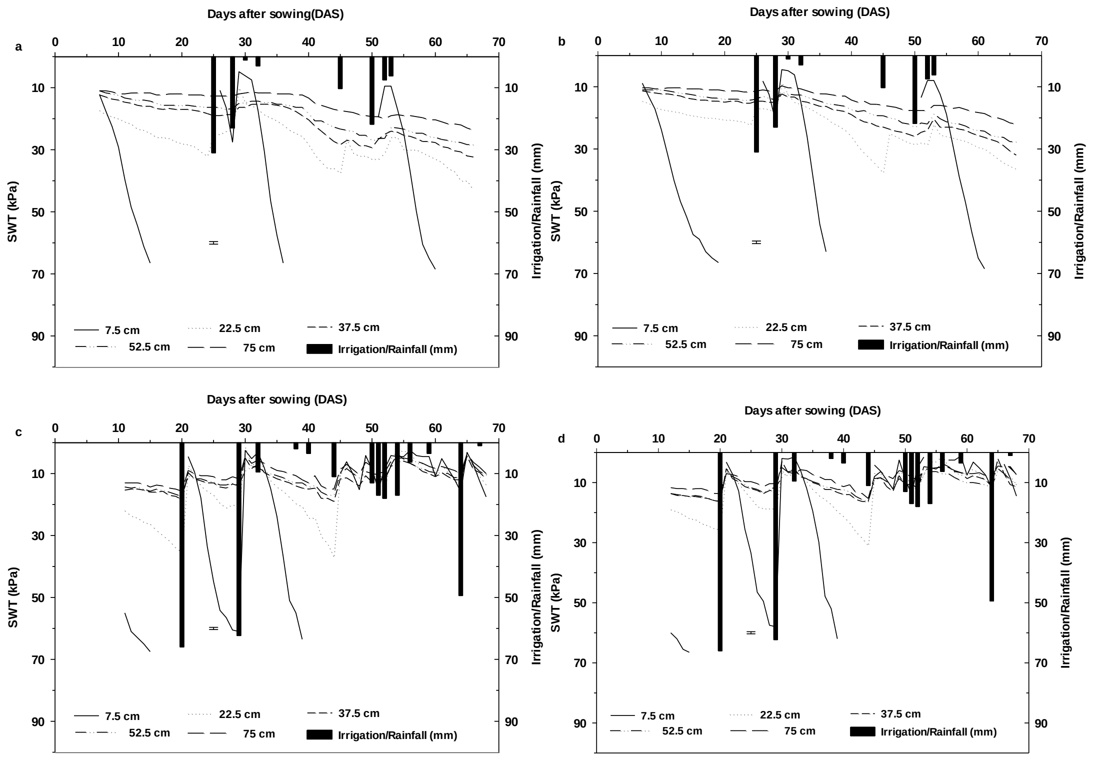

Figure 6. Soil water tension status at 7.5, 22.5, 37.5, 52.5 and 75 cm depth in conventional tillage (a) without residue 2012 (b) with residue 2012 (c) without residue 2013 (b) with residue 2013 treatment during mungbean season (Vertical bars are $LSD_{0.05}$ for comparing different depths).

3.5.1.2. Mungbean

There were significant interactions between CSE, residue treatment and soil depth on soil water tension (SWT) at many measuring dates, with very small lsd (0.8 kPa in 2012 and 0.7 kPa in 2013). For simplicity, the data for the residue retained and removed treatments are presented in two separate figures for CSE3 only (Figs. 6a-d). In 2012, the soil dried fastest nearest the surface and the rate of soil drying decreased as depth increased. Throughout the mung season, the degree of soil drying below 22.5 cm was small, with soil tension never exceeding 30 kPa. There was a slight tendency for the soil to dry more slowly with rice residue retention than removal after irrigation or rainfall in the upper soil layers, but the differences were never significant.

3.5.2 Soil bulk density

There were no significant two-or three-way interactions between cropping system/ establishment method, residue management or depth on bulk density after two years (after harvest of the second *aman* crop). Nor were there any significant effects of CSE or residue management on bulk density (Table 3). Bulk density at 5-10 cm (1.33 g cm^{-3}) was significantly lower than bulk density at 0-5 and 10-15 cm (1.39-1.40 g cm^{-3}).

Table 3. Effects of cropping system/establishment method and *aman* residue management on bulk density after 2 years.

Crop/system[1]	BD (g cm^{-3})
Cropping system/establishment method (CSE) means	
CSE1	1.38
CSE2	1.42
CSE3	1.32
CSE4	1.38
Residue management (R) means	
(-R)	1.38
(+R)	1.37
Depth (D) means	
0-5 cm	1.39
5-10 cm	1.33
10-15 cm	1.40
LSD $_{0.05}$	
CSE	NS
R	NS
Depth	0.04
CSExR	NS
CSExD	NS
RxD	NS
CSExRxD	NS

**NS= Not significant;* [1] *CSE1= T. boro-T. aman (puddle transplanted); CSE2 = CTwheat-CTmung-T. aman (puddled transplanted); CSE3=CTwheat-CTmung-CT aman (dry seeded); CSEE4=STwheat-STmung-ST aman (dry seeded)*

4. Discussion

4.1. Effect of seasonal conditions on crop performance

4.1.1. Wheat

The lower biomass in 2012-13 was associated with lower tiller production. The lower tiller production appears to be due to the much lower plant density (170 and 119 plants m^{-2} in 2011-12 and 2012-13 respectively), and possibly also due to the cooler weather during the tillering stage in 2012-13 (Fig. 2b), which ultimately led to lower spike density, more so in the non-mulched treatment. The reasons for the lower biomass at anthesis in the without residue retention treatment in 2012-13 are not known. Biomass accumulation between anthesis and PM was much low in both the treatments in 2012-13 (2.7 and 3.5 t ha^{-1} in the residue retained and removed treatments respectively) than that in 2011-12 (4.1 t ha^{-1}). The reasons for the difference in growth rate between anthesis and PM between years are also not clear as mean February temperatures and solar radiation were similar during this period.Total biomass production (7.3 and 7.8 t ha^{-1}) and grain yield (3.7-4.3 t ha^{-1}) were also consistent with the findings of Islam *et al.* (2013) for irrigated BARI gom 26.

4.1.2. Aman rice

Temperature was generally favorable for *aman* production each year, with daily mean temperature ranging from 24 to 35 °C in 2012 and 2013. Basak (2010) reported that the optimum temperature for maximum photosynthesis ranges from 25 to 30 °C for rice under the climatic conditions of Bangladesh. Within establishment method, crop development, growth, yield and yield components of the *aman* crops were similar each year, consistent with the similar weather experienced each year in terms of temperature and solar radiation, although total solar radiation during flowering to PM was 20% (PTR) and 30% (DSR) lower in 2013 than in 2012.

4.2. Effect of cropping system establishment (CSE) methods on crop and system yield

Crop establishment method had a significant effect on yield of wheat in the second year (after the first *aman* crop), with lower yield of wheat sown after PTR (3.6 t ha^{-1}) than after DSR (4.0 t ha^{-1}) established with either conventional or strip tillage. This is consistent with the findings of studies on soils with a history of puddling (converse to the situation in the present study), where cessation of puddling and replacement with DSR results in higher yield of wheat starting with the second or third wheat crop (Jat *et al*., 2009; Gathala *et al.,* 2011). The increase in yield of wheat grown after DSR in comparison to PTR in other studies has been shown to be associated with improved soil structure in rice-wheat system (Gathala *et al.,*2011; Singh *et al.,* 2014). In contrast to wheat, there was no effect of CSE on yield of mungbean or rice in both the years. Several studies showed no effect of tillage treatments formungbean on yield when grown in a wheat-mungbean-PTR system (Islam *et al.* 2014). Reports on grain yield of well-managed DSR relative to PTR showed variable results (Kumar and Ladha, 2011). In our study, the grain yield of DSR and PTR were similar each year, consistent with the findings of Sudhir- Yadav *et al.* (2011) and Bhushan *et al.* (2007) on a range of soils (sandy to silty loam to clay loam) using safe alternate wetting and drying water management for both establishment methods.

Total system rice equivalent yield (REY) ranged from 12.6 to 16.0 tha^{-1} across years and CSE x *aman* residue treatments. There was a consistent trend for highest yield in CSE2 (the wheat-mungbean-*aman* system with PTR), with significantly higher yield than yield of CSE1 (the puddled transplanted *boro*-*aman* system) in first year and averaged over two years (by 1.6 t ha^{-1}), but similar yield to the wheat-mungbean-*aman* systems with DSR. The higher REY of CSE2 than CSE1 was due to the higher price received by farmers for mungbean and wheat than for rice, which more than compensated for their lower yields in comparison with the high yield of *boro* rice.

4.3. Effect of rice residue retention on crop and system yield

There was no effect of partial *aman* straw retention in the first year on any individual crop yield, nor on total system REY. However, in 2012-13, wheat and mungbean yields were slightly but significantly higher with rice straw retention than removed, and as a result, total system REY in that year was also significantly higher (by 0.9 t ha^{-1}) with *aman* residue retention. The improved wheat crop performance with rice straw retention could be due to higher soil water availability in the topsoil. In the present experiment, a considerable amount of straw remained on the surface when wheat was sown into the standing residues using both strip and full tillage with the PTOS in a single pass. The soil dried slightly faster without straw retention than with retention after irrigation or rainfall, consistent with the findings of others (Rahman *et al*., 2005; Sidhu *et al*., 2007).The higher tillering and lower tiller mortality in 2012-13 in the straw retained treatment in the present experiment may reflect higher topsoil moisture, which resulted in significantly higher spike density and more grains $spike^{-1}$. The significant response of mungbean to *aman* straw retention in the second year is difficult to explain. By the time of mungbean sowing, there was little un-decomposed rice straw remaining on the soil surface. There was no effect of *aman* straw retention on yield of either T.*aman* or DS *aman* in any system, nor on yield of T. *boro*. Other studies in rice-wheat systems in north west India found that yield benefits of rice straw incorporation did not appear in rice until the fourth crop (Verma and Bhagat, 1992), or six years (Yadvinder-Singh *et al.,* 2005).

4.4. Effects of cropping system/establishment method and aman residue retention on soil properties

There was no significant effect of CSE or *aman* residue retention on bulk density of the soil profile (0-5, 5-10, 10-15 cm) after two complete cropping cycles (4 crops in CSE1, 6 crops in CSE2-4). Other studies have shown differences in bulk density in reduced tillage and conventional tillage in rice-wheat systems after 2 and 4 years (Jat *et al.,* 2009; Gathala *et al*., 2011). Jat *et al*. (2009) also reported that the conventional tillage system had higher bulk density in the 10–15 and 15–20 cm soil layers after two years due to compaction caused by the repeated wet tillage for rice in a rice-wheat rotation.

5. Conclusions

This study has shown that yield of *aman* crop was not affected by establishment method. Yield of wheat was significantly reduced (by 10%) when sown after PTR than after DSR. Furthermore, system productivity (rice equivalent yield, REY) was significantly increased (by 10% or 1.4 t ha^{-1}) by intensifying from a *boro*-*aman* to awheat-mungbean-*aman* system. Productivity of the wheat-mungbean-*aman* systems with PTR (CSE2) or DSR (CSE3) was similar in terms of REY and energy output. Conventional tillage (CT) and strip tillage (ST) did not affect the performance of wheat, mungbean and DS *aman* in terms of any of the measured crop and cropping system parameters including crop and system yield, and energy output. Partial *aman* residue retention significantly increased system yield by (0.6 t ha^{-1}), averaged over two years, due to consistent trends for higher yields of all crops. Finally, after two years, there was no effect of cropping system/establishment method or partial *aman* residue retention on bulk density of the top soil. Therefore, well planned cropping system along with proper management system may be useful for sustainable agricultural productivity.

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