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RESEARCH ARTICLE

# Conservation agriculture effects on yield and profitability of rice-based systems in the Eastern Indo-Gangetic Plain

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**Abstract**

Sustaining productivity of the rice-based cropping systems in the Eastern Indo-Gangetic Plain (EIGP) requires practices to reverse declining soil fertility resulting from excessive tillage and crop residue removal, while decreasing production costs and increasing farm profits. We hypothesize that the adoption of conservation agriculture (CA), involving minimum tillage, crop residue retention and crop rotation, can address most of these challenges. Therefore, the effects of crop establishment methods – strip planting (SP), bed planting (BP) and conventional tillage (CT); and levels of crop residue retention – high residue (HR) and low residue (LR) on individual crop yield, system yield and profitability were evaluated in a split-plot design over three cropping seasons in two field experiments (Alipur and Digram sites) with contrasting crops and soil types in the EIGP. The SP and BP of non-rice crops were rotated with non-puddled rice establishment; CT of non-rice crops was rotated with puddled transplanted rice. In the legume-dominated system (rice-lentil-mung bean), lentil yields were similar in SP and CT, while lower in BP in crop season 1. A positive effect of high residue over low residue was apparent by crop season 2 and persisted in crop season 3. In crop season 3, the lentil yield increased by 18–23% in SP and BP compared to CT. In the cereal-dominated system (rice-wheat-mung bean), significant yield increases of wheat in SP and BP (7–10%) over CT, and of HR (1–3%) over LR, were detected by crop season 3 but not before. Rice yields under CA practices (non-puddled and HR) were comparable with CT (puddled and LR) in both systems. Improved yield of lentil and wheat with CA was correlated with higher soil water content. The net income of SP increased by 25–28% for dry season crops as compared to CT and was equal with CT for rice cropping systems. Conservation agriculture practices provide opportunities for enhancing crop yield and profitability in intensive rice-based systems of the EIGP of Bangladesh.

**Keywords:** Crop establishment methods; Cropping systems; Economics; Non-puddled rice; Soil water content; Strip planting

**List of Abbreviations** AEZ, Agro-Ecological Zone; BDT, Bangladesh Taka; BCR, Benefit-cost ratio; BP, Bed planting; CA, Conservation agriculture; CE, Crop establishment; CT, Conventional tillage; DAS, Days after sowing; EIGP, Eastern Indo-Gangetic Plain; HR, High crop residue retention; IGP, Indo-Gangetic Plain; LR, Low crop residue retention; LSD, Least significant difference; REY, Rice equivalent yield; SP, Strip planting; SWC, Soil water content; 2-WT, Two-wheeled tractor; VMP, Versatile Multi-crop Planter.

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## Introduction

The rice-based system on over 14.4 million hectares in the Eastern Indo-Gangetic Plain (EIGP) underpins food security of over a billion people (~40% of whom live in extreme poverty) (Islam *et al.*, 2019; Ray *et al.*, 2012; Timsina *et al.*, 2018). However, the current rice-based systems are experiencing high labour, water, energy and capital demands which makes them less profitable (Bhatt *et al.*, 2021; Karunakaran and Behera, 2016). Strategies to reduce production costs while enhancing crop yield are now crucial to make these cropping systems more profitable and sustainable.

Conservation agriculture (CA), which integrates minimum soil disturbance, crop residue retention and diversified crop rotation (Johansen *et al.*, 2012), has been evaluated in rice-based systems in several eco-regions of the Indo-Gangetic Plain (IGP), which extends from Pakistan in the west across India and into Bangladesh in the east (Bhatt and Kukal, 2017; Jat *et al.*, 2014), and it has been advocated in diverse agro-ecological zones for smallholders in South Asia (Jat *et al.*, 2020; Joshi *et al.*, 2021). Many positive benefits are claimed for CA such as increased crop yield (Choudhury *et al.*, 2014; Saha and Ghosh, 2013) with reduced labour, fuel and irrigation water requirements (Hossen *et al.*, 2018), which result in lower production costs and improved farm profit (Bell *et al.*, 2019; Haque *et al.*, 2016). Consequently, adoption of CA for growing all crops in rice-based systems of the IGP has been increased over the last decade (Hobbs *et al.*, 2017). By contrast, Pittelkow *et al.* (2015) concluded from a global meta-analysis of 610 studies that minimum tillage or no-tillage, a component of CA, overall reduces yields, yet this response is variable and can produce equivalent or greater yields than conventional tillage (CT) under certain conditions. However, when no-tillage is combined with the other two CA principles of residue retention and crop rotation, its negative impacts are minimized. The intensive rice-based cropping systems of the EIGP are poorly represented in the studies of Pittelkow *et al.* (2015); hence, questions remain about the effects of transitioning from CT to CA on crop yield of rice-based systems in the EIGP. The recent development of planters, such as the Versatile Multi-crop Planter (VMP), specifically designed for small farms in the rice-based cropping systems in the EIGP, is accelerating the development of CA for these cropping systems (Bell *et al.*, 2017; Haque *et al.*, 2017).

Intensive rice-based systems generate a large amount of crop residues: the rice-wheat system produces about 10–14 Mg of crop residue $ha^{-1}$ every year in the IGP (Sarkar *et al.*, 2020). Most commonly in this region, crop residue is partly or completely removed (Dahiya *et al.*, 2013; Ghimire *et al.*, 2017) or burnt due in part to the lack of effective strategies for crop residue management (Singh *et al.*, 2020). However, crop residue burning results in significant losses of carbon and some nutrients, decreases soil microbial populations and pollutes the atmosphere (Porichha *et al.*, 2021). Hence, increased retention of crop residue in CA has the potential to reverse long-term declines in carbon and other nutrients in the rice-based system (Ghimire *et al.*, 2017).

The aim of this study was to evaluate the effects of crop establishment methods and crop residue retention levels on individual crop and on cropping systems performance for a legume- and cereal-dominated cropping system in north-west Bangladesh in the EIGP during the first 3 years of transition from conventional to CA practices. It was hypothesized that CA-based management practices would improve crop yield and profitability of the system as compared with the current conventional cultivation practice of rice-based systems in the EIGP.

## Materials and Methods

Two representative rice-based cropping systems comprising a legume-dominated system, lentil (*Lens culinaris* Medik.) – mung bean (*Vigna radiata* (L.) R. Wilczek) – monsoon rice (*Oryza sativa* L.) and a cereal-dominated system: wheat (*Triticum aestivum* L.) – mung bean – monsoon rice, were evaluated in the current study. Full details of the sites and study are reported by Islam *et al.*

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**Table 1.** Characteristics of the two experimental sites

| Characteristics | Legume-dominated system | Cereal-dominated system |
|---|---|---|
| Location (Supplementary Material Figure S4) | Alipur, Durgapur, Rajshahi, Bangladesh | Digram, Godagari, Rajshahi, Bangladesh |
| Latitude, longitude | 24°28′ N, 88°46′ E | 24°31′ N, 88°22′ E |
| Elevation above sea level | 20 m | 40 m |
| Agro-Ecological Zone (AEZ) | AEZ-11 (High Ganges River Floodplain) | AEZ-26 (High Barind Tract) |
| Crop rotation | Lentil – mung bean – monsoon rice | Wheat – mung bean – monsoon rice |
| General site physiography | Alluvial plain | Drought-prone uplifted and undulating ancient alluvial area |
| Taxonomic soil classification (Huq and Shoaib, 2013) | | |
| Subgroup (USDA) | Typic Haplaquepts | Aeric Albaquepts |
| Soil series | Arial/Sara | Atahar |
| Physiographic unit | Ganges River Flood Plain | High Barind Tract |
| Parent material types | Ganges river alluvium | Madhupur Clay |

(2022) and Islam (2017), and in Supplementary materials (Methods S1 and S2, and Tables S1 to S5). Only pertinent details are provided in the body of this article.

The cereal-dominated system was evaluated on a silty clay upland soil in the High Barind Tract, while the legume-dominated system was evaluated on alluvial loam soil. The experiment was conducted for seven consecutive crops, starting with the 2010–2011 wheat and lentil crops, and finishing with the same crops in 2012–2013.

### *Site characteristics*

Two experimental sites were located in two different farmer's field of the subtropical region in north-west Bangladesh (Supplementary Material Figure S4). The characteristics of the two experimental sites and soils are summarized in Tables 1 and 2.

According to the Köppen climate classification system, the climate of both sites is characterized by hot and humid summers, and cool winters with an average annual rainfall of about 1450 mm, most of which falls from June to October (Chaki *et al.*, 2021). January is the coldest month while April and May are the hottest. The sites had a long history of intensive cropping with transplanting monsoon rice into puddled soil followed by limited retention of previous rice crop residue along with intensive dry tillage used for sowing of each dryland crop (personnel communication with farmers Mr. Abdul Kuddus Gazi and Mr. Neaz Mehedi). Both experimental sites were planted with a uniform puddled transplanted rice crop prior to commencement of the treatments.

### *Experimental design and treatments*

Both experiments were laid out in a split-plot design consisting of three main plot treatments and two sub-plot treatments replicated four times, and sub-plot size of 7.5 m × 7 m at both sites. Three establishment methods, namely strip planting (SP), bed planting (BP) and conventional tillage (CT) for non-rice crops, and non-puddled (on SP and BP plot of non-rice crop) and puddled (on CT of non-rice crop) for the rice crop, were randomly assigned to main plots. Two levels of crop residue retention (high crop residue retention – HR; low crop residue retention – LR) were assigned to the sub-plots. A Versatile Multi-crop Planter (VMP) (Haque *et al.*, 2016) was used for seeding and fertilizing in SP and BP, while the CT was prepared using a rotary tiller powered by a two-wheeled tractor (2-WT) (Supplementary Material Table S1). For each crop in SP and BP, the soil was strip tilled between the rows of the previous crop, in a single pass. Establishment of rice in SP and BP involved strip tillage on dry soil followed by inundation

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**Table 2.** Basic soil properties (at 0–15 cm soil depth) of study sites before starting the long-term experiments

| | Sites | | | |
|---|---|---|---|---|
| Soil properties | Alipur | Digram | Protocol | Reference |
| pH (1:5 $H_2O$) | 7.8 | 6.3 | Glass electrode | Thomas (1996) |
| Electrical conductivity (dS $m^{-1}$) (1:2.5 $H_2O$) | 0.36 | 0.26 | Electrical conductivity meter | |
| Organic carbon (g $kg^{-1}$) | 6.1 | 7.3 | Walkley and Black | Rayment and Higginson (1992) |
| Total N (g N $kg^{-1}$) | 0.74 | 0.95 | Kjeldahl method | O'Neill and Webb (1970) |
| Cation exchange capacity (cmol $kg^{-1}$) | 26.8 | 29.2 | Ammonium acetate extraction | Scholenberger and Simon (1945) |
| Textural class | Silty loam | Silty loam | Hydrometer method | Bouyoucos (1962) |
| Sand (g $kg^{-1}$) | 324 | 164 | | |
| Silt (g $kg^{-1}$) | 520 | 660 | | |
| Clay (g $kg^{-1}$) | 156 | 176 | | |
| Bulk density (g $cm^{-3}$) | 1.61 | 1.46 | Core sampler method | Black and Hartge (1986) |

for 1-2 days to soften the soil before transplanting of 25- to 30-day-old rice seedlings (Haque *et al.*, 2016). For BP, a row of rice seedlings was transplanted manually on each edge of a moist bed at 20 cm spacing. Regardless of treatments, the land was kept flooded during most of the rice growing period.

The LR treatment retained 20% of the cereal residues but none of the above-ground residues of legume (Supplementary Material Tables S2 and S3), which is consistent with current farmer practice. By contrast, the HR treatment involved retention of all legume residues as mulched material and 50% of the cereal residues (the maximum level that could be planted into with the VMP). All treatments were repeated in the same plots for each crop.

### *Crop residue recycling protocols*

The high and low crop residue retention treatments were based on the average height of cereal residue across all experimental plots. In the HR treatment, the rice residues were cut to a standing height of 45–63 cm and of wheat residues to 47–52 cm (50% of total plant height). In the LR treatment, rice residues were cut to a standing height of 22–25 cm and wheat residues to 19–21 cm (i.e. 20% of total plant height, which is close to farmer practice) (Supplementary Material Tables S2 and S3).

The biomass of standing crop residues was then determined from two randomly selected quadrats of 1 $m^2$ in each plot excluding the harvesting area for grain and straw yield. All rice residues were standing at the time of implementation of the crop establishment treatments except at the commencement of planting with lentil. Just after sowing the first lentil crop, the loose rice residues were uniformly distributed to HR at 5 t $ha^{-1}$ and to LR at 2 t $ha^{-1}$. The retained standing residue (50 and 20% of total plant height) was harvested from three quadrats per plot and weighed for that height. Total amount of crop residue of seven successive crops recycled varied from 5.5–6.2 (LR) to 23.5–24.1 t $ha^{-1}$ (HR) at Alipur and from 11.5–12.3 (LR) to 30.0–32.2 t $ha^{-1}$ (HR) at Digram.

### *Agronomy of legume- and cereal-dominated systems*

The field trials at the Alipur site were initiated with winter lentil and with winter wheat at Digram site in 2010–2011 (November–March); they were followed by mung bean in the pre-monsoon season of 2011 (March–May) and then transplanted rice in the monsoon season of 2011 (July–October). Both the sequences were continued up to seven crops, the final crop being lentil and wheat. Supplementary Material Tables S4 and S5 outline details of the production technology followed.

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During the lentil and wheat phase, the crop was initially grown on residual soil moisture in all treatments after the rice cycle. Then, regardless of treatments, two to three post-sowing irrigations (~50 mm of each) were applied to wheat in each of the three study years. During the mung bean phase, the crop was established by applying a pre-sowing irrigation but no post-sowing irrigation was applied, except at Digram in 2011 where a post-sowing irrigation of ~50 mm was applied after mung bean had been sown into residual soil moisture. During the rice phase, all the plots under SP and BP (non-puddled) and CT (puddled) were frequently irrigated depending on rainfall events during the first 14 days after transplanting to ensure adequate crop establishment. A total of six to eight irrigations were applied depending on the amount and distribution of rainfall during the rice cycle in different years. In each irrigation, 50–60 mm water was applied within two days after the disappearance of standing water. Water was applied until the average water depth on the soil surface reached ~50–60 mm at each irrigation event.

The details of nutrient management and biotic stresses are given in Supplementary Material Methods S1 and S2, respectively.

### Experimental measurements

#### *Yield, yield components and system rice equivalent yield*

Plant densities after emergence and at harvest were determined from three randomly pre-selected (just after seeding) quadrats of 1 $m^2$ each outside of the harvest area for grain and straw yield. The crops were harvested when the pods of lentil, spikes of wheat or panicles of rice turned straw colour and pods of mung bean turned black and dried. An area of 3 m × 2 m was harvested for yield determination in the centre of each sub-plot. The harvested bundles were threshed and cleaned, and the grain and straw were weighed. Grain yields of rice, wheat, lentil and mung bean were reported at 14, 12, 11 and 12% moisture content, respectively. Fresh straw was collected from 1 $m^2$ in each plot, and 100 g fresh subsample was oven-dried at 65 °C to a constant weight. Straw yields were reported on a dry-weight basis (oven-dried to constant weight).

The detailed procedures of calculation of the rice equivalent yield (REY) of different crops in the rotation are given in Supplementary Material Method S3.

#### *Soil water content*

A MP406 soil water probe (ICT international, Australia) was used to measure the volumetric soil water content (SWC) during crop establishment. The SWC was measured at three random spots for each treatment at 5 cm increments to 15 cm soil depth at both sites. The MP406 measures the soil dielectric constant by frequency domain reflectometry (Vance, 2013). The measurement of SWC in the seedbed began at sowing and was continued up to 35 days after sowing (DAS) for lentil and 25 DAS (before applying first irrigation) for wheat at 5-day intervals, in each year. These values of SWC were averaged across all measurements in the current study for simplicity.

#### *Economic performance*

The economic performance of each sub-plot treatment was calculated considering all production costs (the sum of fixed and variable costs) based on the local market prices at Rajshahi during 2011–2013 (Supplementary Material Table S6). All prices were converted to US$ using an exchange rate of 1 US$ = 77.7 Bangladeshi Taka (BDT). The land rental value was considered as a fixed cost. The land rental value of a particular crop was estimated by the annual rental cost of land divided by the crop duration (e.g. lentil, wheat and rice – 4 months and mung bean – 3 months). Seedbed rent (for 1 month) and management of rice seedlings were included in variable cost. The costs of human labour (person-hours $day^{-1}$) for land preparation, seeding, irrigation, application of fertilizer and plant protection chemicals, weeding and harvesting, and the cost of production inputs, for example tillage, planting and seed, fertilizer, plant protection chemicals, irrigation, threshing and transport

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cost are considered as variable costs. The cost of tillage operations was calculated by using the time and fuel required for each sub-plot treatment. The non-labour irrigation cost was calculated from the local charges of the adjacent deep tube well supplier. The cost of threshing included the hiring charges of a thresher machine. The gross returns were calculated by multiplying the grain and straw yield (minus the amount of straw retained in the treatment) of each crop by the local market price. For example, the total straw yield of lentil was accounted for the gross return in the LR treatment but not in the HR treatment. Gross margin was calculated as the difference between gross returns and total variable cost. Net incomes were calculated as the difference between gross return and total cost. The benefit-cost ratio (BCR) was calculated by dividing gross return by total cost.

### *Statistical analysis*

All the data on yield and yield components of all crops, REY, SWC, root and shoot biomass, and economic performance were analysed by two-way analysis of variance with crop establishment method as the main plots and crop residue management in the sub-plots, using GenStat 15th Edition (VSN International Ltd, UK). The statistical analyses were performed individually for each cropping system (site), as well as for each cropping season. Only the main effects are presented and discussed where the interaction effects were not significant. The differences between treatment means were separated using the least significant difference (LSD) at $p < 0.05$ (Gomez and Gomez, 1984).

## Results

### *Weather*

The soil was fully wet prior to sowing of the first crop of lentil and wheat after the monsoon season rainfall in 2010. The monthly rainfall and minimum/maximum temperatures for the period November 2010 to March 2013 are shown in Figure 1. Most rainfall was received during the rice growing season, the monsoon period, with more rain in 2011 (1260 mm) than in 2012 (909 mm). High rainfall in November of 2012 (102 mm) delayed sowing of lentil. Subsequent rainfall during the cool dry season was marginal, with lentil relying on residual soil moisture, while wheat received supplementary irrigation. The high pre-monsoon rainfall received during the growing period for mung bean (March–May) in 2011 caused total failure of that crop.

Maximum temperatures were highest during the mung bean growing season, with mean monthly maximum temperatures of 35–38 °C in May (Figure 1). Minimum temperatures were highest through the rice growing period. During the cool dry lentil/wheat season, maximum temperatures reached 23–30 °C, while the minimum temperatures were 9–18 °C.

### *Soil water content*

During lentil establishment at Alipur, only the main effects of establishment method and crop residue management affected SWC at all depths in all the study years (Figure 2 and Supplementary Material Table S7). In crop season 1, average SWC at 0–5, 5–10 and 10–15 cm in SP and CT was significantly higher than in BP. In crop seasons 2 and 3, the SWC at 0–5 and 5–10 cm depths in SP and BP was significantly higher than in CT. In crop seasons 1 and 2, the SWC at 0–5 cm was increased under HR as compared to LR. In crop season 3, the SWC at 0–5, 5–10 and 10–15 cm depths in HR was significantly higher than in LR.

At the Digram site during wheat establishment, the SWC at 0–5, 5–10 and 10–15 cm depths was lower in BP compared to SP and CT in crop season 1 (Figure 3 and Supplementary Material Table S7). In crop season 2, the SWC at 0–5 and 5–10 cm depths in SP was higher than in BP and CT. In crop season 3, the SWC at 0–5 cm depth in CT was lower than with SP and BP but tillage effects were not apparent below 5 cm soil depth. The SWC under HR at 0–5 cm was greater than

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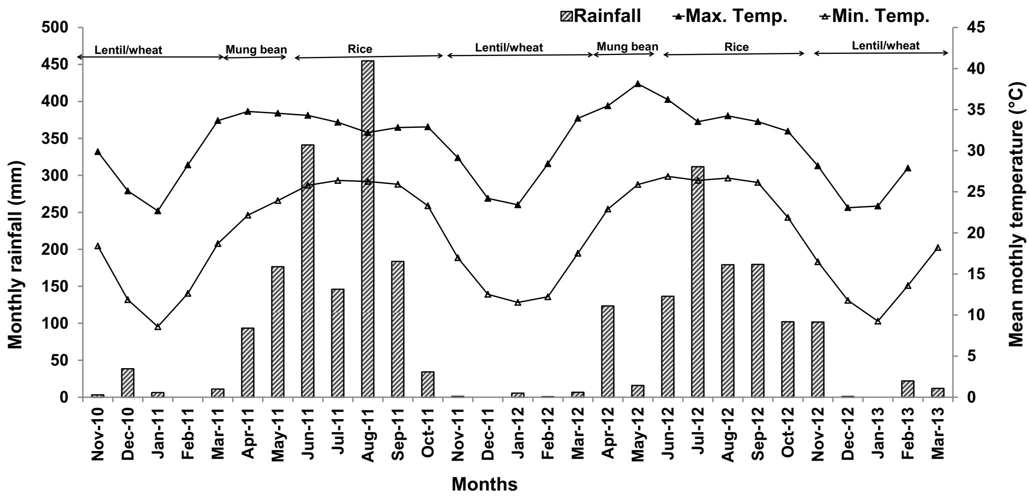


**Figure 1.** Monthly rainfall, mean maximum and minimum temperatures during the experimental period November 2010 to March 2013. Horizontal bars indicate the growth period of each crop.

that in LR in crop season 1 and 2. In crop season 3, the SWC was greater with HR than LR at 0–5 and 5–10 cm soil depths while crop residue effects were not significant at 10–15 cm soil depth.

### *Yield performance of cool dry season crops*

At Alipur in crop season 1, with both HR and LR, the grain yield of lentil was significantly higher in SP and CT than BP, by 19–20%. (Figure 4a and Supplementary Material Table S8). In crop season 2, the grain yield of lentil with HR was 22% higher than LR. In crop season 3, the grain yield was higher by 23% in SP and 18% in BP as compared to CT regardless of crop residue levels. The responses of lentil straw yield closely correlated with those of grain yield ($r = 0.95$).

For wheat at Digram, the effects of crop establishment method and crop residue treatments on the grain yield were not significant in crop season 1 ($p > 0.05$) (Figure 5a and Supplementary Material Table S8). In crop season 2, grain yield of wheat was depressed by 48–64% in BP as compared to SP and CT. In crop season 3, the yield of wheat was 9% higher in SP and 7% greater in BP than in CT, and the yield was 3% higher in HR as compared to LR across crop establishment methods (Figure 5e).

In crop season 1, the straw yield of wheat with HR was 5% higher than with the LR treatment (Figure 5b and Supplementary Material Table S8). In crop season 2, the straw yield of wheat was higher by 19% in SP and 27% in CT than in BP across both levels of crop residue retention; HR had 6–15% greater straw yield than LR across all crop establishment methods (Figure 5d and Supplementary Material Table S8). In crop season 3, averaged over the crop residue levels, the straw yield of wheat with SP was higher by 11 and 8% than that with CT and BP, respectively. Averaged over the crop establishment methods, the straw yield of wheat with HR was higher by 5% than that with LR (Figure 5f and Supplementary Material Table S8).

### *Yield performance of rice and mung bean*

In the legume-dominated system, there were no significant treatment effects on grain or straw yield of the first rice crop (2011) (Table 3). However, grain yields of the next rice crop (2012) were significantly lower in BP than SP and CT across both levels of crop residue retention. In addition, there was higher straw yield with CT than SP and BP with HR, whereas with LR, straw yields of all crop establishment methods were similar.

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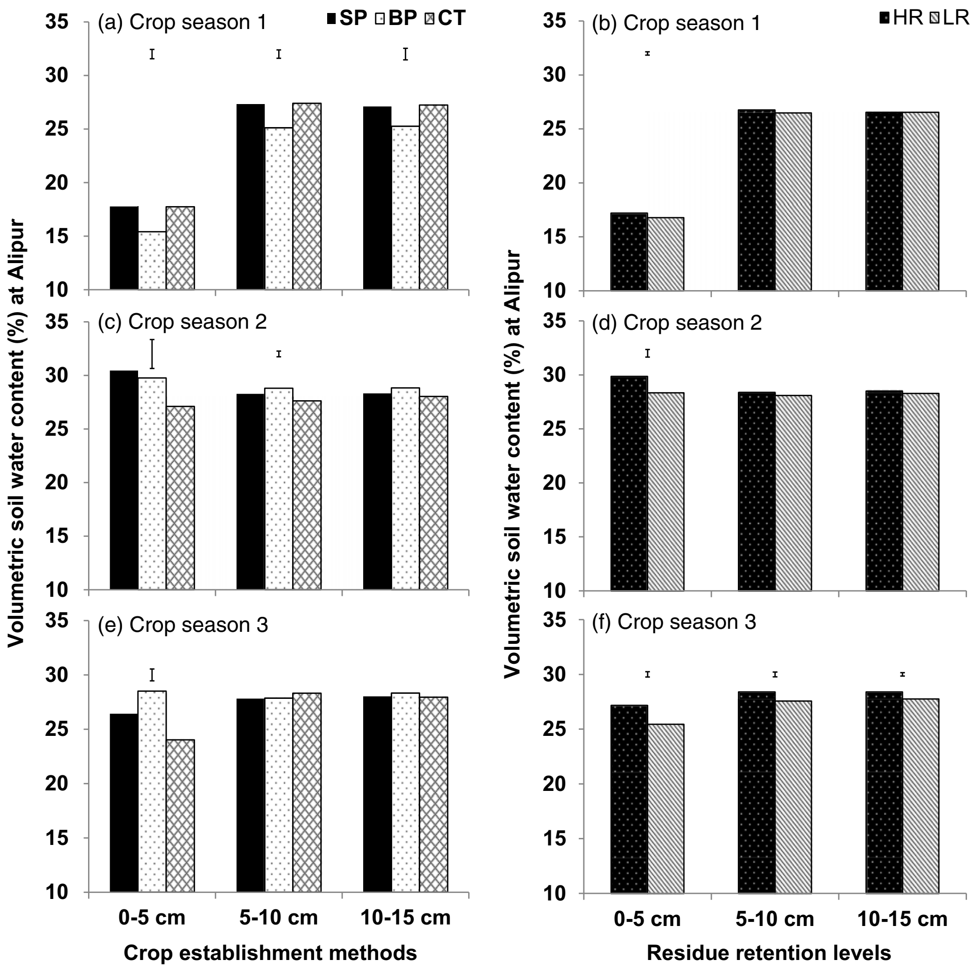


**Figure 2.** The volumetric soil water content (%) for different crop establishment methods (a, c and e) and crop residue retention levels (b,d and f) at 0–5, 5–10 and 10–15 cm depth during the lentil establishment period in crop season 1, crop season 2 and crop season 3 in the legume-dominated system at Alipur. Floating error bars indicate the least significant difference (LSD) at $p \leq 0.05$, for the effects of crop establishment and crop residue retention levels on the dates of measurement.

All pods of the first mung bean crop (2011) were damaged due to heavy rainfall; hence, there was no grain harvested. Grain and straw yields of the mung bean crop in 2012 were significantly lower with SP than CT or BP. High crop residue retention increased mung bean grain yield by 0.3 t $ha^{-1}$ compared with LR, but had no effect on straw yield in 2012.

In the cereal-dominated system, the crop establishment method and crop residue retention had no significant effect on the grain and straw yields of rice (2011 and 2012) and mung bean (2012) (Table 3). Heavy rainfall damaged all pods of first mung bean crop (2011); therefore, no grain yield data could be collected.

### *Rice equivalent yield as a measure of system yield*

In the legume-dominated system, the interaction between crop establishment method and crop residue levels had a significant effect on the REY in the first year (Supplementary Material Table S9). In the first year, REY of CT with HR and SP with LR were significantly higher than that of BP

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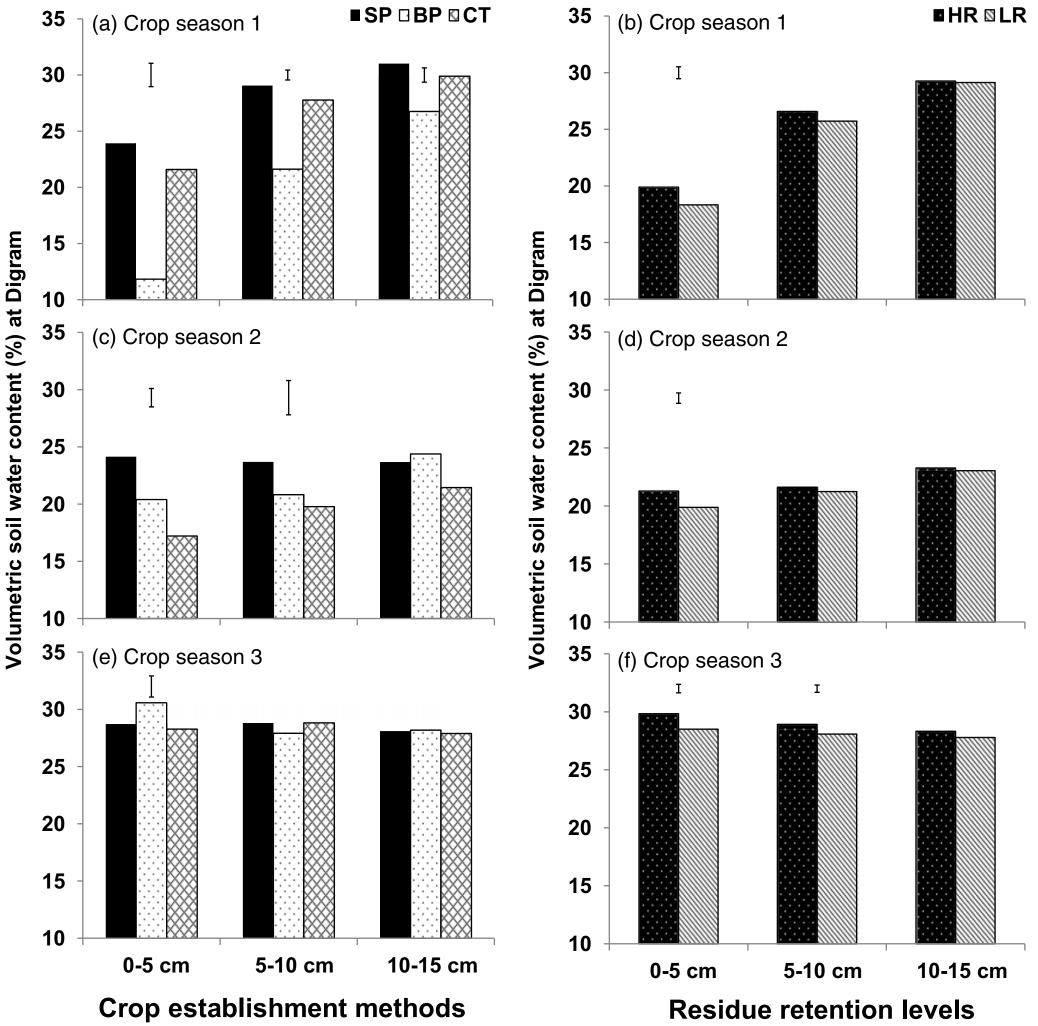


**Figure 3.** The volumetric soil water content (%) for different crop establishment methods (a, c and e) and crop residue retention levels (b, d and f) at 0–5, 5–10 and 10–15 cm depth during the wheat establishment period in crop season 1, crop season 2 and crop season 3 in the cereal-dominated system at Digram. Floating error bars indicate the least significant difference (LSD) at $p \leq 0.05$, for the effects of crop establishment methods and crop residue retention levels on the dates of measurement.

with HR and LR. In cropping year 2011–2012, the REY was higher in CT than in BP and SP, and HR increased REY as compared to LR. The cumulative REY of HR (40.3 t ha$^{-1}$) was higher than that of LR treatment (37.2 t ha$^{-1}$).

In cereal-dominated system, the REY was significantly higher in SP and CT (13.9–14.9 t ha$^{-1}$) than in BP (11.8 t ha$^{-1}$) in 2012–2013 and for the cumulative REY over 2 years (Supplementary Material Table S9).

### *Plant population of non-rice crops*

For lentil at Alipur, plant populations in the first two years were not significantly different due to different crop establishment methods and crop residue levels (Table 4). In crop season 3, there was a significant interaction between establishment method and crop residue management on plant

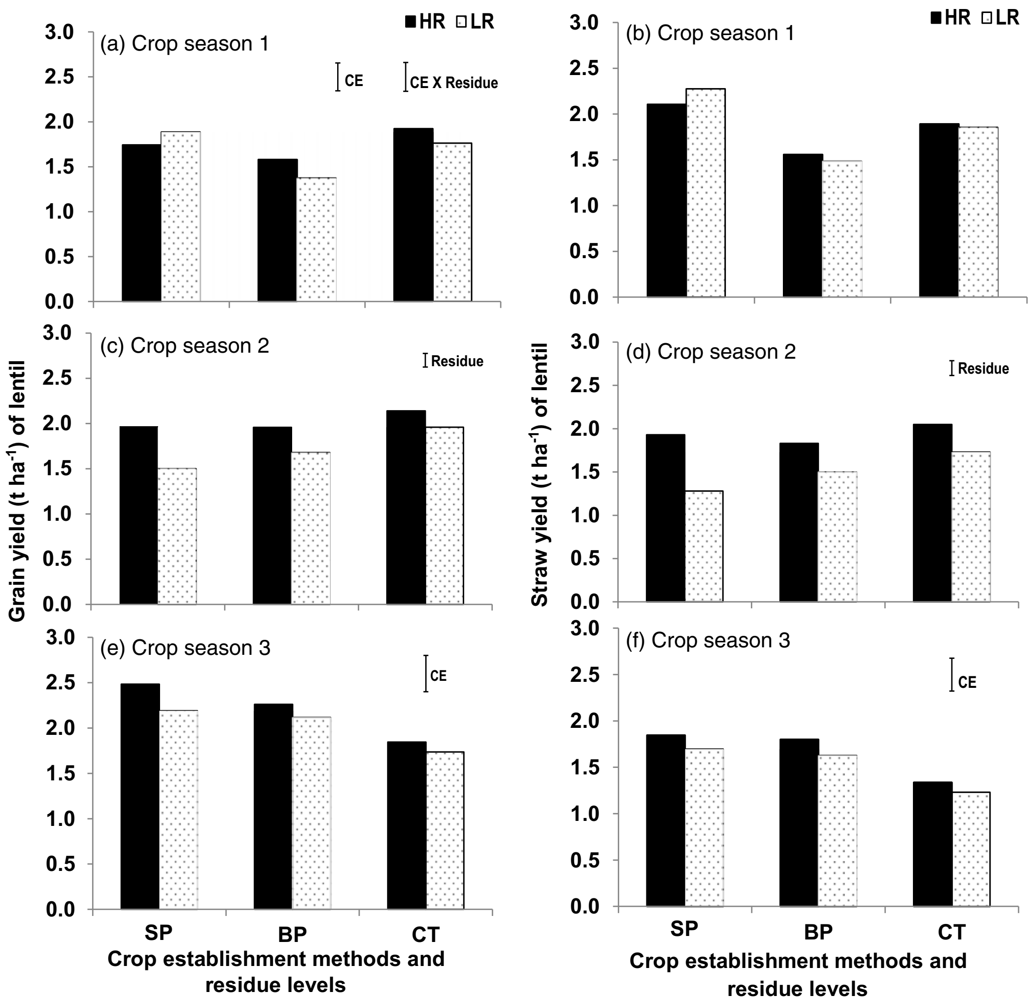


**Figure 4.** Effects of crop establishment methods and crop residue retention levels on grain (a, c and e) and straw yield (b, d and f) of lentil over three growing seasons at Alipur site. CE – Crop establishment method, SP – strip planting, BP – bed planting, CT – conventional tillage; HR – high crop residue, LR – low crop residue. Values are means of four replicates ± standard error of mean, and the floating error bar on each figure represents the least significant difference (LSD) for significant effects at $p \leq 0.05$.

population at 30 DAS and harvest (data not shown). With both HR and LR, plant population was significantly higher in SP than both other establishment methods, by 20–25%.

For wheat at Digram, the plant population was significantly higher in BP with HR than CT and SP with HR at 30 DAS in crop season 1 (Table 4). In crop season 2, the plant population in BP was 58–73% lower at 30 DAS and harvest than the other two establishment methods. In crop season 3, the overall plant population at both times under SP was higher than BP and CT. In crop season 3, averaged over crop establishment methods, the plant population at 30 DAS of LR was 11% higher than that of HR.

For mung bean at Alipur, the plant populations in different crop establishment methods were similar across crop residue retention levels, but the population was significantly higher in HR than in LR in 2011 (Supplementary Material Table S10). Regardless of crop residue retention levels, the plant population was significantly higher in SP than in BP and CT in 2012. Similarly at Digram in

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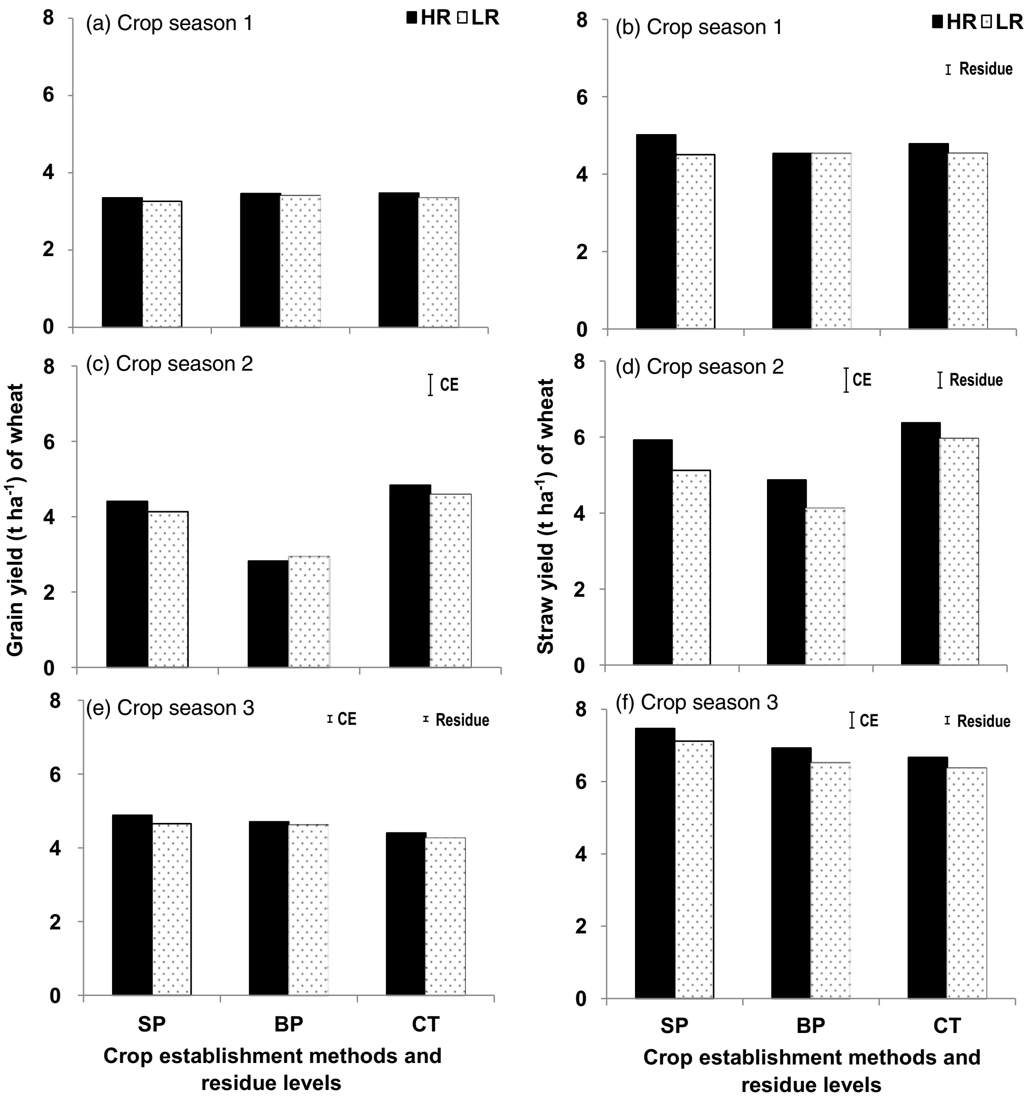


**Figure 5.** Effects of crop establishment methods and crop residue retention levels on grain (a, c and e) and straw yield (b, d and f) of wheat at Digram site. CE – Crop establishment method, SP – strip planting, BP – bed planting, CT – conventional tillage; HR – high crop residue, LR – low crop residue. Values are means of four replicates, ± standard error of mean, and the floating error bar on each figure represents the least significant difference (LSD) for significant effects only at $p \leq 0.05$.

2012, the plant population was significantly higher in SP and CT than in BP and higher in HR than in LR across the crop establishment methods.

### *Relationship between yield and plant population*

In lentil at Alipur, the relationship between plant population and yield across all three years (2010–2013) was positive ($R^2 = 0.31$) and linear (Supplementary Material Figure S5a).

In wheat at Digram, considering the three years results, the correlations of plant population and yield were positive ($R^2 = 0.34$) and linear (Supplementary Material Figure S5b). Similarly in mung

**Table 3.** Effects of crop establishment methods and crop residue retention levels on grain and straw yield of monsoon rice and mung bean of legume-dominated system in Alipur and cereal-dominated system at Digram. Note: No yield results are available for Crop 2 (mung bean) due to crop damage by heavy rainfall

| | | Grain yield (t ha$^{-1}$) | | | Straw yield (t ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|
| Treatment* | | Rice (2011) | ¹MB (2012) | Rice (2012) | Rice (2011) | ¹MB (2012) | Rice (2012) |
| Legume-dominated system in Alipur | | | | | | | |
| CE | SP | 5.5 | 0.9 | 8.3 | 5.8 | 2.3 | 9.9 |
| | BP | 4.7 | 1.4 | 7.0 | 5.2 | 2.8 | 7.5 |
| | CT | 5.4 | 1.5 | 8.1 | 6.2 | 2.4 | 9.9 |
| R | HR | 5.1 | 1.4 | 7.9 | 5.7 | 2.6 | 10.4 |
| | LR | 5.3 | 1.1 | 7.7 | 5.8 | 2.5 | 7.8 |
| $LSD^2_{0.05}$ | | | | | | | |
| | CE | ns | 0.39† | 1.03† | ns | 0.28‡ | 1.37‡ |
| | R | ns | 0.11‡ | ns | ns | ns | 0.74‡ |
| Cereal-dominated system in Digram | | | | | | | |
| CE | SP | 5.8 | 0.8 | 6.3 | 10.5 | 3.6 | 7.1 |
| | BP | 5.6 | 0.7 | 6.1 | 8.9 | 3.5 | 6.9 |
| | CT | 5.7 | 0.7 | 6.9 | 10.3 | 3.7 | 8.5 |
| R | HR | 5.6 | 0.7 | 6.2 | 9.9 | 3.7 | 7.2 |
| | LR | 5.7 | 0.8 | 6.7 | 9.9 | 3.4 | 7.9 |
| $LSD^2_{0.05}$ | | | | | | | |
| | CE | ns | ns | ns | ns | ns | ns |
| | R | ns | ns | ns | ns | ns | ns |

*CE – Crop establishment method; SP – strip planting; BP – bed planting; CT – conventional tillage; R – crop residue level; HR – high crop residue; LR – low crop residue; ¹MB – mung bean; the interaction of CE × R is significant for rice straw yield in 2012; ²the least significant difference (LSD) at $p \leq 0.05$, ns – not significant, †– significant at P≤0.05 and – significant at $p \leq 0.01$.

bean at Digram, the relationship between plant population and yield was positive ($R^2 = 0.28$) and linear (Supplementary Material Figure S5c).

### *Economic performance*

In the legume-dominated system at Alipur, total costs of lentil production ranged from 1191 US$ ha$^{-1}$ in SP to 1268 US$ ha$^{-1}$ in CT across treatments and years (Table 5). The highest gross returns from lentil were obtained with SP, and the net income was higher by 25% than that of CT treatment. The BCR of SP was also higher by 10 and 7% than that of CT and BP in lentil. Averaged over crop establishment methods, the BCR and net income of HR was 7 and 12% higher than that of LR treatment in lentil.

Mung bean production cost ranged from 1026 US$ ha$^{-1}$ with SP to 1094 US$ ha$^{-1}$ for CT (Table 5). However, total variable production costs of HR and LR across crop establishment methods were similar. Mung bean was only profitable in BP and CT, and in HR while the net income in CT was higher than in BP and SP. Averaged over the crop establishment methods, BCR of HR was 21% higher than that of LR.

Total production costs ranged from 1612 US$ ha$^{-1}$ in CT to 1651 US$ ha$^{-1}$ in SP across all treatments and years in rice (Table 5). Rice was profitable in all treatments, but the net income in LR was higher than that of HR treatment. The retention of high crop residue led to lower net income in HR compared to higher biomass sales from low crop residue retention in LR treatment. The higher BCRs (1.14–1.15) were in SP and CT than in BP (1.01).

Considering the legume-dominated system as a whole across three years, the total production costs were higher in CT (3973 US$ ha$^{-1}$) than in BP and SP (3833 US$ ha$^{-1}$ - 3868 US$ ha$^{-1}$) (Table 5). The total variable production costs of HR were higher as compared to LR. However, the net income and BCR of the legume-dominated system were not changed either by crop establishment methods or crop residue retention levels.

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**Table 4.** Effects of crop establishment methods and crop residue retention levels on plant population at 30 days after sowing of lentil at Alipur and wheat at Digram

| | Crop residue level 2010–2011 | | | Crop residue level 2011–2012 | | | Crop residue level 2012–2013 | | |
|---|---|---|---|---|---|---|---|---|---|
| Crop establishment method (CE)* | HR[1] | LR | *Mean* | HR | LR | *Mean* | HR | LR | *Mean* |
| Lentil plant population $m^{-2}$ in Alipur | | | | | | | | | |
| SP | 160 | 173 | *167* | 148 | 144 | *146* | 214 | 202 | *208* |
| BP | 149 | 163 | *156* | 138 | 136 | *137* | 176 | 157 | *167* |
| CT | 124 | 142 | *133* | 141 | 146 | *143* | 144 | 171 | *157* |
| *Mean* | *144* | *160* | | *142* | *142* | | *178* | *177* | |
| $LSD^1_{0.05}$ | | | | | | | | | |
| CE | | ns | | | ns | | | 32.8† | |
| R | | ns | | | ns | | | ns | |
| CE × R | | ns | | | ns | | | 35.3† | |
| Wheat plant population $m^{-2}$ in Digram | | | | | | | | | |
| SP | 87 | 93 | 90 | 74 | 60 | 67 | 144 | 153 | 149 |
| BP | 147 | 118 | 132 | 27 | 29 | 28 | 120 | 122 | 121 |
| CT | 121 | 135 | 128 | 103 | 104 | 103 | 111 | 142 | 127 |
| *Mean* | 118 | 115 | | 68 | 64 | | 125 | 139 | |
| $LSD^2_{0.05}$ | | | | | | | | | |
| CE | | 16.0‡ | | | 25.3‡ | | | ns | |
| R | | ns | | | ns | | | 12.7† | |
| CE × R | | 23.0† | | | ns | | | ns | |

*CE – Crop establishment method; SP – strip planting; BP – bed planting; CT – conventional tillage; R – crop residue level; HR – high crop residue; LR – low crop residue; [1]the least significant difference (LSD) at $p \leq 0.05$, ns – not significant, †– significant at $p \leq 0.05$ and ‡– significant at $p \leq 0.01$.

In the cereal-dominated system, total production costs across treatments and years in wheat ranged from 1057 US\$ $ha^{-1}$ in SP to 1152 US\$ $ha^{-1}$ in CT (Table 5). Total production cost of wheat under HR was higher by 11 US\$ $ha^{-1}$ than that of LR. The net income of SP was 28–54% higher than those of the other crop establishment methods. The BCR of SP (1.28) was higher compared to CT (1.18) and BP (1.13).

Mung bean production cost ranged from 978 US\$ $ha^{-1}$ with SP to 1045 US\$ $ha^{-1}$ for CT (Table 5). However, total production costs of HR and LR across crop establishment methods were similar. The net income was negative for all treatments due to the low grain yield and high labour cost for weeding and pod harvesting.

Total production costs ranged from 1612 US\$ $ha^{-1}$ in CT to 1651 US\$ $ha^{-1}$ in SP across all treatments and years in rice (Table 5). However, total production costs of HR and LR across all crop establishment methods were similar. The high crop residue retention produced lower biomass sales, which led to unprofitable net income in HR. Averaged over crop establishment methods, the BCR was higher (1.18) in LR than in HR (0.94).

Considering the cereal-dominated system (wheat-mung bean-rice) as a whole across three years, the total production costs were higher in CT (2860 US\$ $ha^{-1}$), followed by SP (2736 US\$ $ha^{-1}$) and BP (2701 US\$ $ha^{-1}$) treatments (Table 5). In the case of crop residue levels, total production costs of HR were higher by 11 US\$ $ha^{-1}$ as compared to LR. Overall, the net income and BCR were unaffected by crop establishment methods but higher in LR than in HR.

## Discussion

### *Yield responses to conservation agriculture*

In the first two crop seasons of the conversion from conventional system to CA, there were no consistent differences in crop yield among crop establishment methods. In crop season 3, grain

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**Table 5.** The economics of lentil, mung bean, rice and overall cropping system production under different crop establishment and crop residue retention levels in the legume-and cereal-dominated cropping systems at Alipur and Digram, respectively

| | | Legume-dominated system at Alipur | | | | | Cereal-dominated system at Digram | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment* | | Total variable cost (US$ ha$^{-1}$) | Production cost (US$ ha$^{-1}$) | Gross return (US$ ha$^{-1}$) | Net income (US$ ha$^{-1}$) | BCR[2] | Total variable cost (US$ ha$^{-1}$) | Production cost (US$ ha$^{-1}$) | Gross return (US$ ha$^{-1}$) | Net income (US$ ha$^{-1}$) | BCR |
| Lentil (mean of Crop 1, 4 and 7) | | | | | | | Wheat (mean of Crop 1, 4 and 7) | | | | |
| CE | SP | 805 | 1191 | 2069 | 931 | 1.72 | 735 | 1057 | 1349 | 292 | 1.28 |
| | BP | 813 | 1199 | 1935 | 736 | 1.59 | 744 | 1065 | 1200 | 134 | 1.13 |
| | CT | 882 | 1268 | 1971 | 703 | 1.55 | 830 | 1152 | 1362 | 211 | 1.18 |
| R | HR | 839 | 1225 | 2067 | 842 | 1.68 | 775 | 1097 | 1300 | 203 | 1.19 |
| | LR | 828 | 1214 | 1916 | 738 | 1.57 | 764 | 1086 | 1308 | 222 | 1.20 |
| LSD[1]$_{0.05}$ | | | | | | | | | | | |
| | CE | | | 100.3$^{\dagger}$ | 110$^{\ddagger}$ | 0.06$^{\ddagger}$ | | | 73.5$^{\ddagger}$ | 73.5$^{\ddagger}$ | 0.07$^{\ddagger}$ |
| | R | | | 47.3$^{\ddagger}$ | 92$^{\dagger}$ | 0.03$^{\ddagger}$ | | | ns | ns | ns |
| Mung bean (Crop 5) | | | | | | | Mung bean (Crop 5) | | | | |
| CE | SP | 736 | 1026 | 703 | -323 | 0.69 | 736 | 978 | 595 | -382 | 0.61 |
| | BP | 741 | 1031 | 1068 | 37 | 1.04 | 741 | 982 | 538 | -444 | 0.55 |
| | CT | 804 | 1094 | 1144 | 51 | 1.05 | 804 | 1045 | 570 | -475 | 0.55 |
| R | HR | 760 | 1050 | 1086 | 36 | 1.03 | 760 | 1002 | 545 | -457 | 0.54 |
| | LR | 760 | 1050 | 858 | -192 | 0.81 | 760 | 1002 | 591 | -411 | 0.59 |
| LSD$_{0.05}$ | | | | | | | | | | | |
| | CE | | | 298$^{\dagger}$ | 298$^{\dagger}$ | 0.29$^{\dagger}$ | | | ns | ns | ns |
| | R | | | 88$^{\ddagger}$ | 88$^{\ddagger}$ | 0.09$^{\ddagger}$ | | | ns | ns | ns |
| Rice (mean of Crop 3 and Crop 6) | | | | | | | Rice (mean of Crop 3 and 6) | | | | |
| CE | SP | 1265 | 1651 | 1876 | 431 | 1.14 | 1265 | 1651 | 1720 | 168 | 1.04 |
| | BP | 1217 | 1603 | 1625 | 22 | 1.01 | 1217 | 1603 | 1642 | 40 | 1.03 |
| | CT | 1226 | 1612 | 1846 | 233 | 1.15 | 1226 | 1612 | 1796 | 184 | 1.11 |
| R | HR | 1236 | 1622 | 1684 | 62 | 1.04 | 1236 | 1622 | 1523 | -99 | 0.94 |
| | LR | 1236 | 1622 | 1880 | 396 | 1.16 | 1236 | 1622 | 1916 | 361 | 1.18 |
| LSD$_{0.05}$ | | | | | | | | | | | |
| | CE | | | ns | ns | ns | | | ns | ns | ns |
| | R | | | 78$^{\ddagger}$ | 308$^{\dagger}$ | 0.05$^{\ddagger}$ | | | 131$^{\ddagger}$ | 220$^{\ddagger}$ | 0.08$^{\ddagger}$ |
| CE × R | | | | 233$^{\dagger}$ | ns | 0.14$^{\dagger}$ | | | | | |
| System | | | | | | | System | | | | |
| CE | SP | 2806 | 3868 | 4648 | 1040 | 1.20 | 2736 | 3685 | 3664 | 78 | 0.99 |
| | BP | 2771 | 3833 | 4628 | 795 | 1.21 | 2701 | 3650 | 3380 | -270 | 0.93 |
| | CT | 2912 | 3973 | 4961 | 987 | 1.25 | 2860 | 3809 | 3728 | -81 | 0.98 |

(*Continued*)

**Table 5.** (*Continued*)

| Treatment* | | Legume-dominated system at Alipur: Total variable cost (US$ ha$^{-1}$) | Production cost (US$ ha$^{-1}$) | Gross return (US$ ha$^{-1}$) | Net income (US$ ha$^{-1}$) | BCR[2] | Cereal-dominated system at Digram: Total variable cost (US$ ha$^{-1}$) | Production cost (US$ ha$^{-1}$) | Gross return (US$ ha$^{-1}$) | Net income (US$ ha$^{-1}$) | BCR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R | HR | 2835 | 3897 | 4837 | 940 | 1.24 | 2771 | 3720 | 3367 | -354 | 0.91 |
| | LR | 2824 | 3886 | 4655 | 942 | 1.20 | 2760 | 3709 | 3815 | 172 | 1.03 |
| $LSD_{0.05}$ | | | | | | | | | | | |
| | CE | | | ns | ns | ns | | | ns | ns | ns |
| | R | | | ns | ns | ns | | | 191‡ | 232‡ | 0.05‡ |

*CE – Crop establishment method; SP – strip planting; BP – bed planting; CT – conventional tillage; R – crop residue level; HR – high crop residue; LR – low crop residue; [1]the least significant difference (LSD) at $p \leq 0.05$, ns – not significant, †– significant at $p \leq 0.05$ and ‡– significant at $p \leq 0.01$.[2]BCR – Benefit-cost ratio; [2] gross return, net income and BCR are differed due to yield variation of different treatments.

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and straw yields of both lentil and wheat were significantly greater with SP than CT, with BP being intermediate. The effect of higher crop residue application in promoting yield became apparent in both crops from crop season 2.

In the current practice of CT combined with limited crop residue retention, lentil yields after rice were in the range 1.8–2.0 t ha$^{-1}$ across the three crop seasons, which is consistent with the potential yield of lentil (BARI Masur 6 cultivar) in Bangladesh, that is 2.25 t ha$^{-1}$ (Uddin, 2008). The potential yield of wheat (BARI Gom 24 cultivar) in north-west Bangladesh is 3.5–5.1 t ha$^{-1}$ (Bangladesh Agricultural Research Institute, 2019). Hence, wheat yields with conventional practices fitted well within this range in crop seasons 2 and 3 in the current study.

The introduction of CA practices in cropping systems generally results in a lag phase before those practices result in a yield advantage (Das *et al.*, 2014). This was the case in the two crop rotations of the present study, but only for the cool season crops, lentil and wheat. In a rice-lentil-jute cropping system of the EIGP on a sandy loam textured soil, the yield of lentil and rice increased with SP and BP as compared to CT, and HR increased crop yields over LR in all the crop seasons with no evident lag phase (Salahin *et al.*, 2021). Wheat yield in SP with crop residue retention was also greater than in CT and no-tillage with crop residue burning in the third crop season in a rice-wheat system in a sandy loam soil of the IGP (Gangwar *et al.*, 2006). During the initial years of experimentation, Jat *et al.* (2014) also reported poor grain yield of wheat under a permanent BP system in a rice-wheat rotation of the EIGP. Both Talukder *et al.* (2008) and Lauren *et al.* (2008) reported that crop residue retention significantly increased crop yields on permanent beds after only 1–2 cropping cycles in rice-wheat-maize and rice-wheat-mung bean cropping systems in Bangladesh.

The rice yield in the CA system (non-puddled and HR) was comparable with that in the CT system (puddled and LR) in all the study years in both legume- and cereal-dominated systems. This is consistent with the findings of several other studies (Haque *et al.*, 2016; Hossen *et al.*, 2018; Salahin *et al.*, 2021) for similar climatic conditions and cropping in the ecosystems of the intensive rice-based system in Bangladesh.

The mung bean yield of BP in 2012 was higher than that of other treatments in the legume-dominated system. The crop received substantial rainfall (146 mm) during the growing season (March–May), which was sufficient to create waterlogging, but the raised bed probably mitigated this for mung bean, as found by Hamilton *et al.* (2000). In the cereal-dominated system, however, mung bean yield did not respond to the treatments, probably due to recycling of a considerable amount of crop residue of the previous wheat crop which negated the treatment effects. Mung bean yields were not obtained in 2011 due to excess rainfall (281 mm) received during the growing season in both legume- and cereal-dominated systems. This rainfall stimulated vegetative growth while inhibiting the reproductive growth of the indeterminate mung bean crop (Kumar *et al.*, 2018).

The REY from crop season 1 and the cumulative REY of SP after 2 years were comparable with that of CT and higher than in BP in both systems. Similarly, on a loamy textured soil an improvement of crop yield and farm profit was obtained within 2–3 years in a rice-lentil/wheat-jute cropping system of Bangladesh after conversion to a CA approach with SP and HR relative to a conventional method (Salahin *et al.*, 2021). This suggests that within 2–3 years of adopting SP, both legume- and cereal-dominated rice-based cropping systems of Bangladesh were on course towards improved yield of cool dry season crops, while yield of rice, mung bean and the entire cropping system under CA was comparable with the conventional system.

### *Factors affecting response to conservation agriculture*

There are several possible reasons as to why strip planting and increased crop residue retention could increase cool season crop growth and yield, and why there should be a delay in its manifestation. Firstly, higher lentil yield achieved with SP corresponded with the significantly higher

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plant population but only in crop season 3 (Table 4 and Supplementary Material Figure S5a). However, above a threshold population further increases were not influential for lentil yield as its branching habit allows compensation for lower plant populations (Ouji *et al.*, 2016). The plant population was higher with SP as compared with the current practice of broadcast seeding with CT. However, mechanized planting was not as reliable in BP. In the present study, root diseases of lentil were more severe in BP in crop season 3 (Supplementary Material Table S11) which might be attributed to leftover buried and compacted crop residue in the seeding zone that provides a substrate for these diseases. For wheat and mung bean also in crop season 2, overall the plant population was low in BP (Table 4 and Supplementary Material Table S10), which was attributed to poor seed-soil contact as a result of seeding on crop residue and insufficient soil moisture in the seeding zone for crop establishment (Figure 3). The soil moisture level at the time of sowing into raised beds is a critical factor for germinating seeds on medium to fine-textured soils (Singh *et al.,* 2009).

Another major determinant of yield of the cool season crops, lentil and wheat, is available SWC. The lower SWC at the time of sowing of lentil and wheat in crop season 2 likely minimized plant emergence and establishment, and ultimately yield. For lentil at Alipur in crop season 3, the SWC during establishment was lower in CT and LR, consistent with the lower grain yields in these treatments (Figure 2e, f and e). For wheat at Digram in crop season 3, however, treatment effects on initial SWC values were much less than at Alipur, probably due to intermittent irrigation of the wheat crop.

Other reasons for the gradual increase in yield for the cool season crops with CA may be related to the build-up of soil organic matter. In the present experiments, we also confirmed the increased yield in SP and HR was associated with the improvement of soil physical properties, soil organic carbon and N levels under CA practices (Islam, 2017; Islam *et al.*, 2022). Several other studies in the IGP demonstrated that improvements in soil physical properties, soil organic carbon, N and other nutrients increased crop yields under CA systems (Das *et al.*, 2013; Das *et al.*, 2014; Salahin *et al.*, 2021). In the current study, significant loss of nutrients as a result of removal of most crop residue (Supplementary Material Table S12) was associated with lower yield in LR.

In the current study, crop establishment method had no notable influence on root growth of cool dry season crop, except in the case of BP where despite the improvement in root growth, there was no increase in crop yield (Supplementary Material Table S13). However, HR increased the SWC as compared to LR, which enhanced root growth and yield of cool dry season crops in crop season 3. Previous studies by Rahman *et al.* (2005) and Chakraborty *et al.* (2008) reported that crop residue retention decreased soil strength and thereby increased root growth of wheat.

There is little yield effect from establishing rice under non-puddled conditions as compared with traditional puddling in the current study. In a larger study by Haque *et al.* (2016), rice yields were either increased or unchanged by non-puddled transplanting, whereas Chaki *et al.* (2021) found that rice yields under non-puddled transplanted rice as compared to puddled transplanted rice were similar even for the initial years of experimentation. However, some studies have found lower yield of non-puddled rice as compared to puddled transplanted rice in the initial years (Jat *et al.*, 2014; Kumar and Ladha, 2011). Over time, moving to a non-puddled rice cultivation system may weaken plough pan development which may hamper water retention for rice production, but would be advantageous for root growth of post-rice crops (Mondal *et al.*, 2016).

### *Economic response to conservation agriculture*

Due to the minimal treatment effects on rice and mung bean yields, differences in system yield were largely determined by those affecting lentil or wheat yields. In the legume-dominated system, REY was lower with BP, corresponding with the lower yield of lentil in the first two years. In the cereal-dominated system, the poor performance of wheat resulted also in a significantly lower system yield in the BP treatment. Overall, system yield was not adversely affected by adopting

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SP methods as one component of CA, and there are indications that it can be improved by increasing yields of the winter crop. In a study of a rice-wheat system in the EIGP, adopting CA system also increased net return by 11% as compared to conventional system (Mishra *et al.*, 2021).

For lentil and wheat, higher net returns in SP compared to other crop establishment methods (Table 5) could be attributed to higher yields and lower production cost. The lower production cost in SP was mainly due to lower tillage costs by the absence of 3–4 passes of preparatory tillage for seedbed preparation and saved labour cost for land levelling, seeding and fertilizer application. Consistent with these findings, lower net returns and increased production cost with CT systems have been reported by several researchers in cereal-based cropping systems (Gathala *et al.*, 2013; Jat *et al.*, 2018; Parihar *et al.*, 2016). The results of the present three-year experiment suggest that just adopting one-pass planting by SP for lentil and wheat will offer an additional benefit of 306 and 79 US$ $ha^{-1}$, respectively, compared to existing farmer practice. Similarly, Jat *et al.* (2014) obtained an additional benefit of 149 US$ $ha^{-1}$ by eliminating tillage in the wheat crop under a rice-wheat system in the IGP. In an earlier study on maize-wheat system in India, Ram *et al.* (2012) also reported higher net returns under no-tillage and permanent raised beds than with CT.

Mung bean was not profitable, regardless of treatment, especially in the cereal-dominated system due to low or zero grain yield and high labour cost for weeding and pod harvesting. For rice, establishment method did not significantly effect net return but higher net return was achieved with LR as with HR the sale of straw was foregone.

At system level, when values for the three crops in the system are added, the production cost in the legume-dominated system was higher than in cereal-dominated system mainly due to the increased expenditure on pesticide application and higher seed cost. However, the net returns were also higher in the legume-dominated system compared to the cereal-dominated system mainly due to the high value of lentil compared to wheat. There is a need to either improve the profitability of mung bean in the rotation under CA or to replace it with alternative crops.

There were no significant treatment effects on the total net income of the legume-dominated systems. However, for the cereal-dominated system, net returns were better for LR than HR. Lower net returns in HR plots are attributable to lower income from straw sales. Retention of wheat straw mulch also lowered net returns in a crop rotation with soybean (Ram *et al.*, 2013). Although there are some negative effects of increased crop residue retention on crop profitability, increased retention has obvious benefits in improving soil physical and nutritional status (Alam *et al.*, 2020) and thus may reduce fertilizer requirement over time. However, the current economic value of crop residue meant that increased retention limited the profitability of the CA system with high crop residue retention. Hence, further research is needed to determine the optimum amount of crop residue to be retained for improving soil health, crop yield and profitability without unduly affecting its requirement for livestock feed, fuel and other on-farm needs.

The present study, and other similar studies conducted in the EIGP, has established yield, economic and soil improvement advantages of CA practices on winter crop components. However, these studies have been researcher managed and confined to relatively small plots. The challenge now is to scale up in a more participatory mode with all potential stakeholders, including farmers, agricultural input suppliers, policy and decision-makers, agricultural research and extension organizations and produce consumers. What is required are multi-location operational scale plots comparing the best treatment from small plot studies, for example SP for the winter crop, with the standard practice (CT). They should be farmer managed but extensively monitored to establish relationships across soil types, rainfall patterns, cropping systems, market opportunities, etc. Such evaluations are underway in a Conservation Agriculture Project for addressing various constraints to improve the adoption of CA in different rice-based cropping systems in EIGP (Bell *et al.*, 2019).

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## Conclusion

Successful implementation of CA using mechanized seeding can not only increase yields of cool season crops but also lower costs of production in rice-based systems, as compared with current practice in the EIGP. One-pass sowing and fertilizer application decreased fuel and labour costs which were approximately halved compared to conventional tillage. From its evaluation here in contrasting cereal- and legume-dominated rotations, further testing over a wider range of locations and for extended time periods would be warranted. It would also be instructive to measure the long-term (e.g. ≥ 5 years) effects of CA implementation, especially crop residue return and minimum tillage, on soil properties and their contribution to soil health and sustainability. In addition, further research is needed to determine the optimum level of crop residue retention considering all on-farm needs.

**Supplementary material.** For supplementary material for this article, please visit https://doi.org/10.1017/S0014479722000291

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