Minimum tillage unpuddled transplanting: An alternative crop establishment strategy for rice in conservation agriculture cropping systems

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Abstract

Adoption of conservation agriculture (CA) has been hampered in puddled rice-based cropping systems. In this study, we developed a method for transplanting rice (*Oryza sativa* L.) with minimal soil disturbance (referred to as minimum tillage unpuddled transplanting) that can expand the range of situations where CA could be practiced in rice-based cropping systems. A field experiment was conducted over three years at two sites with unpuddled and puddled rice comparisons in each monsoon season.

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In addition, transplanted rice was grown in three seasons on unpuddled or fully puddled soils in a total of 27 farmers' plots in north-west Bangladesh. In each year and season, minimum tillage unpuddled conditions were established by strip tillage and compared with single pass shallow tillage or bed formation, and with the conventional soil puddling and transplanting. Unpuddled transplanting by any of the three single-pass soil disturbance operations had no negative effect on rice yields across seasons and years. The minimum soil disturbance in strip tillage did not impede transplanting of rice or increase the labour costs of transplanting compared to puddled transplanting except in the farmers' plot of the first season. All single-pass and minimum soil disturbance tillage operations reduced cost of production, and increased the gross margin of rice relative to conventional puddling and transplanting. Minimum tillage unpuddled transplanting reduced the time taken for land preparation and crop establishment and decreased the number of irrigation events required to saturate the soil. Minimum tillage unpuddled transplanting appears to be a feasible approach for establishment of wetland rice in CA systems.

Keywords: aman; bed planting; boro; minimum tillage; single pass shallow tillage; strip tillage.

1. Introduction

Various forms of conservation agriculture (CA) are now being practiced in over 157 million ha globally (Kassam, 2014) but mostly in large mechanized farms in rainfed and supplementary irrigation areas. There is much less application of CA in rice-based systems which support predominantly smallholder farms (Johansen et al., 2012). The common rice establishment method in Asia involves mostly hand transplanting following full tillage and soil puddling. Soil tillage and puddling facilitate rice establishment by increased soil water retention, control of weeds and increased availability of many nutrients. However, soil puddling for rice transplanting: destroys soil aggregates; breaks capillary pores; disperses clay particles that can form an impermeable clayey layer on the surface of coarse-textured soil; creates a plow pan (compacted layer) that impedes root penetration and causes water-logging for following crops. Ploughing the dried puddled layer produces large clods in finer textured soils that limit seed soil contact unless repeated cultivation occurs before seeding following crops (Anonymous 2012a). A diagnostic survey conducted in several rice-wheat areas in South Asia by Fujisaka et al. (1994) reported low wheat (*Triticum aestivum* L.) yields in a rice-wheat system, mainly because of deterioration of soil structure and the development of sub-surface hardpans. Continuation of soil puddling for rice transplanting will negate the benefits of minimum tillage in other crops in the rotation as is reported for the rice-wheat system (Singh et al., 2011).

Direct seeding with minimum tillage is an option for rice establishment that eliminates soil puddling. However, risks of severe weed infestation (Singh et al., 2011), bird damage, low productivity, uncertain and erratic rainfall (Singh et al., 2011), insecure irrigation water supply, and high irrigation water requirement during early seedling stage are the major reasons hindering the replacement of puddled rice transplanting by direct seeding rice in most rice growing areas (Farooq et al., 2011). Furthermore, germination failure and seedling mortality are significant additional reasons for non-adoption of direct-seeded rice establishment in cool season sub-tropical and high altitude rice (e.g., cool season irrigated rice (boro rice) in Bangladesh (Rashid et al., 2009).

Conservation agriculture helps farmers to reduce production costs while improving soil health, crop diversity and timeliness of cultivation (Johansen et al., 2012). Successful development of two-wheel tractor (2-WT) based implements like the Versatile Multi-crop Planter (VMP) for zero tillage, strip tillage, minimum tillage and bed planting have created new avenues for the pursuit of CA in rice-based smallholder farming systems that are common in South Asia (Haque et al., 2011). However, implementation of CA in the whole cropping sequence is hampered until there is a suitable alternative to transplanting of rice crops into fully puddled soils or a more reliable alternative to direct seeding.

The production costs for the transplanted boro (growing season from mid December to -mid April) and aman rice (from mid June to November) (monsoon) rice cropping pattern increased by about 55 % in Bangladesh during 1996–2006 (BRRI, 2007a,b) due to increased wages and of the input prices including fertilizer, irrigation water, and pest control. Scarcity of farm labor and tillage for land preparation and puddled rice transplanting have emerged in recent times as a serious constraint for timely transplanting of rice in many parts of S Asia and SE Asia. Hobbs et al. (2002) described the emerging issues of sustainability of rice-wheat systems and stressed the need to improve water-use efficiency, soil structure, and weed management against the backdrop of increasing scarcity of labor and water. Bhuiyan et al. (2004) reported that the net profit from rice cultivation was static or had declined in some cases over the period which can be attributed largely to rising costs of crop production. Hence there are compelling reasons for decreasing the costs of rice production in South Asia and South-East Asia and preliminary evidence that unpuddled transplanting of rice seedling could provide such benefits (Johansen et al., 2012).

While soil tillage and puddling is conventional practice before transplanting rice seedlings, there is evidence that rice can be transplanted into unpuddled soils. Several minimum soil disturbing options could be used to establish unpuddled transplanting of rice: single-pass shallow tillage (SPST); strip tillage (ST); and; bed formation (Johansen et al., 2012). The SPST method involves full surface soil disturbance to 4-6 cm depth and full residue incorporation in a single pass dry tillage. Hence it reduces the number of tillage operations and depth of tillage compared to conventional puddling but does not apply the principles of CA, namely minimum soil disturbance and crop residue retention. Nevertheless, the shallow soil tillage may be sufficient for weed control and unpuddled transplanting of rice seedlings (Ladha et al., 2009). Strip tillage involves disturbance of a slot up to 6 cm deep and 4-6 cm wide, covering the equivalent to 15-25 % of the soil surface. Hence this can be considered a minimum tillage, residue retention system compatible with CA. Rice seedlings can be transplanted into the wetted disturbed slot. With permanent beds, a narrow strip can also be disturbed on top of the bed and seedlings transplanted into the slot after wetting up the soil. In this system, 16-25 % of the soil surface is disturbed. While these minimum tillage systems have been well tested for a range of upland and irrigated crops (Johansen et al., 2012; Islam et al., 2010), their relative suitability for unpuddled transplanted rice was unknown.

In this study we tested the hypothesis that unpuddled rice could be effectively established and achieve satisfactory yield when soils were saturated following minimum tillage. Preliminary trials gave encouraging results on water saving and cost reduction with unpuddled transplanting in raised beds, strip tillage, and with SPST without any yield penalty (Haque et al., 2009). Minimum tillage unpuddled rice establishment was evaluated over three years' in on-farm experiments in two locations of north-west Bangladesh. Experiments were carried out in farmers' fields in three rice growing seasons to evaluate the novel establishment methods for rice by unpuddled transplanting on raised beds, and following strip tillage or SPST.

2. Materials and Methods

2.1. Experiment 1

Three consecutive years' of aman rice establishment during 2011, 2012, and 2013 was examined at two long-term sites at Durgapur (24°28 N, 88°46 E) and Godagari (24°31 N, 88°22 E) upazila of Rajshahi district in north-west Bangladesh. The cropping rotations were aman rice – lentil (*Lens culinaris* Medik.) – mungbean (*Vigna mungo*) for Durgapur site and aman rice – wheat (*Triticum aestivum*) – mungbean in Godagari site and the sequences were repeated each year. For all three seasons, aman rice was grown as a rainfed crop, however, irrigation was applied if necessary to keep at least 2-3 cm of standing water. The Durgapur site occurs in agro-ecological zone 11 known as the High Ganges River Floodplain, and Godagari site is located in agro-ecological zone 26 known as High Barind Tract (FAO-UNDP, 1988). The average annual rainfall is 1200 mm of which 80 % falls during June to September (Mazid et al., 2002). The average minimum temperature is 11^{o}C in January and the mean maximum is 25.8-32.1^{o}C in July to December (Anonymous, 2012b). Soil samples were collected from the experimental site in four sub-plots to the depth of 15 cm. The soil of the Durgapur site was alluvial with: 32 %

sand, 52 % silt, 16 % clay; the bulk density was 1.54 to 1.70 (g/cm^3); pH was 7.81; organic C was 0.61 %; total N was 0.074 %; available P was 73 mg/kg, and; exchangeable K was 16 mg/kg. The Godagari site contained: 16 % sand, 66 % silt, 18 % clay. The bulk density was 1.41, 1.44 and 1.52 (g/cm^3) at 0-5, 5-10 and 10-15 cm soil depth; pH was 6.30; organic C was 0.73 %; total N was 0.095 %.

Both trials were arranged in the randomized complete block design. The tillage treatments were strip tillage (ST), bed planting (BP) and conventional tillage (CT). Each treatment was replicated four times and each plot size was 105 m^2. Rice seedling establishment treatments were as follows:

i. Traditional puddling (CT): In all three years, the land preparation was done by locally hired 2 wheel tractor (2-WT) using two rotary tillage passes in dry land and two additional rotary tillage passes in inundated field condition two days after irrigation application followed by 3-4 leveling passes prior to transplanting. Two-three seedlings per hill were transplanted manually in 25 cm spaced rows with 20 cm hill spacing.

ii. Strip tillage (ST): In 2011, 2-4 cm wide and 4-5 cm deep tilled zones were made (that preserved about 80 % of untilled soil) in untilled flat land by locally made tools after heavy seasonal rainfall; the following two years 2012 and 2013, the land was fully undisturbed as the surface soil was soft enough to transplant the rice seedling in untilled and unpuddled condition. Two-three rice seedlings per hill were transplanted manually at 25 cm between row and 20 cm between hills.

iii. Bed formed (BP): All three years, 2-4 cm wide and 4-5 cm deep tilled zones were made manually on both edges of the 58 cm-wide bed (center to center) by locally made tools, followed by reshaping the beds after heavy seasonal rainfall. Two-three seedlings per hill were transplanted manually at a spacing of 20 cm apart from hill on top of the bed that accommodated two rows on top of the beds.

At the Durgapur site, 24- and 25-day-old seedlings of hybrid rice cv. Tej and ACI 1 were transplanted in the aman season of 2011 and 2012, respectively; whereas, the 20-day-old seedling of high yielding rice cv. BINAdhan 7 was transplanted in 2013. At the Godagari site, the 30- and 33-day-old seedlings of the high yielding rice cv. Sorna and BRRIdhan 51 were cultivated in the aman season of 2011 and 2012, respectively; and 25-day-old seedlings of cv. BINAdhan 7 were used in 2013.

The recommended fertilizer application (BRRI, 2004) and crop management practices were followed in all crop seasons for all experiments. The total basal fertilizer dose (kg ha^{-1}) for aman season was 27 N, 10 P, 30 K, 5 S, 2 Zn and 0.6 B; and for boro season rice it was 34 N, 15 P, 30 K, 8 S, 2 Zn and 0.6 B. Basal fertilizers were applied as urea or diammonium phosphate, triple superphosphate, muriate of potash, gypsum, and zinc sulfate which was broadcast before the last two tillage operations in case of CT; before the single pass operation of SPST; and for the BP and ST, the basal fertilizers were banded at the time of land preparation. The top dressings of urea fertilizers, at 75 and 58 kg ha^{-1} for boro and aman rice, respectively, were applied at 12-15 days after transplanting (DAT), 27-30 DAT, and 55-60 DAT in all three seasons.

The aman rice in Godagari and Durgapur was harvested during late October to mid-November. No economics data from Experiment 1 are reported in this paper.

2.2. Experiment 2

Three consecutive seasons of on-farm trials were conducted during 2009 and 2010 in fields of Durgapur upazila, Rajshahi. Boro rice (December to April-May) was grown as an irrigated crop in 2009 in eight farmers' fields, and in 2010 on nine farmers' fields; and aman season (July to November–December) rice was grown mostly as a rainfed crop in 10 farmers' fields during 2009. The 20- and 35-day-old seedlings of cv. BRRIdhan28 were transplanted during aman and boro seasons, respectively. The average plot sizes were 394, 1143, and 993 m^{-2} in boro season of 2009, aman season of 2009 and boro season of 2010, respectively.

The tillage treatments were arranged in a randomized complete block design considering each farmer’s field as a replicate for all tillage types. All of the farmers’ fields for each season were located in the same village within a 1 km radius. The experimental area in each farmer’s field had a similar history and crop management practice with similar soil type. Treatments consisted of four rice establishment options as follows:

i. Traditional puddling (CT): The land preparation was done by locally hired 2-WT using two rotary tillage passes in dry land and two additional rotary tillage passes in inundated field condition two days after irrigation application followed by 3-4 leveling passes prior to transplanting. Two-three seedlings per hill were transplanted manually in rows with hill spacing of 20 cm x 20 cm.

ii. Single pass shallow tillage (SPST): Land preparation was done by the locally hired VMP in a single pass tillage operation (Haque et al., 2011) in dry land conditions to finely till the soil up to 6 cm (Johansen et al., 2012). Irrigation water was applied after tillage to inundate the field for 24 hrs before 2-3 rice seedlings per hill were transplanted manually at a row and hill spacing of 20 x 20 cm.

iii. Bed formed (BP): In dry land, the 58 cm (centre to centre) beds were formed by locally hired VMP in a single pass operation (Haque et al., 2011). The irrigation water was applied to inundate the beds for 24 hrs before transplanting 2-3 seedlings per hill. Seedlings were manually transplanted at a spacing of 20 cm between hills on top of the bed that accommodated two rows.

iv. Strip tillage (ST): In dry land, 5-7 cm deep and 4-6 cm wide tilled zones (that preserved about 70 % undisturbed soil) were made by locally hired VMP in a single pass operation (Haque et al., 2011) then the plots were inundated for 24 hrs. The distance between each strip was 20 cm. Two-three seedlings per hill were transplanted manually at the row and hill spacing of 20 cm x 20 cm.

All three seasons, each farmer raised their own rice seedlings in separate plots using farmer's-preserved cv. BRRIdhan28 seeds. The rice seedlings were transplanted during 25-30 January, 2009 for *boro* season of 2009; 25-29 June for *aman* season of 2009; and 05-12 February for *boro* season of 2010.

Fertilizer dose and application methods were same as Experiment 1. In all three years, the basal fertilizers were applied as urea or diammonium phosphate, triple superphosphate, muriate of potash, gypsum, and zinc sulfate which was broadcast before the last two tillage operations in case of CT; 12 to 24 hours prior to rice seedling transplanting in case of ST; and 12-24 hours prior to repairing of the beds. The basal fertilizers were banded under ST at the time of land preparation. The top dressing of urea fertilizers, at a rate 50 - 65 kg ha^{-1} for aman rice was applied at 12-15 days after transplanting (DAT), 20-30 DAT, and 50-60 DAT in all three years.

2.3. Irrigation water management

In boro season, the irrigation was applied from transplanting to tillering stage. The plots were initially supplied with 2-3 cm standing water at each of the irrigation events, and at the later stage 5 cm of standing water was supplied up to grain filling stage. In all treatments, the irrigation water was re-applied after disappearance of standing water and the first signs of hair-line cracks in the surface soil. The number of irrigation applications in each treatment was recorded. The aman season mostly depended on rain water, however, irrigation was applied if necessary to keep at least 2-3 cm of standing water. The total amount of water applied was computed as the sum of water received through irrigation and rainfall.

2.4. Crop protection

In each season, two insecticide applications were used to protect the crop from stem borer, brown plant hopper, rice bug, etc. Non-selective herbicide glyphosate was sprayed at 1.85 kg a.i. ha^{-1} in the field two days prior to final land preparation. For post transplanting weed control, the herbicide Pretilachlor at 450 g ha^{-1} was applied 3 to 5 days after transplanting of rice seedlings, followed by hand weeding at 25 to 30 and 35 to 40 days, in the case of aman and boro rice, respectively.

2.5. Crop harvest

The boro season rice crops from on-farm trials were harvested during 12-17 May in 2009 and 15-22 May in 2010; and the aman season rice of on-farm trials were harvested during 12-16 October, 2009.

2.6. Economic analysis

In Experiment 2, data on labour required were recorded for land preparation, irrigation, and herbicide or insecticide application. Other inputs and labour uses of on-farm trials were considered as constant for all treatments. Total hours (h) required to complete each operation in a particular treatment plot was recorded using a stop watch and converted to person-day ha^{-1} considering 8 hours as equivalent to one person-day and the daily labour wage (mean from 2008 to 2011) was Taka 120 (US$ 1.9) per person day^{-1}.

Each of the treatments of Experiment 2 was evaluated based on total variable cost, gross return, and gross margin. Total variable cost was calculated considering the land preparation cost and labour use. Gross return was calculated by multiplying the amount of produce (grain and straw) by its corresponding price at harvest.

2.7. Statistical analysis

Data on grain, straw, and yield components of rice; and labour use and irrigation frequency were analyzed as a two-way analysis of variance (season by tillage type) with MSTAT-C. Duncan's multiple range test (DMRT) was applied using the same program and was used at the $P<0.01$ level to test the differences among the treatment means.

3. Results

3.1. Grain yield and yield contributing characters

3.1.2. Experiment 1

Across three aman seasons of 2011, 2012, and 2013; 5.97 t ha^{-1} of rice grain yield was recorded in Durgapur site which was statistically greater than at the Godagari site (5.65 t ha^{-1}). Across both of the locations in 2011, the highest rice grain yield was recorded from ST and CT (5.72 t ha^{-1} vs. 5.53 t ha^{-1}; $P<0.05$); and both were significantly higher than BP (5.06 t ha^{-1}) (Figure 1).

In 2012, higher rice grain yields were recorded for CT (7.38 t ha^{-1}) and ST (7.33 t ha^{-1}), and both were significantly higher than BP (6.63 t ha^{-1}) (Figure 1). In 2013, no significant variation on rice grain yield was recorded among the tillage treatments (Figure 1).

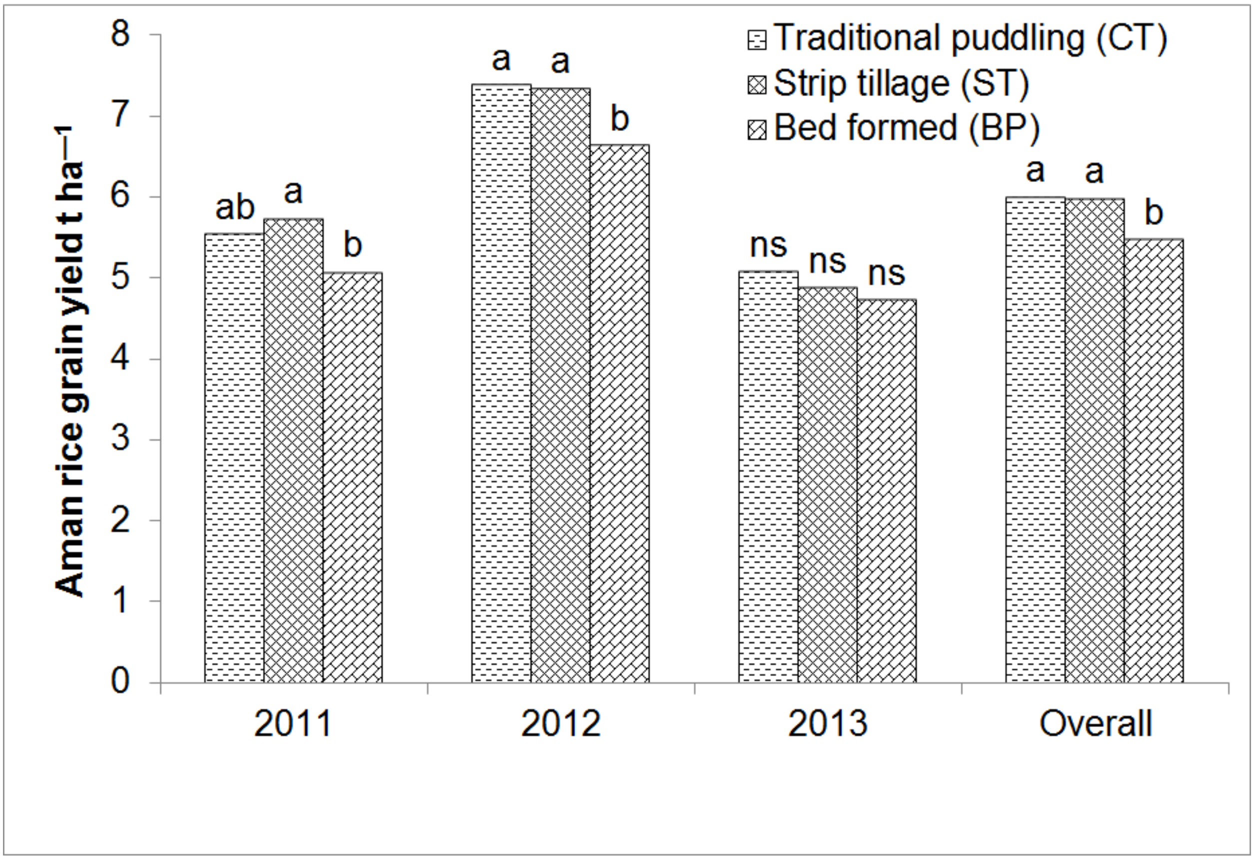

Figure 1. Effect of tillage on aman rice grain yield over the period, Rajshahi (combined of both Durgapur and Godagari sites), Bangladesh. Symbols are as follows: Dashed Horizontal, Outlined Diamond, and Diagonal Brick bars indicate the rice grain yield t ha^{-1} under Traditional puddling (CT), Strip tillage (ST), and Bed formed (BP), respectively.

Among the tillage treatments at Durgapur and Godagari, the mean rice grain yield across three years for CT (5.99 t ha^{-1}) and ST (5.97 t ha^{-1}) was significantly ($P<0.05$) higher than BP (5.47 t ha^{-1}) (Figure 1).

3.1.1. Experiment 2

The highest tiller number (539 m^{-2}) at 80 days after transplanting (DAT), grain yield (5.53 t ha^{-1}), and harvest index (50 %) were recorded in the boro season of 2009, followed by boro season of 2010, and then aman season of 2009 (Table 1). Higher panicle number and grain mass were obtained in the two boro seasons compared to the aman season. The straw yield in the boro season of 2010 was 5.76 t ha^{-1} and statistically similar to the boro season of 2009 but was reduced by about 20 % in the aman season of 2009 (Table 1). Among the seasons, the non-bearing tillers were significantly higher in boro season of 2009 compared to other two seasons (Table 1). All tillage methods produced about 5 t of grain yield ha^{-1} when averaged across seasons with no significant effect of tillage method (Table 2).

Table 1. Mean effects of seasons on rice growth and yield and economic returns (Values are averaged across tillage types: only the main effect of season was significant, P < 0.01).

Parameters	Seasons			CV%
	Boro 2009	Aman 2009	Boro 2010	
Non-bearing tiller (number m^{-2}) §	115a	97b	101b	20
Panicles (number m^{-2}) §	441a	370b	429a	8
1000-grain mass (g) §	21.53a	19.95b	21.20a	4.3
Grain yield (t ha^{-1}) §	5.53a	4.01c	5.33b	6.7
Gross return (US$ ha^{-1}) §	1627a	1015b	1659a	6.7
Gross margin (US$ ha^{-1}) §	1394a	778b	1407a	8.0

§Significant; NS Non-significant. In a row, means followed by a common letter(s) are not significantly different at 1 % level by Duncan's Multiple Range Test.

Table 2. Mean effect of tillage types on grain yield and economic return of rice (the main effect of tillage was significant, P < 0.01 for gross margin only) from on-farm trials.

Parameters	Tillage treatments			
	Traditional puddled	Single pass shallow tillage	Bed formed	Strip tillage
Grain yield (t ha^{-1})^{NS}	4.91	4.98	5.03	4.92
Gross return (US$ ha^{-1}) ^{NS}	1416	1436	1454	1428
Gross margin (US$ ha^{-1}) §	1122b	1209a	1240a	1201a

§Significant; ^{NS} Non-significant. In a row, means followed by a common letter(s) are not significantly different at 1 % level by Duncan's Multiple Range Test.

In boro season of 2009, statistically similar tiller numbers at 80 DAT were recorded in the case of the SPST (566 tillers m^{-2}), CT (552 tillers m^{-2}), and ST (547 tillers m^{-2}); which were significantly higher than in BP (493 tillers m^{-2}) (Table 3). In aman season 2009, significantly lower numbers of tillers were reported in case of traditional puddled (443 tillers m^{-2}) and BP (473 tillers m^{-2}), compared to SPST (465 tillers m^{-2}) and ST (491 tillers m^{-2}). In boro season 2010, the tiller number at 80 DAT was significantly lower (490 tillers m^{-2}) in BP compared to ST (Table 3).

Table 3. On-farm trials' interaction effect of season vs. tillage type on rice yield and yield contributing characters.

Treatments	Tiller number at 80 DAT (m^{-2})[§]	Rice grain yield (t ha^{-1})	Straw yield (t ha^{-1})[§]	Harvest Index (%)[§]	Land preparation cost (US$ ha^{-1})[§]	Transplanting labour (number ha^{-1})[§]	Transplanting labour cost (US$ ha^{-1})[§]	Weeding labour (person-days ha^{-1})[§]	Weeding labour cost (US$ ha^{-1})[§]	Total variable cost (US$ ha^{-1})[§]
Boro 2009 x SPST	566a	5.58	5.65ab	50.1ab	32.75e	52.2b	92.16b	53cde	93cde	218ef
Boro 2009 x CT	552ab	5.40	5.64ab	49.3bcd	88.24b	48.3bc	85.37bc	54cd	96cd	270c
Boro 2009 x BP	493de	5.56	5.72ab	49.6abc	3743c	50.9bc	89.71bc	55cd	96cd	224de
Boro 2009 x ST	547abc	5.59	5.31bc	51.0a	3296e	60.0a	105.79a	46e	82e	221def
Aman 2009 x SPST	465ef	4.08	4.26d	49.0b-e	3493d	45.4cd	80.12cd	65a	114a	229de
Aman 2009 x CT	443f	3.93	4.16d	48.6b-e	88.24b	53.1b	93.68b	63ab	111ab	293b
Aman 2009 x BP	473ef	4.07	4.47d	47.6ef	37.81c	42.8d	75.79d	50de	89de	202f
Aman 2009 x ST	491de	3.94	4.95c	44.4g	32.54e	52.7b	92.96b	55cd	96cd	222de
Boro 2010 x SPST	524bcd	5.28	5.76a	47.9def	33.69de	59.6a	105.12a	56bcd	99bcd	238d

Boro 2010 x CT	516cd	5.39	5.51ab	49.49abc	110.29a	59.8a	105.50a	59abc	103abc	319a
Boro 2010 x BP	490de	5.45	5.83a	48.28c-f	38.06c	42.8d	75.49d	58a-d	102a-d	215ef
Boro 2010 x ST	553ab	5.21	5.93a	46.79f	33.25e	60.3a	106.41a	56bcd	99bcd	238d

§Significant. In a column, means followed by a common letter(s) are not significantly different at 1 % level by Duncan's Multiple Range Test.

CT = Traditional puddling; SPST = Single pass shallow tillage; BP = Bed formed; ST = Strip tillage

Tiller numbers were significantly higher in ST (123 tillers m^{-2}) followed by SPST (112 tillers m^{-2}), CT (100 tillers m^{-2}), and BP (83 tillers m^{-2}), respectively (Table 2). The highest (437 m^{-2}) panicle number was obtained from BP and the lowest (404 m^{-2}) in CT and that was statistically similar to SPST (406 m^{-2}) and ST (407 m^{-2}) treatments (data not shown). The thousand grain weight was also higher (21.4 g^{-1000}) in the BP rice grain which was 2.4, 4.9, and 3.4 % higher than from SPST, CT, and ST, respectively (data not shown). Significantly lower straw yield was recorded in the aman season of 2009 on CT (4.16 t ha^{-1}), SPST (4.26 t ha^{-1}) and BP (4.47 t ha^{-1}) than ST (4.95 t ha^{-1}); however, the harvest index (HI) was significantly lower (44.4 %) in aman season of 2009 on ST (Table 3). Among the tillage treatments, there was no difference among tillage types for the two boro seasons in HI. In boro 2009, HI was statistically similar in SPST (50.1 %), CT (49.3 %), and BP (49.6 %); and only puddled transplanted rice had significantly lower HI compared to ST (49.3 vs. 51 %) (Table 3). In 2010 boro season, the highest HI (49.5 %) was reported in the case of CT rice (Table 3).

3.1.2.1. Rice seedling transplanting

In all seasons, rice seedling transplanting on formed beds had significantly lower labour use i.e., 50.9, 42.8, 42.8 (person-days ha^{-1}.). This is attributed to the fact that BP involved lower number of hills transplanted m^{-2}, and less time was consumed for aligning the row on top of the beds than other tillage methods where strings were needed for accurate alignment of the rows. Among the tillage treatments, the labour use for rice seedling transplanting was highest for ST (57.6 person-days ha^{-1}) but only in the boro 2009 season (Table 3). In subsequent aman and boro 2010 seasons, the labour cost for transplanting ST was similar to that for puddled transplanting. Transplanting costs for labour were significantly lower (by $16-31 ha^{-1}) in BP than CT in aman 2009 and boro 2010 season but not in boro 2009 season (Table 3).

3.1.2.2. Weed control

The labour requirement for weeding in all tillage treatments was statistically similar for both the boro seasons. In aman 2009 season, both BP (50 person-days ha^{-1}) and ST (55 person-days ha^{-1}) had significantly lower labour use for weeding compared to SPST (65 person-days ha^{-1}) and CT (63 person-days ha^{-1}) (Table 3).

3.1.3. Irrigation water use

In both the seasons, BP required 3-4 fewer irrigation events for boro rice cultivation than the other tillage treatments which all had similar numbers of irrigation events. Among the seasons, slightly higher frequency of irrigation was applied (22.3 events) during the boro season of 2009, followed by the boro season (20.8 events) of 2010. The aman season of 2009 was mostly monsoon rain dependent and required only average 2 irrigation events. In the experiment location, irrigation water contractors charged the cost of irrigation based on area irrigated for the full cropping season. Thus, except for the aman season of 2009, no variation was observed among the treatments for irrigation cost.

3.2.1. Economic performance

3.2.1.1. Land preparation cost

Over three seasons, the lowest land preparation cost was recorded in ST ranging from US$32.54[2] to US$33.25 ha^{-1}; and the maximum land preparation cost was incurred in the case of CT corresponding to US$88.24 ha^{-1} in boro and aman during 2009, and US$110.29 ha^{-1} during boro season of 2010 (Table 3).

3.2.1.2. Total variable cost

Significantly higher total variable costs i.e., US$270, US$293, and US$319 ha^{-1}, in boro season 2009, in aman season 2009 and boro season 2010, respectively were recorded for CT (Table 3). The decrease in total variable costs were equivalent to 29, 30, and 38 % for SPST, ST, and BP, respectively, due mostly to lower cost of tillage; and labour use for rice seedling transplanting, and weeding cost (Table 3). Among three seasons, highest total variable cost (US$232.85 ha^{-1}) was incurred for boro rice cultivation in 2009, which was about 7 and 9 % higher, respectively, than the aman season of 2009 and the boro season of 2010 due to higher labour wages, inputs costs, etc (Table 3).

3.2.1.3. Gross return and gross margin

The gross return in boro season rice was US$1627 to US$1659 ha^{-1} which was significantly higher compared to that in the aman season (US$1014 ha^{-1}) of 2009 (Table 1). However, there was no significant difference among the tillage options on gross return (Table 2).

Compared to traditional puddling and transplanting of rice, significantly higher gross margin was accrued for SPST, BP, and ST by about US$87, US$118, and US$79

[2] US$1.00 = Taka 68.00 (exchange rate current in 2009).

ha^{-1}, respectively (Table 2). While boro season had almost double the gross margin of aman season, the effects of tillage were consistent across all seasons (Table 1).

4. Discussion

The unpuddled transplanting treatments provided similar grain yield of rice to that under full tillage and puddling of soil followed by transplanting. Many previous studies on minimum tillage crop establishment have also reported equivalent crop yields to traditional full tillage systems. However, most of the previous research examined minimum tillage *vs.* full tillage rainfed crops (e.g. maize- Sharma et al., 2011) rather than transplanted rice. In a study in Northern India, Sharma et al. (2005) transplanted rice after one pass in wet soil to puddle the soil and reported similar rice yield to transplanting after full soil puddling involving several tillage operations. The present study now shows that a reduced tillage form of unpuddled transplanting of rice also produces similar yield to the conventional crop establishment by transplanting on fully puddled soils. Moreover, it further showed that minimum tillage unpuddled transplanting (following ST or BP) also produces similar rice yield, both in on-farm comparisons in large plots and in two replicated experiments. In the latter case, minimum tillage unpuddled transplanting produced equivalent rice yields to the conventional puddling and transplanting in three consecutive years. This adds to previous results on unpuddled transplanting (e.g., Ladha et al., 2009; Saharawat et al. 2009) which found that unpuddled transplanting into zero tilled soil increased average rice yields on farmer's fields by 0.3 t/ha. The minimum tillage (ST) or zero tillage unpuddled transplanting results contradict the suggestion by Baker and Saxton (2007) that it is not uncommon to experience some yield reduction in the first few no-tillage years, largely because it takes time for the soil to re-establish favourable soil structure after minimum tillage is implemented. This transition period of yield reduction can often be overcome or even averted with increased fertility, strategic fertilizer banding with drill openers and careful crop selection (Baker and Saxton, 2007). While the present study found no cases of decreased rice yield with minimum tillage unpuddled transplanting, Ladha et al. (2009) reported a range of rice yield responses to zero tillage unpuddled transplanting from -0.8 to +1.5 t/ha. Hence there is a need to establish what conditions might lead to decreased yields under unpuddled transplanting, although poor weed control, as discussed below is a likely cause.

While the rice grain yield was unaffected by tillage method, straw yield was higher with ST than other tillage methods and this depressed the harvest index. Singh et al. (2007) reported that wheat sown with ST produced higher straw and grain yield compared to zero tillage, conventional sowing and BP and attributed the improvement to crop establishment in the well tilled strip and the co-location of fertilizer with the seed that increase nutrient availability. In the present study, basal fertilizers were banded near the seed in ST and BP compared to hand broadcasted application for conventional tillage. The relative availability of nutrients to crops under the different tillage methods, especially ST, needs further investigation.

In bed planted rice, the effective row spacing was 29 cm which reduced the plant population relative to other tillage methods that had 20 cm row spacing. Despite lower plant population, equivalent yield was obtained in BP. Hence it is possible that with equivalent plant population, grain yield increases could be obtained with unpuddled transplanting on beds. The present results suggest that wider average row spacing may have helped to increase the number of panicles per plant, thousand grain mass, and to reduce the non-bearing tiller numbers per plant in case of bed planted rice. For cultivars with high tillering capacity, reduced bed size (e.g. 40 cm) could ensure optimal panicle density that might increase grain yield in bed planted rice. Villaseñor-Mir (2008) and Kiliç (2010) reported that achieving optimal yield on narrow raised beds is a variety-specific (Kharub et al., 2008) technology in the case of bread and durum wheat (Triticum durum). Sayre (1998) reported that the crucial step in initiating research on bed-planting of wheat is to test a wide spectrum of varieties with differing heights, tillering abilities, phenology, and canopy architectures in order to understand the proper plant type for optimum performance on beds. Hence there is potential to achieve greater productivity of the unpuddled transplanted rice on permanent beds through research to identify varieties better adapted to this planting approach.

The labour requirement for weeding was lower in CT and SPST than minimum tillage unpuddled transplanted rice since the full tillage systems help to kill weeds before transplanting that reduced weed intensity. Before land preparation, an application of the non-selective herbicide like glyphosate would be useful to control pre-germinated weeds in unpuddled transplanted rice as in the case of minimum tillage wheat (Om et al., 2006), direct seeded rice (Subramanian et al., 2006) and transplanted rice (Natarajan and Kuppuswarmy, 1999). Incomplete submergence of the tops of beds and of soils in the strip tillage treatment enhanced weed emergence. Weed infestation is also a common problem in direct seeding of rice in both wet and dry seeding results in lower grain yield (Singh et al., 2011). Other than hand weeding, there are many pre- and post-transplanting herbicides available (Komatsubara et al., 2009; Zahan et al., 2014). Selection of effective herbicides will play a key role in effective weed control for minimum tillage unpuddled transplanted rice.

Rice seedling transplantation is labour intensive and different tillage methods significantly altered the labour required. Following strip tillage on top of the beds and then 24-hours inundation, farmers could quickly transplant on top of the beds since less time was spent lining up rows; however, in the case of strip tillage, transplanting took longer due to less visibility under the submerged condition of the tilled strip preferred for transplantation. A possible solution to this problem is a wider strip. In addition, retaining less standing water in the field until after transplanting is complete may improve visibility of the tilled zone to speed up unpuddled transplanting after strip tillage. However, incomplete submergence may also compromise the effectiveness of early weed control.

All one-pass tillage systems i.e., SPST, BP and ST attained higher gross margin compared to conventional transplanting into puddled soil but the one-pass methods were all similar (Table 2). There were lower expenses incurred for input use with one-pass minimum tillage and higher earnings from output sales. Reductions in water use as reported in the present study with unpuddled transplanting did not increase the gross margin. In the study area, farmers pay for irrigation water on an area basis, rather than for water volume used. Hence there is limited price incentive to reduce water use at present although declining groundwater levels in the study areas suggest an imperative to reduce water use for sustainability of the water resource (Rahman and Mahbub, 2012). A change in water pricing policy to a charge for volume of water used would be advantageous to water saving planting methods used for unpuddled transplanting, especially bed planting. Indeed pricing water based on volume consumed is increasingly practiced in Bangladesh (Md. Nur Mohammed, Department of Agriculture Extension, Rajshahi, personal communication) and hence should encourage a shift to rice establishment methods that save water, like minimum tillage unpuddled transplanting. It should further be noted that no attempt was made in the present study to optimize irrigation water requirements in different minimum tillage methods for growing rice after unpuddled transplanting. The present study suggests that reduced water is required but not by how much or what is the minimum water requirement in different tillage methods to grow rice in unpuddled systems. It is possible that greater saving than reported here are possible.

Validation of minimum tillage unpuddled transplanting and other one-pass unpuddled methods for rice land preparation requires additional research and development. Such investigations should consider improved tillage implements. There may be merit in altering the speed of rotating blades, the depth and the width of slots to prepare an optimum soil tilth for unpuddled transplanting in ST. Single pass shallow tillage, BP and ST need testing in more diverse agro ecological conditions through on-farm trials to determine how robust these methods are for rice establishment by unpuddled transplanting. The soil type, tilth and cloddiness may interact with the length of wetting in order to facilitate unpuddled transplanting. In addition, sandy soils may re-gain high strength after wetting much faster than clay soils and this will affect the window of time when unpuddled transplanting can be effectively accomplished by manual labour (e.g., White et al., 1997). Mechanized transplanting into unpuddled soils is another labour- and cost-saving option worth investigation following initial evaluation by Hossen et al. (2014).

The present rice cultivars have been selected under puddled transplanting. It remains unclear whether these cultivars are most suitable for minimum tillage unpuddled rice or other forms of unpuddled transplanting. Above we have discussed a possible advantage of cultivars with high tillering capacity for BP. For minimum tillage methods, early vigor of transplanted seedlings would be beneficial for suppressing weeds (Dingkuhn et al., 1999). Changes in nutrient availability and soil strength under unpuddled transplanting may also favour cultivars with greater early rooting vigor or nutrient uptake efficiency (Borrell et al., 1998). The lower HI under ST may point to reduced nutrient availability with the minimum soil disturbance and a need for either altered fertilizer regimes or more nutrient use efficient cultivars for ST. However, initial studies on the N fertilizer requirements for rice under unpuddled transplanting following ST have shown no change in fertilizer N requirement versus conventional puddling (Jahiruddin et al., 2014).

The present study examined responses of single rice crops in Experiment 2 to unpuddled transplanting in three different seasons. However, rice is grown in 2- or 3-crop rotations in South and South-East Asia rice-based systems on over 12 million ha (Aggarwal et al., 2004). In Experiment 1, we also examined at two sites the response to ST and BP practiced repeatedly for 3 crops per year, so that the rice crop examined were crops 3, 6 and 9, respectively in the sequence. The benefit of minimum soil disturbance and crop residue retention which are achieved by unpuddled transplanting of rice seedlings into beds and following ST need to be assessed for the remaining crops in the systems. Moreover the benefits of unpuddled transplanting of rice seedlings over several years need to be assessed, as soil organic matter accumulates and soil structure develops. Other long term trends for unpuddled transplanting of rice such as weeds, disease, and insects would also need to be monitored.

5. Conclusions

From 27 on-farm comparisons, across three seasons, the present study demonstrates that minimum tillage unpuddled rice transplanting was feasible without any yield penalty. Moreover, the unpuddled rice transplanting in different tillage systems reduced the cost of rice cultivation and frequency of irrigation events in the case of BP which would ultimately enhance gross margin for the rice farmers. In three consecutive years in two replicated experiments minimum tillage unpuddled transplanting produced equivalent rice yields to the conventional puddling followed by transplanting. This suggests that the benefits from unpuddled transplanting in terms of cost and water savings can be sustained over time. Hence there is solid evidence in farmers' fields that minimum tillage unpuddled rice transplanting could be an option for rice establishment under CA systems. This suggests that several minimum tillage unpuddled transplanting options i.e., bed formed, or strip tillage could be promoted in the traditional puddled boro and aman rice areas where direct seeding is not possible or feasible. Alternatively, these unpuddled transplanting options for rice can supplement the practice of direct seeding rice establishment where the latter is not feasible. Further validation of this approach requires research and development on suitable tillage implements, evaluation of better land preparation methods under minimum tillage systems and testing in more diverse agro-ecological conditions and soils through on-farm trials.

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