Expl Agric.: page 1 of 19 © *Cambridge University Press 2017*
doi:10.1017/S0014479717000370

MECHANISED MINIMUM SOIL DISTURBANCE ESTABLISHMENT AND YIELD OF DIVERSE CROPS IN PADDY FIELDS USING A TWO-WHEEL TRACTOR-MOUNTED PLANTER SUITABLE FOR SMALLHOLDER CROPPING

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(*Accepted 19 June 2017*)

SUMMARY

Shortages of hired labour are leading to greater interest in mechanisation for crop establishment in smallholder agriculture. Due to small field sizes, mechanised planters mounted on four-wheel tractors are not a suitable technology. The Versatile Multi-crop Planter (VMP) was developed for zero tillage (ZT), strip planting (SP) or single pass shallow tillage (SPST) on flat land and for forming and planting on tops of beds, each in a single pass operation, when mounted on a two-wheel tractor (2WT). The aim of the present study was to evaluate the field performance of the VMP in comparison to conventional broadcast seeding and full rotary tillage (2 to 4 passes; called CT) for establishing chickpea (*Cicer arietinum* L.), jute (*Corchorus olitorius* L.), lentil (*Lens culinaris* Medikus), maize (*Zea mays* L.), mung bean (*Vigna radiata* L. R. Wilczek), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) in 15 locations of Bangladesh. Plant populations emerging from all single pass operations viz. SP, ZT, and bed planting (BP) were generally satisfactory and in 12 out of 15 experiments plant populations after SP were similar to or greater than after CT. In addition, SP gave comparable or greater plant populations than SPST and BP planting methods. Overall, the SP planting achieved comparable yields and lower costs of establishment than CT. We conclude that effective and reliable planters are now available for sowing a range of crop species on small fields with minimum soil disturbance. This opens up realistic options for the development of mechanised conservation agriculture suited to small field sizes.

INTRODUCTION

Mechanised sowing of crops is spreading across Asia and Africa, but in these regions four-wheel tractors (4WT) with planters are often too expensive for most smallholder farmers. Moreover, since average field sizes are typically smaller than 1000 m^2, 4WT are generally too large to manoeuvre and provide effective tillage at acceptable cost

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(Johansen *et al.*, 2012). For these reasons, 2WT have become very popular in China (10 million), Thailand (2.6 million), Philippines (1.5 million), Bangladesh (700 000) and India (117 000) (Haque *et al.*, 2016a). Presently, the 2WT are mostly operated in fully rotary tillage mode (Johansen *et al.,* 2012). However, there are promising developments in minimum soil disturbance planters for 2WT (Haque *et al.,* 2016a; 2018; Johansen *et al.*, 2012). The one widely used option in Bangladesh to date is the Single Pass Shallow Tillage planter (SPST), also known as the Power Tiller Operated Seeder (PTOS), involving shallow full rotary tillage of the top soil (up to 0.04 m) (Roy *et al.*, 2009; Wohab *et al.,* 2007). Full tillage such as this can be harmful to soil structure and soil health (Johansen *et al.*, 2012). In addition, the shallow depth of tillage results in shallow seed placement that makes rainfed crops more vulnerable to drought (Baker and Saxton, 2007a).

Mechanised tillage and row sowing with 2WT-mounted planters can be adapted for minimum soil disturbance operations by strip planting (SP) or zero tillage (ZT) (Johansen *et al.,* 2012; Krupnik *et al.,* 2013). Planting crops such as wheat on shallow raised beds (called Bed planting (BP) here) is also common in the North-West of Bangladesh (Krupnik *et al.*, 2013; Miah *et al.*, 2014). Disturbance of the surface soils decreases in the sequence from SPST and BP to SP to ZT. These mechanised planting operations allow sowing in a single pass and therefore decrease time from harvest of one crop to sowing the next. In intensive cropping systems that are common in the Eastern Gangetic plain (EGP), there is limited time between harvest and planting of the next crop and delays due to tillage are harmful for timely sowing of the next crop. Any delays to planting may lead to limiting conditions (soil, temperature, water) for either crop establishment or for subsequent crop growth and yield (e.g. for chickpea, see Vance *et al.,* 2014; for wheat, see Kamruzzaman *et al.,* 2001).

One option for decreasing costs of production is mechanised single pass planting that allows for the concurrent sowing of the seed and placement of fertiliser into rows. In addition, minimum soil disturbance planting and other single pass tillage operations save seed, fuel and labour costs and allow a higher net income (Gathala *et al.,* 2015; Johansen *et al.,* 2012). Tillage costs using CT are relatively high (Lal, 2009) and costs of crop production in Bangladesh are high relative to other countries (Roy *et al.,* 2009). Decreasing costs of crop production through mechanised single pass sowing will make locally grown crops more competitive with cheap imports.

In the diversified cropping systems of the EGP, characterised by small and fragmented land holdings, farm managers benefit if they have a choice of crop establishment options (ZT, SP, SPST and BP). Across the lowlands of the EGP, a diverse range of crops are grown in the cool, dry season after rice harvest and in the pre-monsoon season, notably wheat, maize, rice, lentil, chickpea, jute, mustard (*Brassica juncea* (L.) Czern) and mung bean. These crops vary not only in seed size and seed rate but also row spacing and plant-to-plant spacing. Until recently, all planters mounted on 2WT were capable of planting in only one or two of these planting modes (commonly SPST, BP and/or SP), limiting the planting choices (tillage type and crop) of farmers and the options for local service providers to hire out their planter for contract sowing (Johansen *et al.,* 2012). With the advent of the Versatile

Multi-crop Planter (VMP), multiple planting options including ZT, SP, SPST on the flat together with BP (both new and permanent beds), and even conventional tillage (CT) seeding options and the capacity to handle variations in seed size, seed rate and row spacing are now available in a single planter (Haque *et al.,* 2011a). Both Dongfeng and Saifeng 2WT that are widely available in Bangladesh can be hitched to VMPs (Haque *et al.,* 2011a). The redesigned square rotary shaft and easily adjustable and removable blades are novel features of the VMP allowing rapid set up for the different planting options (Haque *et al*., 2011a). The flexible blade adjustment system enables row spacing to be adjusted for varied crop establishment options among fields by the operators with minimal time delay. However, until now there was limited experimental evidence that planters for 2WT such as the VMP are able to establish satisfactory crop stands in different tillage modes and with different crops.

The aims of the present study were to (i) evaluate establishment of a wide range of non-rice crops sown with the VMP under diverse conditions, with single pass and minimum soil disturbance planting in dry, early wet and main wet seasons; (ii) determine in a selection of cases whether the yield is comparable to existing planting practices involving multiple-pass full tillage operations and broadcast seeding; and (iii) quantify the associated costs and labour requirements of crop establishment with the different planting modes.

MATERIALS AND METHODS

The experiments

The VMP was evaluated with various crops and soils across 17 districts of Bangladesh. However, data for this paper are based on 15 experiments in Rajshahi, Thakurgaon, Panchagarh and Gazipur districts with seven crop species (Supplementary Figure S1 (available online at https://doi.org/10.1017/S0014479717000370); Table 1). These districts of Bangladesh are situated in the North (Thakurgaon and Panchagarh), Northwest (Rajshahi) and central (Gazipur) parts of the country, creating a range of weather conditions, soil types, sowing times and cropping rotations over which the VMP was tested. Since the aim of the study was to assess the crop establishment performance with the VMP, 12 of experiments only reported on VMP operations for crop establishment and the plant populations while only three determined crop yield. Subsequent papers will focus on crop growth and yield. The configuration of the four different planting types and the conventional tillage are as follows: SP: 0.02–0.04 m wide and 0.04–0.05 m deep tilled strips were made (that preserved about 80% of untilled soil) in untilled flat land by VMP. Seed and fertilizers were placed at the base of the strips by a tyne opener in single pass operation; SPST: up to 0.06 m depth of surface soil was fully disturbed by rotary tynes operated by the VMP that placed basal fertilizers and seed in rows in a single pass operation; ZT: deep slits (0.06 m) up to 0.04 m wide were made (about 80% undisturbed soil) with tyne openers in untilled flat land by VMP. Seed and fertilizers were placed simultaneously behind tyne openers in a single pass operation; BP: beds 0.25–0.30 m wide at the top and 0.58–0.60 m wide at the base (height from the furrow

Table 1. Details of field trials sown with the Versatile Multi-crop Planter (VMP) in different tillage modes. [1]CT = conventional tillage; SP = strip planting; BP = bed planting; SPST = single pass shallow tillage; [2]EP = emergence population; NS = nodulation scoring; FP = final plant count, GY = grain yield, SY = straw yield.

Experiment number, location (district-upazila), and replication (n)	Sowing date	Soil type	Crop species and cultivar	Tillage treatments[1]	Depth of seeding (m)	Seed rate (kg ha^{-1})	Irrigation (Yes/No)	Data collected and reported[2]
1. Rajshahi-Durgapur (4)	10–11 Nov 2010	Silty loam	Lentil (BARI Masur 6)	CT, SP, BP	0.03	34	Yes	EP, NS, FP, GY, SY
2. Panchagarh-Atwari (4)	8–9 Nov. 2009	Loam/silty loam	Lentil (BARI Masur 3)	SP, SPST, BP	0.03–0.05	34	No	EP
3. Thakurgaon-Sadar (4)	10–11 Nov. 2009	Loam/silty loam	Lentil (BARI Masur 4)	CT, SP	0.03–0.05	34	No	EP, NS
4. Thakurgaon-Sadar (6)	2–4 Dec. 2010	Loam/silty loam	Lentil (BARI Masur 4)	SP, SPST, BP	0.03–0.05	34	No	EP, NS
5. Sadar-Gazipur (3)	1 Nov. 2009	Clay loam	Lentil (BARI Masur 5)	CT, ZT, SP, SPST, BP	0.03	34	Yes	EP
6. Rajshahi-Sadar (3)	25 Nov. 2009	Sandy clay	Chick-pea (BARI Chola 5)	CT, SP	0.05–0.08	45	No	EP, NS, FP, GY, SY
7. Thakurgaon-Sadar (4)	20 Nov. 2009	Loam/silty loam	Chick-pea (BARI Chola 5)	CT, SP	0.05	37.5	No	EP, NS
8. Gazipur-Sadar (3)	1 Nov. 2009	Clay loam	Chick-pea (BARI Chola 5)	CT, ZT, SP, SPST, BP	0.03	42	Yes	EP
9. Rajshahi-Godagari (4)	12 Apr. 2011	Silty clay loam	Mung bean (BARI Mung 5)	CT, SP, BP	0.03	38	Yes	EP, NS
10. Rajshahi-Durgapur (4)	23 Mar. 2011	Silty loam	Mung bean (BARI Mung 6)	CT, SP, BP	0.04	38	Yes	EP, NS, FP, GY
11. Gazipur-Sadar (12)	1–3 Nov. 2010	Clay loam	Maize (NK 46)	CT, BP	0.04	18	Yes	EP
12. Gazipur-Sadar (14)	1–3 Nov. 2010	Clay loam	Rice (BRRI Dhan 28)	SP, SPST, BP	0.04	28	Yes	EP
13. Gazipur-Sadar (3)	1 Nov. 2010	Clay loam	Wheat (Prodip)	CT, ZT, SP, SPST, BP	0.03	120	Yes	EP
14. Rajshahi-Godagari (4)	13 Dec. 2010	Silty loam	Wheat (Prodip)	CT, SP, BP	0.04–0.06	120	Yes	EP, FP, GY, SY
15. Gazipur-Sadar (3)	9 Mar. 2010	Clay loam	Jute (O 897)	CT, ZT, SP, SPST, BP	0.02	3.5	Yes	EP

to the bed top was about 0.18–0.20 m) were made by VMP and seed and fertilizers were placed in rows near the two edges of the beds in single pass with the VMP; and Conventional tillage and planting (CT): Land preparation was done by locally hired 2WT using four rotary tillage passes in dry land followed by two levelling passes. Seed and basal fertilizers were broadcast manually before the last tillage operation.

Rajshahi district

The experiments were conducted in Digram and Choighati (in Godagari upazila), Agoilpur (Rajshahi Sadar upazila) and Alipur (Durgapur upazila) villages in Rajshahi district. The average annual rainfall of Rajshahi district is 1200 mm of which 80% falls during June to September (Mazid *et al.*, 2002). Monthly mean temperatures during November, December, January, February, March and April for Durgapur upazila and Godagari upazila are shown in Table S1 (Anonymous, 2017). In the High Barind Tract (HBT) of Rajshahi, grey terrace soils are predominant (Brammer, 1996). The HBT soils (Godagari site) had silty clay texture while those from the Durgapur site were sandy loam.

Dry and cool season lentil, chickpea and wheat were grown from November–December to March–April. All crops were grown in farmer's fields. Details of the experiments are reported in Table 1.

Thakurgaon and Panchagarh districts

Three experiments were conducted in Thakurgaon district in Sadar upazila, and one experiment in Panchagarh district of Atwari upazila. The average annual rainfall of Thakurgaon and Panchagarh districts is 2147 mm of which about 90% occurs during May to September (weather data reported from nearest weather station at Dinajpur district). Monthly mean temperatures during November, December, January, February, March and April for In Sadar upaliza, Thakurgaon are shown in Table S1 (Anonymous, 2017). The soil texture at the trial sites in farmers' fields was sandy loam. Details of the trials are shown in Table 1. Dry and cool season lentil and chickpea were planted during November.

Gazipur district

The average annual rainfall of Gazipur district is about 2036 mm of which about 80% rainfall occurs during May to September. Monthly mean temperatures during November, December, January, February, March and April for Gazipur, upaliza are shown in Table S1 (Anonymous, 2017). In 2009, a lentil trial (Experiment 5, Table 1) was carried out at the Bangladesh Sugarcane Research Institute (BSRI), Joydebpur, Gazipur. In addition, four on-station trials (Experiments 8, 11, 12 and 13, Table 1) examined the crop establishment performance of VMP for wheat, chickpea, lentil and jute. A separate trial (Experiment 12 in Table 1) was conducted at BSRI to establish direct seeded rice (DSR) using a vertical disk seed meter.

Crop establishment and management practices

In all experimental sites, the lentil, mung bean and DSR were sown by VMP at 0.2 m row spacing except in BP systems, where considering the whole planted area, including the inter-bed space, the effective row spacing was 0.29 m. The maize seed was planted in rows 0.6 m apart, and 0.18–0.25 m plant-to-plant spacing. Before sowing, the lentil, chickpea and mung bean seeds were primed with sodium molybdate and *Rhizobium* at 1.5 g kg^{-1} and 10 g kg^{-1}, respectively, following the practice of Johansen *et al.* (2007). Plot size for all crops was in the range 100 to 1750 m^2.

At planting, triple super phosphate fertiliser (20% P, 1.3% S and 20% Ca) was used as basal P fertiliser for all lentil, chickpea and mung bean crops at the rate of 100 kg ha^{-1}. For wheat, 150 kg of diammonium phosphate ha^{-1} (18% N and 20% P), 110 kg of muriate of potash ha^{-1}, 123 kg of gypsum ha^{-1}, 6 kg of boron ha^{-1} were applied as basal fertiliser. For rice 27, 10, 30, 5, 2 and 1 kg ha^{-1} of N, P, K, S, Zn and B, respectively, were applied using the same fertilisers as for wheat. The basal fertiliser applied in the maize crops was 185, 275, 275, 185, 17 and 12 kg ha^{-1} of urea, triple super phosphate, muriate of potash, gypsum, zinc sulphate and boric acid, respectively. In the case of direct-seeded rice, topdressings of urea fertiliser at the rate of 58 kg ha^{-1} were applied at 30 days and 55 days after sowing. Two urea top dressings at the rate of 185 kg ha^{-1} were applied to maize at 38 and 62 days after sowing.

Generally, no irrigation was applied for lentil and chickpea cultivation. Before emergence, a light irrigation was applied to rice, wheat, maize, mung bean and lentil plots of the Godagari site; and all crops at Sadar upazila in Gazipur district to ensure favourable moisture for plant establishment. Wheat was irrigated at 21, 49 and 68 days after sowing. The maize crop was irrigated four times at 26, 48, 67 and 84 days after sowing. In Gazipur, the rice field was irrigated twice at 14 and 20 days after sowing.

In case of lentil, mung bean and chickpea, weeds were hoed when shoots were about 0.1 m tall. The first hoeing of weeds was done in the wheat, maize and rice fields at 22–30, 25 and 20 days after sowing, respectively. A second-hand weeding was done in maize and rice fields at 48 and 40–45 days after sowing, respectively.

At early seedling stage, Rovral® (*Iprodione*) at the rate of 0.5 kg ha^{-1} and Bavistin® (*Carbendazim 50%*) at the rate of 0.75 kg ha^{-1} were applied 2–4 times in lentil and chickpea plots of Thakurgaon Sadar (Experiments 3, 4, 7, Table 1) and Atwari upazila (Experiment 2, Table 1) to control root disease. Ripcord® (21.1% Cypermethrin, 70.5% Xylene) at the rate of 250 mL ha^{-1} and Helicoverpa Nuclear Polyhedrosis Virus (HNPV) was applied in Rajshahi chickpea fields (Experiment 6, Table 1) to control pod borer (*Helicoverpa armigera*). The HNPV was sprayed at the time the small size larvae (<1.5 cm) appeared in the fields.

Plant population

For the evaluation of crop establishment after sowing with the VMP in different soils, we collected emergence data from 15 experimental locations with seven crop

Table 2. Emergence of crop species (plants m^{-2}) under different tillage systems with the Versatile Multi-crop Planter. Values are means of 3–4 replicates (n) (± standard errors). CT = conventional tillage; ZT = zero tillage; SP = strip planting; SPST = single pass shallow tillage; BP = bed planting.

		Tillage					
Experiment, district-location	Crop	CT	ZT	SP	SPST	BP	LSD
1. Rajshahi-Durgapur	Lentil	133 ± 11	–	167 ± 16	–	156 ± 22	ns
2. Panchagarh-Atwari	Lentil	–	–	50	53	53	ns
3. Thakurgaon-Sadar	Lentil	55	–	52	–	–	ns
4. Thakurgaon-Sadar	Lentil	54 ± 1	–	56 ± 4	–	–	ns
5. Sadar-Gazipur	Lentil	26 ± 5	122 ± 11	202 ± 12	146 ± 10	121 ± 11	42.7
6. Rajshahi-Sadar	Chick-pea	33 ± 2	–	34 ± 1	–	–	ns
7. Thakurgaon-Sadar	Chick-pea	51 ± 7	–	53 ± 9	–	–	ns
8. Gazipur-Sadar	Chick-pea	39 ± 4	29 ± 3	28 ± 4	51 ± 8	26 ± 3	22.0
9. Rajshahi-Godagari	Mung bean	57 ± 9	–	24 ± 2	–	24 ± 2	16.2
10. Rajshahi-Durgapur	Mung bean	62 ± 3	–	68 ± 2	–	72 ± 9	ns
11. Gazipur-Sadar	Maize	5 ± 1	–	–	–	7 ± 1	1.27
12. Gazipur-Sadar	Rice	–	16 ± 1	–	17 ± 1	17 ± 2	ns
13. Gazipur-Sadar	Wheat	140 ± 7	183 ± 12	178 ± 8	128 ± 8	63 ± 11	59.7
14. Rajshahi- Godagari	Wheat	128 ± 11	–	90 ± 4	–	132 ± 5	16
15. Gazipur-Sadar	Jute	28 ± 3	81 ± 9	93 ± 7	82 ± 10	77 ± 7	38.5

Table 3. Final plant count (plants m^{-2}) of lentil, chickpea, mung bean and wheat under different tillage methods. Values are means of 3–4 replicates (n). CT = conventional tillage; SP = strip planting; BP = bed planting.

		Tillage		
Experiment, district-location	Crop	CT	SP	BP
1. Rajshahi-Durgapur	Lentil	129 ± 11	155 ± 11	145 ± 20
6. Rajshahi-Sadar (Choighati)	Chickpea	51 ± 11	50 ± 3	–
10. Rajshahi-Durgapur	Mung bean	32 ± 2	36 ± 2	39 ± 4
14. Rajshahi-Godagari	Wheat	100 ± 11	87 ± 1	86 ± 7

species (Tables 1 and 2). In addition, final plant population was counted in lentil plots during harvesting at Durgapur upazila (Experiment 1, Table 3). In the case of chickpea, the final plant population was recorded at the trial of Rajshahi Sadar (Experiment 6, Table 3). The mung bean (Experiment 10, Table 3) and wheat final plant populations were recorded from the trials at Durgapur (Experiment 14, Table 3). The data were collected from three or four quadrats (each quadrat was 0.5 m^2), randomly selected from locations in each plot.

Evaluation of crop growth, yield and yield contributing characters

In addition to crop establishment and VMP performance, which was the main purpose of this study, at three experiments (Experiments 1, 6 and 14, Tables 1 and 5) we evaluated the tillage effect on grain and straw yield at harvest. The above-ground biomass was split into grain, and stem plus leaf recorded from quadrats (0.5 m wide and 1 m long in three or four locations from each plot) of lentil plots in Durgapur upazila (Experiment 1, Tables 1 and 5) and wheat in Godagari upazila of

Rajshahi (Experiment 14, Tables 1 and 5) While only yield was obtained for chickpea in Rajshahi Sadar (Experiment 6, Tables 1 and 5).

Twenty legume plant (lentil, chickpea and mung bean) roots were excavated from 1 m^2 quadrats placed randomly within experimental plots. The nodulation score was rated on the basis of nodule number and mass by using visual rating criteria proposed by Rupela (1990).

Machine performance data collection

The VMP was used to establish all crops for all planting modes except for CT. As the seed meter of VMP was connected by a chain-sprocket arrangement to the 2WT wheel axle, the speed of the tiller was not a factor in seed calibration, unless there was wheel slippage. The wheel slippage and operating speed were calculated according to Michael and Ojah (1978). Data on labour requirement, operational time, time loss and field capacity were recorded during the field operation. The time losses due to turning, clogging and operators' personal needs were also recorded. Field capacity (the field area covered per unit time, ha hr^{-1}) was determined using the formulae of Hunt (1973).

Data analysis

Data for each species were analysed as a one-way analysis of variance (for planting type effects) using MSTATC and Excel programs for mean and standard error (SE) calculation.

RESULTS

Crop establishment

Plant population for lentil at Durgapur (Experiment 1) was similar at emergence (133–167 plants m^{-2}) for CT, SP and BP planting methods with very little loss of emerged plants by harvest (Tables 2 and 3). At the Gazipur trial (Experiment 6, Table 2), planting by single pass methods increased lentil plant populations from 26 to 121–202 plants m^{-2}, with maximum population obtained with SP. By contrast, in the Northern districts of Thakurgaon (Experiments 3 and 5, Table 2), and Panchagarh (Experiments 2 and 4, Table 2), plant populations with CT and single pass planting methods were < 55 plants m^{-2}. Foot rot diseases (caused by *Fusarium oxysporum* and *Sclerotium rolfsii*) were observed in lentil with all planting methods in the Northern locations, attributed in part to high soil water at sowing and during emergence.

In all chickpea experiments, the plant populations after emergence ranged between 26 and 57 plant m^{-2}. Recommended plant populations for chickpea across the region are 18 to 33 plants m^{-2} (Ali *et al.*, 2007; Johansen *et al.*, 2008a; Saxena, 1987). In chickpea experiments, planting by CT produced satisfactory plant populations (Experiments 6, 7 and 8, Table 2). Single pass planting likewise produced satisfactory plant populations that were not significantly different from CT in most cases. Chickpea at Gazipur (Experiment 8, Table 2) had significantly higher plant populations (51 plants m^{-2}) emerging from SPST than other planting methods (Table 2).

Table 4. Nodulation scoring of lentil, chickpea, mung bean roots under different tillage systems. Values are means of 3–4 replicates. Scoring of nodulation (1–5 scale, with 1 = minimal nodulation and 5 = supra-nodulation) on the basis of nodule number and mass by using visual rating criteria given by Rupela (1990). CT = conventional tillage; SP = strip planting; SPST = single pass shallow tillage; BP = bed planting.

Experiment, district-location	Crop	Tillage			
		CT	SP	SPST	BP
1. Rajshahi-Durgapur	Lentil	1.4 ± 0.16	1.2 ± 0.17	–	1.3 ± 0.04
2. Panchagarh-Atwari	Lentil	–	1.2 ± 0.31	1.1 ± 0.12	1.2 ± 0.23
3. Thakurgaon-Sadar	Lentil	1.6 ± 0.48	1.9 ± 0.25	–	–
6. Rajshahi-Sadar	Chickpea	3.2 ± 0.45	3.3 ± 0.25	–	–
7. Thakurgaon-Sadar	Chickpea	1.4 ± 0.48	1.8 ± 0.29	–	–
9. Rajshahi-Godagari	Mung bean	1.9 ± 0.11	1.8 ± 0.20	–	1.8 ± 0.10
10. Rajshahi-Durgapur	Mung bean	3.3 ± 0.13	2.7 ± 0.12	–	2.6 ± 0.12

The mung bean plant population in CT (Experiment 9, Table 2) was twice as high as SP and BP both of which had unsatisfactorily low populations. By crop maturity, the mung bean plant populations in Experiment 10 dropped by about 50% compared to emergence, but the decline was similar for all planting methods (Table 3). In experiment 10 at Durgapur, all planting methods (CT, SP and BP) produced similar and adequate plant populations (Table 3).

With CT planting, the emerged maize population was 75% of the optimal population of 6.7 plants m^{-2} in Bangladesh (Haque *et al.*, 2006), while the target populations were achieved by the BP system using the VMP (Experiment 11, Table 2).

For direct seeding of rice, there is no basis for comparison to the CT as planting involves full puddling and transplanting. The emergence count of direct-seeded rice was between 16 and 17 plants m^{-2} with no significant difference between planting methods (Experiment 12, Table 2).

When sown by CT, wheat achieved 128–140 plants m^{-2} (Experiments 13 and 14, Table 2). The SP and ZT planting operations produced similar plant populations as CT at Gazipur (Experiment 13, Table 2). At Durgapur, BP gave the same wheat plant population as CT, while SP had 30% fewer plants. However, wheat plant populations at maturity were comparable for all planting methods on account of greater loss of plants in CT and BP than SP (Experiment 14, Table 3).

At the Gazipur experiment, the jute plant population of all single pass sowing methods ranged from 77 to 93 plant m^{-2} which was about three fold higher than planting by CT (Experiment 15, Table 2).

Nodulation of pulse crops

A nodulation score of 3 or more is associated with vigorous legume growth in soils of low mineral nitrogen status (Rupela 1990 and subsequent experience in using that methodology; C. Johansen personal communication). There was limited nodulation of lentil with scores between 1.1 and 2 across all planting methods (Experiment 1, Table 4). The nodulation score of chickpea was adequate in all planting methods at Rajshahi sites (2.47 to 4.2, Experiment 6) while the score was < 2 at Thakurgaon

Table 5. Grain and straw yield (kg ha^{-1}) of lentil, chickpea and wheat under different tillage methods. Values are means of 3–4 replicates ± standard errors. CT = conventional tillage; SP = strip planting; BP = bed planting.

Experiment, district-location	Crop	Tillage CT	Tillage SP	Tillage BP	LSD
		Grain yield			
1. Rajshahi-Durgapur	Lentil	1843 ± 170	1814 ± 78	1475 ± 108	313
6. Rajshahi-Sadar	Chickpea	1790 ± 38	1872 ± 55	–	ns
14. Rajshahi-Godagari	Wheat	3414 ± 176	3305 ± 78	3437 ± 155	ns
		Straw yield			
1. Rajshahi-Durgapur	Lentil	1873 ± 150	2190 ± 369	1521 ± 84	
14. Rajshahi-Godagari	Wheat	4659 ± 183	4758 ± 159	4531 ± 114	

(Experiment 7), where excessive soil water at planting may have inhibited nodule formation (Table 4). At Rajshahi, chickpea nodulation scores in SP were similar to CT (Experiments 6 and 7). During 2010, the mung bean at Godagari had a low nodulation score in all planting types (Experiment 9, Table 4). Mung bean at Durgapur in CT had a nodulation score which was 20% and 25% higher than the SP and BP, respectively (Experiment 10, Table 4).

Grain and straw yield of lentil, chickpea and wheat

Lentil planted by CT at Durgapur had a grain yield of 1843 kg ha^{-1}, which was similar to SP, but 25% higher than BP (Experiment 1, Table 5). By contrast, SP produced higher straw yield than CT while straw yield in BP was lower than CT (Experiment 1, Table 5). Chickpea in the Rajshahi Sadar produced 1790 kg of grain ha^{-1} in CT, which was comparable to that with SP planting (Experiment 6, Table 5). Wheat grain and straw yield were not significantly different between CT, SP and BP in Durgapur (Experiment 14, Table 5).

Costs and labour inputs at crop establishment

The field capacity for CT-planted crops was lower than for all single pass planting except for BP with jute and lentil (Table 6). Where single pass planting treatments (SP, ZT, SPST) were used to sow chickpea, jute and wheat, the field capacity was similar (Table 6). The field capacity for lentil and jute establishment using SP was higher than for BP but for other crops it was similar. Indeed the field capacity for lentil SP was significantly higher than all other planting methods and was never lower than other single pass planting methods for other crops. Single pass planting methods had a field capacity of 0.08 to 0.11 ha hr^{-1} for chickpea and wheat, while they were lower for jute (0.06–0.08 ha hr^{-1}) and lentil (0.06–0.11) (Table 6).

Under CT, highest fuel consumption was reported for planting wheat (41 L ha^{-1}) followed by jute, lentil and chickpea (Table 6). The CT fuel consumption exceeded that for SP and SPST for all crop species. The relative fuel consumption for SP compared to CT ranged from 14% in jute to 19% in lentil, 24% in wheat and 25% in chickpea. ZT also reduced fuel consumption relative to CT in all crops except jute.

Table 6. Performance evaluation of the Versatile Multi-crop Planter for the field capacity, fuel consumption, labour use for land preparation and total cost of land preparation (fuel plus labour usage) to establish wheat, chickpea, lentil and jute at the Sadar upazila, Gazipur district, Bangladesh, 2010. ZT = zero tillage; SPST = single pass shallow tillage; SP = strip planting; BP = bed planting; CT = conventional tillage.

Treatments	Number of tillage passes used to field preparation and sowing seed	Field capacity for final land preparation and sowing (ha hr^{-1})	Fuel consumption (L ha^{-1})	Labour used for land preparation and seeding (person-hours ha^{-1})	Total cost for land preparation, fuel and seeding (US$ ha^{-1})
Chickpea in ZT	1	0.100ab	8gh	20fg	49fg
Chickpea in SP	1	0.097a–c	6h	21fg	51fg
Chickpea in SPST	1	0.090a–c	9gh	22fg	55fg
Chickpea in BP	1	0.110a	31bc	19g	60e–g
Chickpea in CT	4	0.043fg	24d	40a–c	104bc
Jute in SP	1	0.077c–e	5h	27d–f	64e–g
Jute in SPST	1	0.080b–e	21de	26d–g	69ef
Jute in ZT	1	0.063d–f	31bc	32c–e	90cd
Jute in CT	4	0.037g	36b	32c–e	92cd
Jute in BP	1	0.047fg	30c	44ab	116ab
Lentil in SP	1	0.110a	6h	18g	44g
Lentil in ZT	1	0.083b–d	23de	24e–g	68ef
Lentil in SPST	1	0.060ef	23de	34cd	89cd
Lentil in CT	4	0.033g	31bc	34cd	93cd
Lentil in BP	1	0.053fg	23de	38bc	97cd
Wheat in SP	1	0.090a–c	10gh	22fg	54fg
Wheat in SPST	1	0.087bc	14fg	23fg	59e–g
Wheat in ZT	1	0.087bc	18ef	25e–g	65ef
Wheat in BP	1	0.077c–e	31bc	27d–f	80de
Wheat in CT	4	0.027g	41a	48a	131a
CV %		13.8	11.7	13.6	10.7

Values in a column followed by a common letter are not significantly different at $p < 0.01$ by least significant difference test. Labour use includes cost of hand broadcasting seed and fertiliser in the case of CT.

The relative fuel consumption in BP was 76% of CT for wheat, 74% for lentil, 83% for jute and 129% for chickpea (Table 6). The lowest fuel consumption was recorded for SPST, SP and ZT with chickpea, SP with jute and lentil and SPST and SP with wheat.

Total labour use for land preparation and seeding in CT ranged from 48 person-hours ha^{-1} for wheat to 32–34 person-hours ha^{-1} for jute and lentil (Table 6). Single pass planting decreased the labour requirements by 45–50% in chickpea and wheat. For jute, labour requirements for single pass planting were not significantly different to CT. For lentil, only SP significantly decreased labour requirements, which were roughly halved compared to CT.

The total cost for land preparation, fuel and seeding was highest for CT in wheat and chickpea followed by lentil and jute. Relative to CT, total cost was approximately halved for wheat and chickpea by planting using SPST, SP or ZT (Table 6). By contrast, in these crops BP only reduced total costs by 38–42%. For lentil planting, only SP (by 53%) and ZT (by 27%) decreased total costs of land preparation, fuel and seeding. For jute, BP increased total costs compared to CT, while only SP (by 25%) and SPST (29%) decreased total costs (Table 6).

DISCUSSION

The efficacy of mechanised single pass planting compared to conventional tillage and broadcast sowing of seeds is judged first by whether it reliably achieves satisfactory plant populations after emergence, and does so at least as well as with CT. In addition, with single pass planting the aim was to decrease time needed for planting operations and the labour requirements, which, in turn, will decrease overall costs of planting. In the experiments described here, all of these criteria were met as planting by VMP equalled or exceeded the performance of CT. The VMP has capability for seed and fertilizer application in variable row spacing (0.20–0.60 m) and plant-to-plant spacing using SPST, SP, ZT, BP and even CT mode line sown, and was evaluated on many soil types in Bangladesh (Figure S1). In addition to the direct savings of cost and labour for in-field operations, the planter has flexibility for multi-crop planting and capacity for rapid adjustment of row spacing on a field-by-field basis, which may increase the business profitability of planting operations by local service provider. By using the VMP, the establishment costs for various crops in different tillage systems were significantly reduced compared to CT (Table 6), as also found by Haque *et al.* (2018).

Crop establishment

Planting by SP gave comparable or greater plant populations after emergence to CT in 12 out of 15 experiments. Similarly, SP gave comparable or greater plant populations than SPST and BP planting methods. The exception to this was in one chickpea experiment at Gazipur, where SP had only 28 plants m^{-2} compared to 51 plants m^{-2} with SPST (Table 2). However, the lower population with SP was still within the range that is considered adequate for chickpea (Johansen *et al.*, 2008a). There is emerging evidence that the planters for 2WT achieve variable plant populations. In the present study, the BP system had a higher wheat population of

132 plants m^{-2} than the SP had a plant population of 90 plants m^{-2}. However, Hossain *et al.* (2004) reported lower plant population compared to CT for wheat (−32%), mung bean (−67%) and maize (−29%) while using a 2 WT-mounted bed planter. Across all evaluations of SP by VMP, the plant populations were generally greater than the recommended minimum for the growing environment and at least as good as CT except in 3 out of 15 cases with chickpea, wheat and mung bean. These findings suggest that the VMP can reliably establish target plant populations of numerous crops from the small seeded jute to the large maize and chickpea seeds.

Planting wheat on beds was gained popularity in Durgapur and Charghat upazilas in Rajshahi district with about 98% of farmers using this procedure (Miah *et al.,* 2014). However, due to unavailability of mechanised planters, 96% of those farmers prepared land by CT and then formed the beds manually, which is costly and labour intensive (Miah *et al.,* 2014). BP using the VMP was able to achieve satisfactory plant density in most cases, although the plant population was lower than other single pass tillage options, for example, with wheat at Godagari in Rajshahi district. The lower plant population in BP compared to the other planting methods may partly reflect the wider row spacing as the inter-bed space is not planted. In addition, observations at planting suggest that when soil water is marginal, the extra drying that occurs during bed forming may reduce germination of wheat seeds due to water deficit, especially if seeds are sown close to the edge of the bed that dries most rapidly. However, in principle, these are operational constraints that experienced operators should be able to avoid in future by better judgement on the optimal soil moisture for bed forming and by seeding closer to the bed centre when water content is marginal.

Minimum soil disturbance planting systems allow for better control of seeding depth, seed drop and, depending on operator skill, the ability to place seed in a zone of optimum soil water content for crop establishment and emergence (Baker and Saxton, 2007a). For hand broadcast seeding under CT, the recommended seed rate for lentil is 34 kg ha^{-1} (Sarker *et al.,* 2004). In the case of CT, this seed rate is justified as hand broadcasting results in seeds being incorporated at a range of depths and soil water contents in the seed bed. Under higher soil moisture, deeply placed seed may rot before germination, while surface-placed seed may fail to germinate under conditions of soil dryness; it is mostly the seeds buried at optimum moisture level that germinate in CT. The seed rate of 34 kg ha^{-1} may be higher than necessary when the VMP is used for single-pass planting and can result in excessive plant populations of lentil. In the case of sowing a crop with the VMP and minimum soil disturbance, the seed is placed under optimum soil water contents and placed at a uniform depth in the soil. In addition, the roller attachment to the machine is designed to improve seed soil contact and enhance seedling germination and emergence. Excessively high plant populations of lentil can increase the risk of stemphylium disease and hence are undesirable (C. Johansen, personal communication). Haque *et al.* (2004) reported that compared to CT the seed rate could be minimized under different tillage systems using planting machinery. The results of a number of experiments (Bell *et al.,* 2013) in different sites confirmed that reducing seed rate to 83% of the recommended seed rate for chickpea and lentil provided sufficient plant population when sown by SP. Further

study to optimize seed rate under different minimum soil disturbance planting using machinery for different crops would be advisable.

Seed sowing with consistent and optimal depth is vital to avoid planting too shallow in dry soil conditions or too deep in wet condition. Heege (1993) reported that within seeding depths from 25 to 45 mm, the emergence of wheat dropped by 30% when the depth increased or decreased by 6 mm from optimum. In the case of machine sowing, the depth of seeding should be optimized depending on soil moisture content, soil texture, relative humidity, evaporation, tillage methods, seed size and seed treatment methods (Baker and Saxton, 2007b). Seed placement at optimum depth is a critical factor for germination, plant stand, vigour and grain yield (Campbell *et al.*, 1985). Mechanised row sowing with planters such as the VMP allows greater control and consistency in depth of seed placement.

Seed sowing by ZT and SP at high soil water content in clay soils that dry rapidly can create hard smeared layers that restrict plant root proliferation in the inter-row space as well as into the sub-soil (Bell *et al.*, 2013). In Thakurgaon district, machine planting on sandy soil at relatively higher moisture and low temperature resulted in root rot that killed a substantial proportion of lentil seedlings or resulted in stunted growth in the case of chickpea (Bell *et al.*, 2013). Hence, on wet soils further refinement of mechanised planting may be needed to optimise plant populations using minimum soil disturbance.

Crop yield

In three experiments where grain yield was reported in this study, the minimum soil disturbance planting had similar yields to the CT system for lentil, chickpea and wheat (experiments 1, 6, 14; Table 5). For the chickpea sown in Rajshahi Sadar, the grain yield was comparable to the yields reported by other researchers and higher than chickpea yields in farmers' fields that are typically 500 to 700 kg ha^{-1} (Ali *et al.*, 2007; Johansen *et al.*, 2008b; Musa *et al.*, 2001; Vance *et al.*, 2014). The national wheat grain yield and lentil seed yield of Bangladesh are close to 3 and 0.92 Mg ha^{-1}, respectively (BBS, 2009, 2013). In the present study, minimum soil disturbance planting by SP or ZT has produced higher than average wheat and lentil grain yield (Table 5). Baker and Saxton (2007b) suggests that some yield reduction in the first few years is likely after implementing the minimum tillage, largely because it takes time for the soil to re-establish favourable soil structure after minimum soil disturbance is implemented. Salahin *et al.* (2014) reported significantly higher crop yield from the third continuous crop under all minimum soil disturbance planting options by VMP, which was similar to a report by Islam *et al.* (2011). Results from many trials in Bangladesh with other minimum soil disturbing planters also supported the yield increases (Johansen *et al.*, 2012; Miah *et al.*, 2010; Vance *et al.*, 2014).

The BP method for lentil at Durgapur upazila during 2010 and 2011 had lower grain yield compared to SP and CT (Table 5). When considering the whole planted area, including the inter-bed space, the effective row spacing in BP was 29 cm compared to 20 cm with SP and this may explain the decreased grain yield. Narrower

bed width or suitable cultivars with greater branching or tillering might increase grain yield in BP by compensating for the lower plant density (Feng *et al.*, 2015). Villaseñor-Mir (2008) reported that the planting on narrow raised beds is a variety-specific technology in the case of bread and durum wheat. 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 morphology and phenology. Sayre (1998) also recommended that wheat breeders and agronomists jointly identify and understand the proper plant type needed for optimum performance on beds. Hence, there may be scope for further selection of crop varieties for improved performance on BP.

Costs and labour inputs at crop establishment

Crop establishment by VMP in different single pass planting systems significantly reduced the crop establishment cost (Table 6). In traditional systems, 4 to 8 tillage passes are preferred to establish the major crops in Bangladesh (Wohab et al., 2007). The amount of fuel used and the time, labour and cost requirements are related to the number of tillage operations performed (Baker and Saxton, 2007b; Derpsch et al., 2010; Gathala et al., 2015). While the effective area coverage per unit time of a single pass with the CT systems was higher compared to all other single pass tillage types, after four tillage operations (preferred for CT) there was greater fuel consumption, labour and machinery use than with single pass operations (Table 6). Cost reductions in the experiments in this study were comparable with many studies where single pass planting systems reduced the crop establishment cost significantly including those with small 4WT (Erenstein and Laxmi, 2008; Haque et al., 2004; 2010; 2011; 2016b; Islam et al., 2010).

The present study has examined crop establishment and yield of single crops in rice-based cropping systems using the VMP, a mechanised row sowing planter. Depending on the mode of minimum soil disturbance planting implemented by the VMP, SP or ZT may be applied to the field. This allows the potential for conservation agriculture (CA) practices to be followed in these regions. However, full adoption of CA practices under rice-based rotations remains a challenge. Soil puddling for rice often causes subsurface compaction, which may adversely affect the yield of the succeeding crop due to reduction in root penetration through the shallow plough pan (Hobbs and Moris, 1996). Amelioration of the soil compaction requires additional tillage and energy for succeeding crops. The minimum soil disturbance crop establishment of rice can be achieved using direct seeding or by a novel non-puddled transplanting technique where VMP were used to prepare the strip (Haque *et al.,* 2016b). Thus, the VMP or similar planters could be used for major rice growing areas where transplanting of the rice seedlings is commonly practiced and ultimately remove further barriers to adoption of CA in rice-based systems.

CONCLUSION

Across several soil types and agro-ecological zones, reliable establishment of seven crop species was achieved with the two types of single pass minimum soil

disturbance planting systems (SP, ZT). Plant populations after crop establishment with conventional tillage were less than or equal to the plant populations when compared to one or more of the single pass minimum soil disturbance planting methods in 12 of 15 experiments. Total costs of land preparation, fuel and seeding were also less with ZT, SP and single-pass shallow tillage than with BP and conventional tillage in most cases. These two parameters, plant population and total cost, indicate that the use of minimum soil disturbance techniques for mechanised crop establishment will benefit the production systems of smallholder farmers in rice-based systems. From this study it can be concluded that single pass minimum soil disturbance planting by VMP mounted on a 2WT will allow adoption of conservation agriculture techniques, reduce crop production cost and maintain grain yield at levels reached with conventional tillage Thus, the VMP for single pass minimum soil disturbance planting should be a suitable planter for smallholder farmers in rice-based cropping systems in Bangladesh and similar agro-ecologies.

Acknowledgements. The authors gratefully acknowledged the funding contribution of ACIAR (LWR 2005/001) and CIMMYT for research and development of the VMP. The authors also acknowledge the following persons who continuously supported through technical advice and feedback on performance and development of VMP: RJ Esdaile, Raj K Gupta, MA Wohab, M Marufuzzaman, MA Rahman, Mahbub Engineering Workshop, Alam Engineering Workshop, service providers and VMP users.

SUPPLEMENTARY MATERIAL

For supplementary material for this article, please visit https://doi.org/10.1017/S0014479717000370

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