Article

Tillage and residue management effects on productivity, profitability and soil properties of a rice-maize-mungbean system in Bangladesh

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Abstract: Farmers' conventional tillage (CT) and residue removal practices in rice-maize systems in South Asia's Eastern Gangetic Plain (EGP) are input-intensive, costly and soil degradative. We conducted a rice-maize-mungbean (R-M-MB) system experiment with six tillage and three residue management treatments in Bangladesh representing the EGP. Maize yields were significantly ($p \leq 0.05$) higher under permanent (PB) or fresh (FB) beds and strip tillage (ST) than CT but no differences in mungbean yields. Rice yields under PB, FB and CT were similar, but significantly higher than under zero or minimum tillage and ST. Yields of all crops increased significantly ($p \leq 0.05$) with residue retention compared to no retention. Total system productivity was highest under PB followed by FB and ST. Compared with CT, gross margins in PB, FB and ST increased by 18, 13 and 11%, and soil organic matter (SOM) and total N contents across tillage treatments increased by 11-16% and 12-24%, respectively. After three years, SOM and total N and available P and S contents increased significantly ($p \leq 0.05$) by residue retention. Results demonstrate the potential of PB, FB and ST with residue retention, for improving the productivity, profitability and soil health under R-M-MB systems in Bangladesh and similar soils in the EGP.

Keywords: Permanent raised beds, strip tillage; rice-maize-mungbean system; crop residue management; soil health; productivity; profitability

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1. Introduction

In Bangladesh, as in much of South Asia, most field crops are planted after removal of crop residues from the fields followed by intensive tillage. Furthermore, in the case of rice, the soil is normally puddled, followed by manual transplanting, which has a very high labour requirement. These traditional practices, however, pose concerns regarding the sustainability of crop production. Intensive tillage degrades soil structure, leads to rapid oxidation of soil organic matter (SOM), increases labour and fuel requirements and overall production cost, and increases greenhouse gas emissions [1]. It also delays establishment of crops, leading to reduced yield and income [2,1]. At the same time, in South Asia and particularly in Bangladesh, more food needs to be produced on less land, using less labour and water. Further, there is a growing concern regarding labor scarcity for agriculture due to migration from rural to urban areas within and outside the countries [3].

Potential strategies to tackle these challenges could be mechanized farming and the use of conservation agriculture (CA) [4,5]. Conservation agriculture utilizes three basic principles - no or reduced tillage, permanent ground cover and judicious crop rotation [6,7]. With the advent of zero till wheat, mechanized dry seeding of rice, increasing market availability of herbicides and rising concern over soil degradation, CA systems have gained increased attention in recent decades in the

Indo-Gangetic Plain (IGP) of South Asia [6-8]. The use of CA in the rice-wheat (R-W) cropping systems of the IGP has been the subject of much research, and has been shown to maintain or increase crop yields, increase profitability, and improve soil fertility [6,7,9].

Zero or reduced tillage with residue retention can improve soil physical, chemical and biological properties [10,1,4], facilitate timely planting, and decrease production costs related to labor, fuel and machinery. The use of drill seeders and reduced tillage can also reduce drudgery and sustain profit [1,4,5]. In the Eastern Gangetic Plain (EGP), [11] reported an average wheat yield gain of 19% with zero tillage without residue retention in large number of farmers' fields. However, a meta-analysis of large set of global data demonstrated that yields with zero tillage but without residue retention are lower than conventional tillage especially in the humid tropics [12]. Nevertheless, in contrast to sub-Saharan Africa where CA and conservation tillage practices have been found to be more labour intensive [13], such technologies may hold potential to tackle labour and energy shortage in agriculture in Bangladesh and in the EGP [14,11,8].

Rice-maize (R-M) cropping systems, practiced widely in South Asia, have potential in climates ranging from tropical to sub-tropical and even warm temperate regions of Asia [15]. In these systems, rice is grown during the warm rainy season (July-October), followed by maize during the dry, cool rabi/winter season (November-March). In the EGP, and especially in Bangladesh, these systems have emerged by replacing boro (winter) rice or wheat by a winter (rabi) maize crop, driven by the high demand for maize from the expanding poultry and aquaculture industries. In Bangladesh, winter maize and wheat are grown respectively on approx. 0.35 and 0.43 Mha after rice, and summer mungbean grown on approx. 0.14 Mha after winter maize or wheat [16]. There is potential to grow MB on an additional 0.6 Mha under rice-maize-mungbean (R-M-MB) and rice-wheat-mungbean (R-W-MB) systems due to its shorter growth period (approx. 2 months), providing important benefits to nutrition security [16]. While the potential for R-W-MB systems has received considerable attention in Bangladesh and in the EGP, R-M-MB systems have received little attention.

For the rapid expansion of R-M-MB systems, sustainable and cost-effective technologies with lower labour requirement and rapid turnaround between crops are needed. Potential technologies include mechanized direct-seeding of all crops, reduced or zero tillage and residue retention. These can reduce the turn-around time between crops facilitating timelier crop establishment, as well as reduce the labour requirement and cost of crop establishment. Furthermore, where establishment of the rainy season rice crop is dependent on rainfall, as in much of the EGP, direct-seeding into non-puddled soil ("dry seeded rice", DSR) facilitates earlier establishment in the main field by 1-2 weeks in comparison with transplanted rice (TPR) [17-19]. In most areas of the EGP and particularly in Bangladesh, farmers sow rabi crops after several passes of dry tillage after rice harvest and keep the land fallow for several days, resulting in loss of soil moisture and delayed planting. The shorter turnaround times between crops with mechanized seeding allows better use of residual soil moisture, better emergence and a more uniform plant stand, faster and more efficient weeding, and reduced labor requirements for inter-cultural operations.

Crop residue retention promotes nutrient cycling, increase nutrients availability to crops, and increases SOM content [20-21]. Retention on the soil surface confers the additional advantages of suppression of soil evaporation and of weeds [20-21]. Suppression of soil evaporation increases soil water content and can reduce irrigation water requirement. Residue retention could also play an important role in R-M systems of the EGP, where the residues of both crops are generally removed from the fields [14]. High yielding R-M systems are more extractive of nutrients, particularly N, P, or K, than R-W or rice-rice systems [21]. Further, inclusion of a legume such as mungbean in the system and retention of legume residue can improve the nitrogen economy of following cereal crop [20].

However, although there are several studies on the effects of alternative tillage and residue management options on yield and soil properties of various crops and cropping systems, and particularly R-W systems of the IGP, the results are still contradictory. Further, although there are few such studies on the rapidly expanding R-M systems in the Western IGP [25, 27], there are very few such studies on R-M and almost none for emerging R-M-MB systems in the EGP [14,28,29]. Hence, there is a need to investigate the effects of alternative tillage and residue management options for the emerging R-M-MB systems in Bangladesh and in the EGP. This is important because policy makers and farmers still need to be convinced of such promising technologies for their large-scale uptake and adoption by farmers. Thus, the current study was conducted with the R-M-MB systems with alternative tillage and residue management options, with an objective to identify the most productive and profitable options for Bangladesh and for areas with similar soils and climate in the EGP.

2. Materials and Methods

2.1 Experimental site, soil and climate

A three-year field experiments with a rice-maize-mungbean (R-M-MB) sequence was conducted at the Bangladesh Rice Research Institute (BRRI) Regional Station in Rajshahi (25000N; 88000E). Rajshahi is situated in the High Ganges River Floodplain, which mainly comprises highlands (lands above normal flood level, 12%of the area); medium highlands (lands normally flooded up to about 90 cm deep during the flood season, 33%of the area); and medium lowlands (lands normally flooded between 90 and 180 cm deep during flood season, 18%of the area) [33]. The experimental site was classified as highland, with a calcareous dark grey and brown floodplain soil of sandy loam texture (sand, silt and clay of 56, 23 and 21%, respectively, in the 0-15 cm layer).

The initial (baseline) soil analysis (0-15 cm depth) after rice harvest in October 2010 revealed slightly alkaline (pH, 8.5), with soil bulk density of 1.34 Mg m-3 and soil porosity of 50%. The SOM content was low (1.37%), total N very low (0.07%), and available P (10 µg g^{-1} soil), exchangeable K (0.19 meq 100^{-1}g soil), available S (9.8 µg g^{-1} soil) and available Zn (0.4 µg g^{-1} soil) all were low compared to critical levels [29].The soil bulk density and soil porosity data for 0-15 cm depth measured during November after rice harvest each year and other soil parameters (also at 0-15 cm depth) measured after three years were compared against the initial values as well as to final values among treatments. There were no soil cracks at the time of measuring the bulk density in any year.

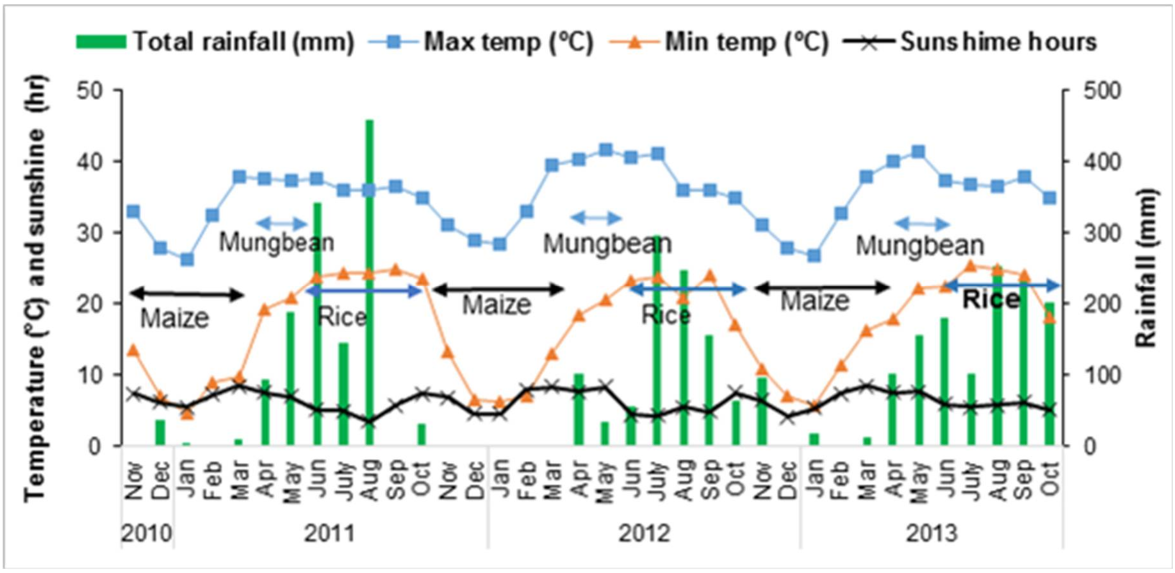

Figure 1. Mean monthly sunshine (hrs), minimum and maximum temperatures (^{0}C) and monthly rainfall (mm) during the experimental period from 2010 to 2013. Rajshahi, Bangladesh.

The climate of the area is semi-arid subtropical characterized by hot summers and cold winters. The hottest months during the experimental period were May and June in 2011 and 2013, when the daily maximum temperature reached up to 41^{0}C, whereas December and January were the coldest months with minimum temperature often dropping to 5-6^{0}C. Temperatures were relatively low during the maize season but high during the rice and mungbean seasons (Figure 1.). In all years, rainfall was low during the maize and the early stage of the mungbean crops, and high during the later stage of mungbean and during the rice (wet) season. The weather patterns were similar across the years, and did not differ much from the long-term averages.

2.2 Experimental design, treatments and crop establishment

The experiment was conducted in a 2-factor split plot design with tillage treatments in main plots and residue management treatments in sub-plots, in four replicates. There were five alternative tillage treatments (zero tillage - ZT, strip tillage - ST, minimum tillage -MT, permanent raised beds-PB, and fresh raised beds-FB), which were compared against each other as well as against conventional tillage (CT). The two alternative residue management options (retention of 50% and 100% of the previous crop's residue on soil surface of the succeeding crop) were compared against removal of all residues (0% retention). Each sub plot consisted of 8.0 m x 6.0 m (48 m^2).

Conventional tillage: The field was cultivated three times with a power tiller attached to a 2-wheel tractor (2WT) followed by leveling off the field using a bamboo ladder drawn by a 2WT before planting of all crops. Maize and mungbean were sown manually in rows on the conventionally tilled flat land while rice seedlings were transplanted manually on the puddled soil.

Zero tillage: A hand drawn plough ("Lithao," section 2.3.1) was used to make narrow furrows in the soil with a row spacing of 60 cm (maize), 30 cm (mungbean) and 20 cm (rice). Maize was sown manually with 20 cm spacing between seeds within each row, while mungbean and rice seeds were distributed as evenly as possible along the rows to achieve the desired seed rate (section 2.4).

Strip tillage and minimum tillage: A "power tiller operated seeded" (PTOS, section 2.3.2) was used to till the soil (to a depth of about 5 cm) and sow seeds in both the ST and MT treatments. In ST, two-third of the tines were removed, leaving only 16 tines, which tilled a strip approximately 1-2 cm wide. In MT, all 48 tines were retained on the tiller, and the entire soil surface was tilled. In both cases, tillage and sowing were conducted with a single pass. Row spacing was (60 cm for maize, 30 cm for mungbean, and 20 cm for rice.

Permanent beds and fresh beds: Narrow raised beds were prepared in untilled soil using a bed planter (section 2.3.3), and seeds sown at 4-5 cm depth simultaneously with bed formation. In FB, beds were demolished manually after harvest of each crop, and new beds were prepared for planting of the subsequent crops, but in PB, subsequent crops were established without demolishing and reforming the beds. Thus, at the start of the experiment, for the first crop, both PB and FB were exactly similar. The PBs were renovated by manually removing weeds and plant debris, and, in situations when the beds became eroded (e.g. due to heavy rainfall), they were repaired by putting soil from the adjacent furrows to the top of the bed after harvest of the previous crop.

2.3 Tillage and planting machines

2.3.1 Lithao

A locally-made hook-like iron made structure called Lithao was used for making small furrows, and seeds sown manually under ZT. The Lithao was used because it was cheap, readily available, easy to use, and could perform the same job as that of the ZT drills now available in Bangladesh.

2.3.2 Power tiller operated seeder

The PTOS combines the function of tillage (rotary tiller 400-480 RPM) and seeding in a single machine, drawn and powered by a 2WT. The PTOS is 120-cm wide, allowing sowing of six rows of rice at 20-cm spacing, two rows of maize at 60-cm and 4 rows of mungbean at 30-cm spacing. Operating capacity is typically 0.14–0.20 ha hr^{-1} [34]. This seeder can accomplish several operations in a single pass- tillage (up to 5cm), placement of seed and fertilizer in a furrow, and seed covering by a post-furrow opener roller bar [1]. [34] reported that compared with traditional broadcast sowing under full tillage by a rotary tiller, the PTOS requires less than half the time and fuel for sowing due to reduced number of passes and shallow seeding, although it disturbs the soil surface considerably due to use of 400–480 rotor RPM speed.

2.3.3 Bed planter

The bed planter used in this experiment tills the soil, delivers the seed and fertilizer, and shapes the bed, in a single pass. The bed planter is powered and drawn by a 2WT, and was developed jointly by BARI, Cornell University, and the International Maize and Wheat Center (CIMMYT) [30,31]. Beds with 54-60cm furrow to furrow distance, 30-35 cm bed top width, and 15-20 cm bed height can be formed, and the beds can accommodate 2 rows of rice and mungbean and 1 row of maize. We maintained 60 cm furrow to furrow width to allow 60 cm row-to-row distance for maize and 30 cm row-to-row distance for mungbean, and 60 cm to maintain three rows for rice. Once beds were established, the seasonal reshaping of beds using the bed planter with the tines removed involved only minimal soil disturbance.

2.4 Crop management

A medium-duration variety BRRI dhan39 maturing at about 118 days was used for rice in all years. All DSR plots were sown between 10 and 15 June @ 25–30 kg seeds ha^{-1} into moist soil after rainfall. Seeding depth was about 1-2 cm. Seeds for the TPR were sown on moist seedbeds at the same time as dry seeding, and 25-day old seedlings were transplanted between 5 and 10 July with a spacing of 25 cm x 15 cm and 2-3 seedlings hill^{-1}. Rice was harvested during second or third week of October each year. Maize was sown between 10 and 15 November, depending on the time of rice harvest and the time when the soil was dry enough to allow tillage and seeding operations. Maize was harvested during the first fortnight of April each year. Mungbean was sown at 35 kg ha^{-1} immediately after maize harvest during the second or third week of April and was harvested during 7-9 June each year. All crops were harvested manually.

Fertilizers were applied to all crops using recommended practice (BARC, 2012). In all crops, N, P, K, S, Zn and B fertilizers were supplied through urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum, ZnSO4 and borax, respectively. Fertilizer N, P, K, S and B were applied to rice @76, 12.5, 25, 8 and 7.5 kg ha^{-1}. In DSR, urea was applied in 3 equal splits at 10 days after seeding (DAS), 25–30 DAS, and 45–50 DAS. In TPR, urea was broadcast in 2 equal splits, at 15–20 days after transplanting (DAT)and 35–40 DAT. Fertilizer in maize was applied @250, 70, 170, 30, 5 and 1.4 kgha^{-1} N, P, K, S, B, and Zn, respectively. Nitrogen was broadcasting 3 equal splits as basal just before sowing, and at V6 and V10, while K was broadcast in 2 equal splits as basal and at V10. Fertilizer P was band-placed basally at 2-3 cm depth. Fertilizer rates in mungbean were broadcast just before sowing @20, 15, 20, 10 and 2 kgha^{-1} for N, P, K, S and Zn, respectively.

Maize and TPR were grown with 2–3 irrigations each year, each irrigation providing around 50–60 mm water, but in DSR, whether on flats or beds, no post-sowing irrigation was provided as the soil moisture due to pre-monsoon rainfall was enough for rice seedling establishment and post-sowing rainfall enough for its growth and development. In rice, gap filling was done as and when required, generally after 10-15 days of seeding/transplanting. Thinning was carried out in all crops as and whenever required. Pest and diseases were controlled using recommended practices as needed, and there were no major infestations. No pre-planting herbicides were applied in CT. In all the alternative tillage treatments, glyphosate (Roundup) was applied to the untilled soil @ 1.0 kg a.i. ha^{-1} using 500 L ha^{-1} water 3 days before sowing. There were no major weeds in TPR and maize and mungbean. However, weeds in DSR were controlled using either the broad-spectrum post-emergence herbicide Pyrazosulfuron @20 g a.i. ha^{-1} during 1-3 DAS, or if still some weeds left by spraying Fenoxaprop @56 g a.i. ha^{-1} during 25-30 DAS.

2.5 Crop residue management

The biomass of residues of each crop in 50% and 100% residue retention treatments was determined from the same 10 m^2 sampling area used for grain yield in each plot, while in 0% residue retention plots, all residues were removed from the field. The amount of residues applied in each treatment is provided in Table 1. To enable residue treatments for the first maize crop in 2010, a uniform crop of aman (monsoon) season rice was grown prior to the maize crop. The rice was harvested at ground level, and the straw was spread uniformly, but without covering the plants, after emergence of the maize seedlings. After harvest, the maize stalks were cut and chopped into 5-10 cm lengths and placed in the residue retained treatments after emergence of the mungbean seedlings. The maize stalks were chopped as it was difficult to operate the bed planter or the PTOS through the standing maize plants. Mungbean residues were however retained on the rice plots without chopping.

Table 1. Amount of crop residue retention (oven dry basis, t ha^{-1}) in CR$_{50}$ and CR$_{100}$across tillage treatments and years in the rice-maize-mungbean system^a

		2010-11			2011-12			2012-13		
Tillage options	Residue options	Maize	Mungbean	Rice	Maize	Mungbean	Rice	Maize	Mungbean	Rice
ZT	CR$_{50}$	2.85	1.76	2.25	3.03	1.56	2.81	2.61	1.68	2.24
	CR$_{100}$	6.13	3.89	5.91	6.67	3.56	6.03	6.63	3.75	5.21
ST	CR$_{50}$	2.96	1.65	2.42	2.40	1.75	2.39	3.07	1.64	2.19
	CR$_{100}$	5.31	3.76	5.54	6.82	3.76	5.01	6.73	3.45	4.97
MT	CR$_{50}$	3.26	1.61	2.43	2.79	1.51	2.49	2.69	1.52	2.54
	CR$_{100}$	6.41	3.67	5.82	7.33	3.47	5.38	6.58	3.39	5.39
PB	CR$_{50}$	3.21	1.69	2.34	3.32	1.57	2.22	2.91	1.59	2.22
	CR$_{100}$	5.44	3.72	5.70	7.17	3.51	5.14	7.55	3.92	5.12
FB	CR$_{50}$	3.41	1.58	2.49	2.92	1.67	2.59	2.92	1.50	2.67
	CR$_{100}$	6.78	3.62	5.76	8.00	3.52	6.01	7.49	3.87	5.79
CT	CR$_{50}$	3.34	1.62	2.64	2.34	1.70	2.43	2.51	1.76	2.52
	CR$_{100}$	5.43	3.88	5.88	6.16	3.49	5.62	6.52	3.77	5.60

^{a}ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage; CR$_0$=no retention of crop residues, CR$_{50}$=retention of 50% crop residues, CR$_{100}$= retention of 100% crop residues.

2.6 Soil analysis

2.6.1. Initial soil properties

Initial soil chemical properties were determined from 9 cores (0-15 cm) were collected in October 2010 from each replicate. The samples within each replicate were mixed thoroughly to make one composite sample per replicate. The samples were air-dried and stored in laboratory prior to analysis. The soil was analysed for particle size distribution, bulk density, total porosity, pH, SOM, total N, exchangeable K, and available P, S and Zn at the BRRI Soil and Plant Analysis Laboratory at Gazipur, Bangladesh. Soil pH was measured in a 1:5 soil suspension in water. Soil organic carbon was determined by the modified Walkey and Black method [36]. Total N was measured by the Kjeldahl method by following three steps: digestion, distillation and titration. Available P was determined by the Olsen method and exchangeable K was extracted with NH$_4$OAc and determined by atomic absorption spectrophotometry (AAS). Available S was extracted using calcium dihydrogen phosphate and determined by turbidimetric method. Soil Zn content was determined on DTPA extract by AAS [33].

The soil cores, taken on volume basis, were oven dried and bulk density was calculated as described by [38]. There were no soil cracks at the time of measuring the bulk density in any year. Particle density of soil was taken as 2.65 Mg m^{-3} [39]. The total porosity of the soil was calculated from bulk density and particle density according to the following equation:

$$\text{Soil porosity (\%)} = 1- (\text{bulk density}/\text{particle density}) *100$$

2.6.2. Intermediate and final soil analysis

Intermediate soil samples were collected in November each year after rice harvest. Four samples (0-15 cm) were collected from four sites within each sub plot. The samples were collected from mid-way between the rice rows in the flat plots and on the beds. Soil chemical properties were determined by the same laboratory, using the same methods, as for the initial sampling (section 2.6.1). Bulk density and soil porosity were also determined in early November after rice harvest each year. In the beds, bulk density was measured at four sites across the beds/furrows – middle of the top of the bed, half way down each sloping side, and in the base of the furrow. Since there were no significant differences in bulk density at these four positions, the values were averaged for each plot.

2.7 Data collection, economic and statistical analysis

Grain yields of all crops were determined by harvesting a 10 m^2 area in each plot. Grain moisture content at harvest was determined using a grain moisture meter, and yields were reported at moisture contents of 14%, 15.5% and 10% for rice, maize and mungbean, respectively. Total system productivity was determined as system rice equivalent yield (REY, t ha^{-1}), calculated by summing the REY of individual crops for each treatment combination. Rice equivalent yield for maize and mungbean was calculated from the price and yield of individual crops as follows:

$$\text{REY (t ha}^{-1}\text{)} = \frac{\text{Grain yield (kg ha}^{-1}\text{) of individual crop x price of respective crop (\$ kg}^{-1}\text{)}}{\text{Price of rice (\$ kg}^{-1}\text{) x 1000}}$$

To perform economic analysis, the amount of labor (number of man-hours) required for machinery operation, seeding, transplanting, irrigation, weeding, pesticide, herbicide and fertilizer application, harvesting, threshing and grain drying, and transport, and the cost of tillage and machinery hiring were recorded each year. Fuel consumption was measured separately for each tillage treatment by filling the fuel tank before and after each application in each year (Table 2). The prices of inputs such as seed, fertilizer, pesticide, fuel, herbicide, etc., and farm gate prices of the grain and rice straw were collected from farmers and the local market each year (Table 3). Maize and mungbean stover are not sold in the Bangladesh markets and thus have no tangible economic value, and were not included in the economic analysis. The local currency (Bangladesh Taka, BDT) was converted to US$ based on a conversion rate of 80.0 BDT for 1 US$ (www.xe.com; accessed on 14/2/2019).

Table 2. Labour and tillage and fuel cost for different tillage options under rice-maize-mungbean system (average of 3 years)

Tillage options[a]	Labour cost (US$ ha^{-1})				Tillage and fuel cost (US$ ha^{-1})			
	Maize	Mungbean	Rice	System	Maize	Mungbean	Rice	System
ZT	430	340	390	1160	0	0	0	0
ST	344	270	320	934	14.2	14.5	14.6	43.3
MT	352	275	325	952	15.7	15.9	16.1	47.7
PB	364	279	328	971	16.7	16.9	17.3	50.9
FB	366	281	330	977	16.8	16.8	17.0	50.6
CT	440	346	398	1184	35.5	34.8	36.3	107

[a] ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage

Data were analyzed statistically for each year separately with a computer based statistical package MSTAT-C (Michigan State University, East Lansing, MI, USA), following the base procedure by [40]. Visual inspection of the data distribution such as frequency distribution (histogram) and box plots were used to assess normality of data distribution and confirm homogeneity of variance.

Significant effects of treatments were determined by analysis of variance (ANOVA) and treatment means were compared at 5% level of significance by the Duncan's Multiple Range Test (DMRT) and by LSD values.

Table 3: Prices of various inputs and outputs (US\$) used for calculation of economic analysis in different years

Item	Unit[a]	Year			
		2010	2011	2012	2013
Inputs					
Rice seed	US\$kg^{-1}	0.44	0.44	0.44	0.44
Maize seed	US\$ kg^{-1}	-	3.63	3.63	3.63
Mungbean seed	US\$kg^{-1}	-	0.88	0.88	0.88
Glyphosate (roundup)	US\$kg^{-1}	11.1	11.1	11.1	11.1
Pendimethalin 33 EC	US\$kg^{-1}	-	11.0	11.0	11.0
Bispyribac Na^{+} 10 SC	US\$kg^{-1}	-	50.0	50.0	50.0
Urea	US\$ kg^{-1}	0.25	0.25	0.25	0.25
TSP	US\$ kg^{-1}	0.29	0.29	0.29	0.29
MOP	US\$ kg^{-1}	0.19	0.19	0.19	0.19
Gyspsum	US\$ kg^{-1}	0.10	0.10	0.10	0.10
Zinc sulphate	US\$ kg^{-1}	1.13	1.13	1.13	1.13
Borax	US\$ kg^{-1}	3.25	3.25	3.25	-
Virtago40 WP (Insecticide)	US\$kg^{-1}	138	138	138	138
Labor wage	US\$ Man day^{-1}	3.13	3.44	3.75	3.75
Fuel	US\$ L^{-1}	0.76	0.81	0.81	0.81
Irrigation	US\$ ha^{-1}	70.3	70.3	110	110
Outputs					
Paddy grain	US\$ t^{-1}	213	225	225	231
Maize grain	US\$ t^{-1}	-	213	225	235
Mungbean grain	US\$ t^{-1}	-	625	750	750
Paddy straw	US\$ t^{-1}	18.8	18.8	18.8	18.8

[a] Conversion rate: Bangladesh Taka 80 = 1 US\$ (each year)

3. Results

3.1 Effects of tillage and residue retention on yield of component crops and cropping system

Yields of all crops, and system REY, were significantly ($p \leq 0.05$) affected by the interactions between tillage and residue management in all years but not by the main effect of either tillage or residue management (Table 4). At all residue levels in all years, maize yield on PBs and FBs was significantly ($p \leq 0.05$) higher than in CT. In the absence of residues, maize yield of ST and MT was never higher than yield of CT, while yield of ZT was higher than yield of CT in the first 2 years. While there was a trend for higher maize yield with 50% residue retention compared with 0% in all treatments except CT, the effect was seldom significant. With 100% residue retention, however, yield of ZT and ST was significantly higher than that of CT in the first two years, but not in the third year, while yield of MT was significantly higher than that of CT in the first year only.

There were few and small significant ($p \leq 0.05$) differences in mungbean yield of different treatment combinations (Table 4). None of the alternative tillage treatments had significantly higher yield than that of CT, regardless of residue level. Within a residue level, there were almost no significant effects and no consistent trends of the tillage treatments. Within tillage treatments, there was a trend for mungbean yield to increase slightly with 50 or 100% residue retention in the second and third years, but with no significant effects, apart from significantly higher yield with 100% retention in RT and CT than with 0% retention.

In rice, none of the alternative tillage treatments significantly ($p \leq 0.05$) out-yielded CT (Table 4). Some of the CT x residue treatment combinations however out-yielded some of the other treatment combinations. In the absence of rice residues, there was a consistent trend for lower yield of ZT, ST and RT than the other tillage treatments, with some significant differences in the second and third years, but with increasing levels of residue retention, there was a trend for rice yield to increase, which was more consistent in the second and third years, and more consistent and pronounced in ZT and ST. Full residue retention significantly increased rice yield in comparison with no residue retention in ZT in the second and third years, and in ST, RT and PBs in the third year. In the absence of residue retention, there was a consistent trend for higher system REY on PB than in other tillage treatments, with significantly ($p \leq 0.05$) higher yield than all other treatments except FBs in the first and second years and ZT in the third year. With 50% residue retention, REY of PBs was significantly higher than that of ZT in all years, however, there were no consistent effects of tillage with full residue retention. There was a consistent trend for residue retention to increase system REY in all tillage treatments, with significant differences between 0 and 100% retention in the second and third years.

Table 4. Grain yield (t ha^{-1}) of maize, mungbean and rice, and rice equivalent system productivity as affected by different tillage and residue management options under rice-maize-mungbean system^a.

Residue option	Tillage option					
	ZT	ST	MT	PB	FB	CT
			Maize yield			
2010-11						
CR$_0$	10.4a-e	10.1a-e	9.9b-e	10.8a-c	10.6a-d	9.37de
CR$_{50}$	9.73c-e	10.5a-e	10.0a-e	11.1a	11.1a	9.38de
CR$_{100}$	10.7a-c	11.2a	10.2a-e	11.1ab	10.5a-d	9.3e
2011-12						
CR$_0$	10.4a-e	9.7c-e	10.0b-e	10.6a-d	9.9b-e	9.41e
CR$_{50}$	9.8c-e	10.4-e	10.0b-e	10.7a-c	11.1a	9.79c-e
CR$_{100}$	10.9ab	11.3a	10.3a-e	11.3a	10.6a-d	9.56de
2012-13						
CR$_0$	10.1e	10.5a-e	10.3c-e	10.8a-e	10.3b-e	9.89e
CR$_{50}$	10.1de	10.8a-e	10.4a-e	11.7ab	11.8a	10.4a-e
CR$_{100}$	11.0a-e	11.0a-e	11.1a-e	11.7a-c	11.5a-c	10.4a-e
			Mungbean yield			
2010-11						
CR$_0$	1.15ab	1.10ab	1.06ab	1.22a	1.12ab	1.09ab
CR$_{50}$	1.12ab	1.14ab	1.18a	1.14ab	1.02b	1.16ab
CR$_{100}$	1.13ab	1.15ab	1.12ab	1.14ab	1.13ab	1.21a
2011-12						
CR$_0$	1.12c	1.13c	1.11c	1.21a-c	1.19a-c	1.14bc
CR$_{50}$	1.13c	1.16bc	1.11c	1.18a-c	1.16bc	1.28ab
CR$_{100}$	1.22a-c	1.21a-c	1.24a-c	1.23a-c	1.24a-c	1.31a
2012-13						
CR$_0$	1.11bc	1.12bc	1.19a-c	1.14b-c	1.09c	1.17a-c
CR$_{50}$	1.15bc	1.19a-c	1.22a-c	1.19a-c	1.19a-c	1.27ab
CR$_{100}$	1.22a-c	1.27ab	1.24a-c	1.16a-c	1.22a-c	1.33a
			Rice yield			
2010-11						
CR$_0$	3.77c	3.84c	3.79c	4.36bc	4.10bc	4.29bc
CR$_{50}$	4.06bc	3.90bc	4.43a-c	4.29bc	4.21bc	4.55ab
CR$_{100}$	4.26bc	4.41a-c	4.27bc	4.28bc	4.42a-c	5.05a
2011-12						
CR$_0$	3.68d	3.97b-d	3.83cd	4.35a-d	4.27a-d	4.08a-d

CR$_{50}$	4.21a-d	4.26a-d	3.92cd	4.50a-c	4.52a-c	4.36-d
CR$_{100}$	4.41a-d	4.15a-d	3.71d	4.83a	4.74ab	4.39a-d
2012-13						
CR$_{0}$	4.58de	4.55e	4.61de	5.35a-c	4.89c-e	5.66ab
CR$_{50}$	4.92c-e	5.12b-e	5.17b-d	5.14b-d	5.26a-c	5.63ab
CR$_{100}$	5.78a	5.56ab	5.27a-c	5.80a	5.53ab	4.83c-e
			System REY			
2010-11						
CR$_{0}$	16.8b-e	16.5de	16.1e	17.9a-c	17.18a-e	16.2e
CR$_{50}$	16.4de	17.0a-e	17.2a-e	18.0ab	17.57a-d	16.6c-e
CR$_{100}$	17.5a-d	18.2a	17.1a-e	17.9a-c	17.49a-d	17.2a-e
2011-12						
CR$_{0}$	17.9d-g	17.3g	17.5fg	19.a-d	18.0b-g	17.5g
CR$_{50}$	17.6e-g	18.2b-g	18.1b-g	18.9a-d	19.2a-c	18.6fg
CR$_{100}$	19.3ab	19.7a	18.7a-e	19.7a-d	19.1a-c	19.0a-f
2012-13						
CR$_{0}$	18.4e	18.8de	18.9de	20.0a-e	18.9de	19.5c-e
CR$_{50}$	18.9de	19.9a-e	19.6b-e	20.9a-c	21.1a-c	20.3a-d
CR$_{100}$	20.8a-c	20.8a-c	20.5a-c	21.4a	21.1ab	19.7b-e

Main effects of tillage and residue management were not significant; Interaction means across columns and rows followed by the same lower-case letters are not significantly different at the 0.05 level of probability by DMRT. [a]ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage; CR$_{0}$=no retention of crop residues, CR$_{50}$=retention of 50% crop residues, CR$_{100}$= retention of 100% crop residues.

3.2 Effect of tillage and residue retention on production cost and profitability

The main effect of tillage or residue management options as well as their interactions did not have significant effects on the cost of cultivation, gross return, gross margin and BCR in the individual years (data not shown) but there were significant interaction effects ($p \leq 0.05$) when data for three years were considered together (Table 5).The 3-year average cost of cultivation ha^{-1} was highest ($p \leq 0.05$) in CT (US$ 1987), lowest in ST (US$1785), and intermediate in others. The cultivation cost was highest (US$2002) in CT with CR$_{0}$ while it was lowest (US$1769) in ST with CR$_{100}$. The 3-year average gross return ha$_{-1}$ for the system was highest in PB (US$ 4552) and FB (US$ 4453) while it was lowest in ZT and MT (US$4295). The interactions showed that the gross return was highest for PB plus CR$_{100}$ (US$ 4630) while it was lowest (US$ 4165) for ZT plus CR$_{50}$. There was slightly different pattern for gross margins, with highest for PB (US$ 2752) and lowest for CT and ZT (US$ 2347). Gross margins were highest for PB×CR$_{100}$ and ST×CR$_{100}$ (US$ 2844) and lowest for CT×CR$_{0}$ (US$ 2189). The BCR was highest for PBs and FBs (2.50) and lowest for ZT and CT (2.20) and was highest for ST×CR$_{100}$ and PB×CR$_{100}$ (2.60) and lowest for CT×CR$_{0}$ (2.09).

Table 5. Effect of tillage and residue management options on economic performance of rice-maize-mungbean system, 2010-11 to 2012-13 (data are means for three years)[a]

Residue option	Tillage option					
	ZT	ST	MT	PB	FB	CT
			Cost of cultivation ($ ha^{-1})			
CR$_{0}$	1950ab	1796e	1807c-e	1817cd	1828c	2002a
CR$_{50}$	1925b	1790e	1788de	1795cde	1805c-e	1983a
CR$_{100}$	1920b	1769e	1783e	1790de	1800c-e	1975a
			Gross return ($ ha^{-1})			
CR$_{0}$	4174c	4137a	4129a	4473ab	4257bc	4191c
CR$_{50}$	4165c	4332bc	4325bc	4554ab	4551ab	4365b
CR$_{100}$	4538ab	4617ab	4440b	4630a	4550ab	4399b
Gross margin ($ ha^{-1})						
CR$_{0}$	2224de	2341cde	2322cde	2656ab	2429bcd	2189e
CR$_{50}$	2240de	2542bc	2537bc	2759ab	2746ab	2382cd
CR$_{100}$	2618b	2848a	2657ab	2840ab	2750ab	2424bcd
			Benefit cost ratio			

CR_0	2.14d	2.30bc	2.29bc	2.46ab	2.33bc	2.09d
CR_{50}	2.16d	2.42b	2.42b	2.54ab	2.52ab	2.20d
CR_{100}	2.36bc	2.61a	2.49a	2.59a	2.53ab	2.23cd

Main effects of tillage and residue management were not significant; Interaction means across columns and rows followed by the same lower-case letters are not significantly different at the 0.05 level of probability by DMRT. [a]ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage; CR_0=no retention of crop residues, CR_{50}=retention of 50% crop residues, CR_{100}= retention of 100% crop residues.

3.3. Effect of tillage and residue retention on soil physical and chemical properties

There were significant effects of interactions of tillage and residue management on all soil physical and chemical parameters (Tables 6-7). Conventional tillage increased bulk density and decreased SOM, total N, and available P while alternative tillage treatments, particularly PB, ST and ZT reduced bulk density and increased available P. Likewise, full residue retention reduced bulk density and increased the values of all other parameters while no residue retention had the opposite effects.

3.3.1 Soil bulk density and porosity

Bulk density of the topsoil (0-15 cm) ranged from 1.24 to 1.55 Mg m^{-3} over treatments and years (Table 6). Within a residue level, there were no significant ($p \le 0.05$) effects of tillage treatment, apart from higher bulk density of MT and CT than FBs and PBs in the absence of residues in the first year. There was a trend for bulk density to decrease with residue retention, but there were very few significant differences. The soil porosity across all treatments and years after three years of R-M-MB cropping ranged from 49.7 to 53.4% (Table 6). Soil porosity was lower in the first year (49.7-51.7%) compared to third year (51.2-53.4%). After the first year, the interactions showed no significant ($p \le 0.05$) effects while after second or third year they showed significant effects($p \le 0.05$). PBs with CR_{100} resulted in the highest porosity while CT or FBs, each with CR_0, resulted in lowest porosity. Soil porosity increased from 50 (initial) to 52-53% (final) after three years of R-M-MB cropping, but with no significant differences between tillage treatments, and higher increase in full residue retention compared to no retention.

3.3.2 Soil pH and soil organic matter

Soil pH in the top 0-15 cm depth after three years of R-M-MB cropping ranged from 8.3 to 8.5 and was not significantly ($p \le 0.05$) influenced by either tillage or residue management options (Table 7). Data revealed no significant change in soil pH after three years of R-M-MB cropping (pH 8.-8.5 across treatments) compared to baseline (pH 8.5). Soil organic matter (SOM) content at 0-15 cm depth after three years of R-M-MB ranged from 1.32 (CT) to 1.53% (MT) (Table 7). SOM was 11-16% higher across alternative tillage treatments compared with CT. Irrespective of tillage options, SOM was significantly higher ($p \le 0.05$) in CR_{100} compared to CR_0. Tillage and residue interaction effect was highest (1.64%) in ZT withCR_{100} and lowest ($p \le 0.05$) in CT with CR_0 (1.22%). SOM increased from 1.37% (initial) to 1.52% (final) after three years of R-M-MB cropping, with significant increase in alternative tillage treatments but a decrease in CT. SOM after three years of cropping was significantly higher for full or partial residue retention (1.46-1.54%) but was lower for no retention (1.32%) compared to baseline (1.37%).

Table 6. Effect of tillage and residue management options on soil physical properties (0-15 cm depth) under rice-maize-mungbean-system[a].

Residue option	Tillage option					
	ZT	ST	MT	PB	FB	CT
			Bulk density (Mg m^{-3})[b]			
			2010-11			
CR_0	1.31a-c	1.30abc	1.33a	1.29abc	1.29a-c	1.33a
CR_{50}	1.28bc	1.29abc	1.29abc	1.30a-c	1.32ab	1.30abc
CR_{100}	1.29abc	1.28bc	1.29abc	1.27c	1.30a-c	1.30abc

			2011-12			
CR_{0}	1.30abc	1.31ab	1.31ab	1.29a-c	1.32a	1.31ab
CR_{50}	1.29abc	1.31ab	1.29abc	1.27bc	1.28abc	1.29abc
CR_{100}	1.29abc	1.28abc	1.27bc	1.26c	1.27bc	1.29abc
2012-13						
CR_{0}	1.27ab	1.28ab	1.28ab	1.27ab	1.28ab	1.29a
CR_{50}	1.26ab	1.25ab	1.26ab	1.25ab	126ab	1.28ab
CR_{100}	1.24b	1.25ab	1.26ab	1.24b	1.26ab	1.27ab
			Soil porosity (%)^{c}			
			2011-12			
CR_{0}	50.7a	50.5b	50.7a	50.5b	50.4b	51.3a
CR_{50}	51.4a	51.7a	50.5	51.3a	51.3a	51.9a
CR_{100}	51.4a	51.6a	51.8a	52.1a	52.1a	52.4a
			2012-13			
CR_{0}	51.2c	52.1abc	51.8abc	51.6bc	51.6bc	52.1abc
CR_{50}	51.9abc	52.4abc	52.9ab	52.4abc	52.5abc	52.7abc
CR_{100}	52.1abc	53.2ab	52.7abc	52.4abc	52.4abc	53.4a

Main effects of tillage and residue management were not significant; Interaction means across columns and rows followed by the same lower-case letters are not significantly different at the 0.05 level of probability by DMRT; ^{a}ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage; CR_{0}=no retention of crop residues, CR_{50}=retention of 50% crop residues, CR_{100}= retention of 100% crop residues; ^{b}Initial analysis: Bulk density = 1.34 Mg m^{-3}; soil porosity= 51.0; ^{c}Main effects as well as interaction effects not significant in 2010-11.

3.3.3 Soil nutrients

Total N content of soil across all treatments after three years of R-M-MB cropping ranged from 0.08 (CT) to 0.10% (ST and PB) and was significantly higher ($p \leq 0.05$) in CR_{100} (0.10%) compared to CR_{0} (0.08%) (Table 7). Considering interactions, total N ranged from 0.07% in CT with CR_{0} to 0.12% in ST with CR_{100}. Total N increased from 0.07% (initial) to 0.08-0.10% (final) after three years of R-M-MB cropping, with increase in alternative tillage treatments as well as full residue retention. Available P content of soil after three years of R-M-MB cropping ranged from 9.3 (ST) to 10.8 µgg^{-1} soil (ZT) across all treatments, and was highest (10.4 µg g^{-1} soil) in CR_{100} and lowest in CR_{0} (9.6 µgg-1 soil) (Table 7). Considering interactions, available P ranged from 8.1 (STxCR_{0}) to 11.3 (ZTxCR_{50}) µgg^{-1} soil. Soil available P changed from 10 (initial) to 9.3-10.8% (final) after three years of R-M-MB cropping, with increase in ZT, FB and PB and in full or partial retention of residues. Exchangeable K content of soil after three years of R-M-MB cropping ranged from 0.21 to 0.26 cmol kg^{-1} soil across tillage and residue management options with their significant interaction effects (Table 7). Exchangeable K, ranged from 0.19 cmol kg^{-1} soil for CTxCR_{0} to 0.26 cmol kg^{-1} soil for PBxCR_{100}. Soil exchangeable K increased from 0.19 (initial) to 0.23-0.26 cmol kg^{-1} soil (final) after three years of R-M-MB cropping, with no significant differences between tillage treatments, but was higher in full or partial residue retention than no retention.

Table 7. Effect of tillage and residue management options on soil chemical properties (0-15 cm depth) after three years under rice-maize-mungbean system^{a}

Residue option	Tillage option					
	ZT	ST	MT	PB	FB	CT
			Soil pH			
CR_{0}	8.47ab	8.40ab	8.37ab	8.37ab	8.30b	8.43ab
CR_{50}	8.33ab	8.37ab	8.40ab	8.44ab	8.40ab	8.37ab
CR_{100}	8.50a	8.33ab	8.37ab	8.33ab	8.30b	8.37ab
			SOM (%)			
CR_{0}	1.27c	1.31a-d	1.51ab	1.32a-d	1.31a-d	1.22d
CR_{50}	1.47abc	1.41a-d	1.57ab	1.58ab	1.40abcd	1.36aabcd
CR_{100}	1.64a	1.55a	1.52ab	1.56ab	1.59ab	1.38aabcd

Total N (%)						
CR_{0}	0.08bc	0.09bc	0.09bc	0.08bc	0.08bc	0.07c
CR_{50}	0.09bc	0.09bc	0.10ab	0.10ab	0.09bc	0.08bc
CR_{100}	0.10ab	0.12a	0.09bcd	0.12a	0.11ab	0.09bc
Available P (µg g^{-1} soil)						
CR_{0}	11.0a	8.1c	9.5a-c	10.4a-c	9.5abc	9.2abc
CR_{50}	11.3a	10.2abc	8.6bc	10.5ab	10.1abc	9.9abc
CR_{100}	10.1abc	9.7abc	10.3abc	11.0a	10.8ab	10.6ab
Exch. K (cmol kg^{-1} soil)						
CR_{0}	0.20bc	0.22abc	0.23abc	0.21abc	0.21abc	0.19c
CR_{50}	0.24abc	0.22abc	0.22abc	0.24abc	0.23abc	0.22abc
CR_{100}	0.25ab	0.24abc	0.23abc	0.26a	0.23abc	0.23abc
Available S (µg g^{-1} soil)						
CR_{0}	21.1ac	22.7ab	19.2abc	17.5c	21.3abc	18.3bc
CR_{50}	18.1bc	17.7bc	18.4bc	20.4abc	19.5abc	18.2bc
CR_{100}	19.2abc	20.1a-c	19.7abc	19.4abc	23.2a	21.9ab
Available Zn (µg g^{-1} soil)						
CR_{0}	0.52ab	0.38b	0.59a	0.48ab	0.50ab	0.51ab
CR_{50}	0.49ab	0.44ab	0.44ab	0.57a	0.47ab	0.47ab
CR_{100}	0.43ab	0.41ab	0.54ab	0.53ab	0.52ab	0.49ab

Interaction means across columns and rows followed by the same lower-case letters are not significantly different at the 0.05 level of probability by DMRT; [a]ZT=zero tillage, ST=strip tillage, MT= minimum tillage, PB=permanent bed, FB=fresh bed, CT=conventional tillage.CR_{0}=no retention of crop residues, CR_{50}=retention of 50% crop residues, CR_{100}= retention of 100% crop residues; [b]Initial analysis: pH = 8.5; SOM= 1.37%; TN = 0.07% P = 10 µ g^{-1} soil; K = 0.19 meq 100g^{-1} soil; S= 9.8 µ g^{-1}; soil; Zn= 0.4 µ.

Exchangeable S content of soil after three years of R-M-MB cropping ranged from 18.7 to 21.3 µgg^{-1} soil across tillage and residue management options, with no significant tillage effect but with significant residue effect ($p \leq 0.05$) (Table 7). Soil available S for interactions ranged from 17.5 µgg^{-1} soil for PBxCR_{0} to 23.2 µgg^{-1} soil for FBxCR_{100}. Available S increased significantly from 9.8 (initial) to 19.2-23.2 µg g^{-1} (final) after three years of R-M-MB cropping, with no significant differences between various tillage treatments as well as between residue retention treatments. Available Zn content of soil after three years of R-M-MB cropping ranged from 0.41 to 0.52 µgg^{-1} soil across tillage and residue management options (Table7). Soil available Zn was highest (0.59 µgg^{-1} soil) for MTxCR_{0} and lowest (0.38 µgg^{-1} soil) for STxCR_{0}. Available Zn increased significantly ($p \leq 0.05$) from 0.40 (initial) to 0.41-0.54 µgg-1(final) after three years of R-M-MB cropping, but with no significant differences between tillage treatments as well as between residue retention treatments.

4. Discussion

4.1 Tillage and residue management effect on crop and system productivity

The results of the current study indicated that the grain yield of maize was higher in permanent beds (PBs) followed by fresh beds (FBs) in all years. Similar to our results, higher maize yield under PB compared to flat beds was also reported by [38] and [39]. For maize grown under R-M systems too, [14] and [39] obtained higher yields under beds compared to flats. In our study, next to PB and FB, higher yields were found in strip tillage (ST), minimum tillage (MT) and zero tillage (ZT) compared to conventional tillage (CT). Our results are similar to those of [29] who found significantly and consistently higher maize yields from ST compared to CT from many sites and years in Southern Bangladesh, though, contrary to their own findings, they [28] did not observe consistent difference in maize yields between ST and CT in another study. However, our findings differ from the findings of [45] and [46], who found no difference between ZT and CT in maize in India.

Our study showed higher grain yield of mungbean in CT compared with alternative tillage options, which might be due to better pulverization of soil in CT providing favorable conditions for its growth and yield. Our results agree with [43] and [48], who also found higher or similar grain yield in CT compared to ZT or other reduced tillage methods, but differ from [45] who reported an increase in mungbean yield on PBs compared to CT. In our study, grain yields of direct-seeded rice (DSR) under PBs and FBs were similar to transplanted rice (TPR) in all years. However, compared with TPR under CT (CT-TPR), yields were lower for DSR under ZT, ST and MT in the first two years but were similar in the third year. Gathala et al. [2] also reported higher rice yields in CT-TPR than ZT-DSR but [49] reported similar rice yields under ZT and CT. Our results showing higher or similar grain yields of rice in PBs and FBs compared to CT also agree with many other studies [9,14]. [47] also reported that permanent beds with all straw left as stubble had the highest maize and wheat yields in Central Mexico.

In our study, the alternative tillage plus rice residue retention either partially or fully increased the grain yield of maize. Our results agree with [37] who concluded that, compared with full straw removal, 50% straw retention increased grain yield of maize by 32%, and with [41] who also reported higher maize yields under ZT with rice straw retention. Our study also showed significantly higher mungbean yield with full residue retention compared with no retention. In the initial two years, only full residue retention resulted in significantly higher grain yield of rice than no retention but in the third year, rice yields with partial retention were also significantly higher than with no retention. The yield increase was probably due to a mulching effect on conservation of soil moisture, reduced weed growth, and more efficient use of nutrients. Legume residues can meet N needs of high-yielding rice cultivars, and have synergetic effects on improving rice growth and yield [25,49]. In Bangladesh, [29] reported that approximately 4-4.5 kg N is added to soil from 1 ton of mungbean residue, which may not be enough to supply all N requirements of the high-yielding rice crop. Residue retention, however, can certainly increase rice yield as compared to removal, as has also been demonstrated by [44] and [48] in Bangladesh. In our study, rice was directly seeded without puddling instead of transplanting of seedlings in puddled soil in all tillage treatments, except CT. In many studies, growing DSR without puddling had beneficial effects on the succeeding maize or wheat [14, 50]. In our study, compared with CT, the system REY of R-M-MB sequence was higher under PBs followed by FBs. This result differed from [14] who observed no significant differences between FBs and PBs for R-M systems in Bangladesh but agreed with [9] for R-W system in the EGP of India. The REY of R-M-MB system was lower under MT and ZT compared to PBs or FBs. These findings are similar to those of [50] and [51] who also reported similar or higher system REY under PBs than ZT. In our study, we also found the highest system REY with full residue retention compared with no retention across years. [49] also concluded that returning of stubbles of previous crops was effective in increasing the REY of R-W system. Consistent with findings of the current study, PBs with residue retention provided benefits in terms of increased yield in R-W systems [9], maize–wheat systems [53] and soybean-wheat systems [54].

4.2 Tillage and residue management effect on profitability

Our study showed that the cost of production was higher in CT than all alternative tillage options primarily due to high labor and fuel cost for land preparation for maize and mungbean, high cost for transplanting rice seedlings, and due to manual seeding in the other two crops. Due to the lower cost for labour and fuel and higher yields, gross margins and BCRs were also higher under PBs and ST compared to CT, which are consistent with findings of [14] and [9-10]. Some scientists also reported that PBs can enable farmers to reduce the production cost, and increase yield and net returns for farmers [55-57]. Irrespective of tillage options, our results of higher gross return, gross margin and BCR under full residue retention compared with no retention are consistent with other previous results [9, 58]. Despite such clear benefits observed from PBs and ST with residue retention, we recognize some limitations of applying these findings to farmers' fields as our analysis is based on data from an on-station experiment where labour data were measured from the sub-plot size of 48 m^2. For obtaining more realistic estimation of labour and other inputs and for wider applicability of the results with greater confidence, we suggest that economic analysis in future be conducted from on-farm experiments with large plot size.

4.3 Tillage and residue management effect on soil properties

Our study showed no effect of tillage or residue management on soil bulk density during the first two years suggesting that soil structure doesn't change much in a shorter time. Following intensive tillage and puddling for TPR over several years, there will be soil compaction and aggregates settlement resulting in the formation of a puddled layer and consequent increase in the soil bulk density of surface layer [10,59]. In contrast, some other studies reported higher soil bulk density under ZT compared with tilled soil [69]. Our study indicated that irrespective of tillage options, soil bulk density decreased with the increase of residue retention. As in our study, [61] also reported that minimum soil disturbance under ZT, ST and PBs with left over crop residues can decrease soil bulk density, while, different to our study, another study revealed that no tillage with returning of crop residues can increase the soil bulk density [62].

Our study didn't show any significant effect of tillage on soil porosity but showed an increase by addition of crop residues after the final year of experimentation. In contrast to our findings, [63] showed an increase in soil porosity under reduced tillage, but similar to ours, [64] and [41] also reported an increase in porosity by addition of crop residues. Similar to the findings of [65] but different to those of Kumar and Yadav (2005), our study did not show any effect of tillage or residue management on soil pH. On the other hand, our results showed significantly lower SOM in CT compared to that in alternative tillage treatments. In line with our results, [66] and [65] also found higher SOM under reduced tillage than under CT. Likewise, our results of higher SOM under PBs than CT were similar to the findings of [40] and [67]. Conventional tillage can lower carbon levels of agricultural soils due to increased decomposition rates and carbon redistribution. Our study also showed that the crop residue retention under reduced tillage can significantly increase SOM than under no retention. [28] and [24] also demonstrated that inclusion of mungbean and/or incorporation of crop residue in R-W system has potential to increase SOM while maintaining high yield. Crop residue incorporation enhances microbial activity, resulting in higher SOM [68-69]. [70] and [65] also reported that SOM can be maintained if maize is grown under reduced or no tillage with residue retention. Similarly, [40] reported an increase of SOM by 13-41% on the surface of the raised beds after 4 years of rice straw retention.

From the review of 74 studies on soil carbon changes with CA and conventional tillage, [70] concluded that bulk density increases in ZT than in CT in the top soil. [72] also reported that CA often changes the topsoil and immediate layers (0-15 cm depth) for SOM, but it is quite possible that CT may distribute SOM to lower soil layers. Hence, if soil samples are taken from the same depth within the plow layer, more mass of soil will be taken from ZT than CT, resulting in increased SOM in ZT than CT. Hence, [71] suggested that the samples be taken on mass basis rather than standard depth basis to account for any changes in bulk density affecting SOM storage calculations, and such sampling would be more critical if there are significant amounts of SOM beneath the lowest sampling depth. We recognize this as a limitation of our study and suggest that future studies should sample soils for determination of SOM and other chemical properties on mass basis and not on depth basis to account for bulk density.

In line with [65], [66] and [69], our study also demonstrated significantly higher soil total N under ST compared with CT but not with other tillage treatments. Likewise, in line with [73] and [65], we also observed higher total N content under full residue retention compared with no retention. We also observed an increase in soil available P under ZT compared to CT, and significantly higher under full residue retention compared with no retention. These results are similar to those of [66] and [69] but different to that [65]. Likewise, [62] also reported an increase of soil nutrients availability, including P, through release of inorganic P from decaying residues under no tillage practiced over multiple and successive seasons. It should be noted that although total N and available P showed significant differences between treatments, their contents varied little, and such small differences may not be significant agronomically or biologically.

Our study didn't show any significant influence of tillage or residue retention on soil exchangeable K. These results differ from most studies [65,72] but agree with [61]. Uptake of higher amount of K by high yielding hybrid maize could be the main reason for soil K remaining static [29]. [68,70] also reported that soil nutrient supplying capacity, including K, could be maintained if maize is grown under no tillage or raised beds with residue retention. The current study also showed no significant effect of tillage on soil exchangeable S or Zn, a finding similar to that of [61] but dissimilar to that of [70].

5. Conclusions, recommendations and policy implications

From the results of this study, we conclude that the grain yields of maize under R-M-MB systems can be higher in all alternative tillage options compared with CT. In mungbean and rice, however, yields under PBs, FBs and ST appear to be similar to CT. Therefore, alternative tillage practices, particularly PBs, FBs and ST, can result in higher system productivity and minimize input costs such as fuel and labor, etc. resulting in higher gross margins and BCRs. Compared with CT, SOM and soil total N contents at 0-15 cm depth appear to be higher and bulk density lower in all alternative tillage treatments but may overestimate the SOM in reduced tillage if not accounted for bulk density. Retention of crop residues can increase crop yields and farmer income, and can also increase SOM, and total N, available P and available S contents of soil.

Further, in rice although there can neither be significant yield advantages nor reductions from alternative tillage options compared to CT, there can be significant advantages in terms of reductions in production cost and labour use, and can increase farmer income. All the alternative tillage options can have yield benefits over CT in maize and no distinct benefits in mungbean, but there can be reduced production cost and increased income in both crops. On a system basis also, PBs and ST can exhibit significant yield advantages over CT. Likewise, although there can be slight benefits of partial residue retention on yield and income of all crops, full residue retention may be required to obtain significant yield and income benefits, including improvement in the soil physical and chemical properties. Planting on PBs and FBs and by ST with residue retention can be advantageous where farmers shift from R–R or R-W to R–M-MB systems in Bangladesh, by assuring higher potential for income generation and without reductions in total system productivity. However, full residue retention may not be practicable and realistic in Bangladesh and in the EGP as residues have many uses such as in livestock feeding, fencing, fuel, etc.

Despite the potential advantages of PBs or FBs shown in this study and more than 20 years of research on raised beds in both research stations and farmers' fields in the IGP of South Asia showing their agronomic and economic benefits over CT, farmers in South Asia, including those in Bangladesh, have poorly adopted these technologies. The main reasons for non-adoption are lack of farmers' access to machinery (i.e., bed planters) and lack of appropriate training to service providers and farmers for operation and maintenance of those machinery. Lack of support from policy makers and inadequate extension support for expansion of technologies also hinder the farmer adoption of these technologies. We suggest that agronomic researchers align their field studies by co-developing the technologies with farmers or by quickly moving the technologies from research stations to farmers' fields with an aim of achieving rapid adoption of these technologies by farmers. Further agronomic research and socio-economic and policy studies are needed to determine what types of farmers and soil types these alternative tillage and residue management practices or options may be most appropriate for R-M-MB systems, as well as to parse out which biophysical and socioeconomic conditions are prerequisite for the rapid adoption and implementation of these systems.

We recommend for conduct of further agronomic and socio-economic research to determine trade-offs of residue retention under PBs, FBs and ST with an aim of improving grain and system productivity, profitability, and soil fertility and considering the multiple uses of crop residues under varying climatic and socio-economic conditions of Bangladesh in particular, and EGP in general. Also, future research is required to find out the geographic areas for successful cultivation and 'socioeconomic niches' for adoption of the R-M-MB systems which would help propose appropriate technology targeting research and supportive extension policy for out-scaling of alternative tillage practices such as PBs, FBs and ST and residue management technologies for R-M-MB systems in Bangladesh and the EGP.

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