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# Long-term conservation agriculture increases nitrogen use efficiency by crops, land equivalent ratio and soil carbon stock in a subtropical rice-based cropping system

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## ABSTRACT

Conservation Agriculture (CA) is still a relatively new approach for intensively cultivated (3 crops yr$^{-1}$) rice-based cropping systems that produce high crop yield and amounts of residues annually. With the recent development of transplanting of rice into tilled strips on non-puddled soil, CA could become feasible for rice-based cropping patterns. However, the effect of increased retention of crop residues on crop response to nitrogen (N) fertilization rate in strip tilled systems with the transplanted rice and other crops grown in the annual rotation is yet to be determined. For nine years, we have examined the effects of soil disturbance levels - strip tillage (ST) and conventional tillage (CT), two residue retention levels –15% residue by height (low residue, LR) and 30% residue (high residue, HR) and five N rates (60%, 80%, 100%, 120%, and 140% of the recommended N fertilizer doses (RFD)) for a rice-wheat-mungbean cropping sequence. The 100% RFD was 75, 100 and 20 kg N ha$^{-1}$for rice, wheat, and mungbean, respectively. Rice yields were comparable between the two tillage systems for up to year-6, wheat for up to year-3 but mungbean yield markedly increased in ST from year-1; however, the land equivalent ratio increased from year-1, principally because of higher mungbean yield. Introduction of ST increased land equivalent ratio by 26% relative to CT, N use efficiency and partial factor productivity. Nitrogen fertilizer demand for maximum yield in ST was increased by about 10% for rice and 5% for mungbean but decreased by 5% for wheat. Although fertilizer N demand had increased in ST system due to higher yield than CT, the N requirement declined by50–90% when the same yield goal is considered for ST as for CT. The soil organic carbon stock (0–15 cm) after 8 years increased from 21.5 to 30.5 t ha$^{-1}$ due to the effect of ST plus high crop residue retention. Annual gross margin increased by 57% in ST over CT practice and 26% in HR over LR retention. In conclusion, after 9 years practicing CA with increased residue retention under strip tillage, the crops had higher N use efficiency, grain yield, land equivalent ratio and annual gross margin in the rice-wheat-mungbean cropping system while the N fertilizer requirement increased minimally.

## 1. Introduction

Rice in Asia is typically established by transplanting seedlings or sowing germinated seeds on puddled soil. Attempts to introduce Conservation Agriculture (CA) practices by zero tillage at sowing of rice into standing crop residue have been hampered by inadequate weed control (Farooq et al., 2011). An alternative method for establishing rice with minimum soil disturbance by transplanting on non-puddled soil has recently been shown to produce similar or higher yield to transplanting on puddled soil, but with significant cost savings and thus increased

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gross margin (Haque et al., 2016; Bell et al., 2019; Salahin et al., 2021). It also decreases greenhouse gas emissions (GHG) relative to conventional puddling and transplanting (Alam et al., 2016, 2019).

The traditional practice of tilling saturated soil, referred to as puddling, degrades soil structure, causes soil organic carbon (SOC) degradation and decreases permeability in sub-surface layers (Alam et al., 2020a; Jahangir et al., 2021). This has an adverse effect on the growth and yield of following winter crops including wheat (*Triticum aestivum L.*) due to delayed sowing as puddled soils take more time to dry to field capacity. In addition, it can restrict root development and water and nutrient use in the major South Asian rice-wheat cropping system (Gathala et al., 2011), though others did not explicitly support this conclusion (Humphreys et al., 2005). In the Indo-Gangetic Plain, farmers delay puddling for rice transplanting until the onset of monsoon rain, which might not only lower rice yields but also decrease the following wheat yields by delayed sowing (Hobbs and Gupta, 2003). Therefore, the omission of puddling might reduce the cost of rice production, create favorable soil conditions for the post-rice crop growth and yield, and reduce turnaround time between crops. Thus, non-puddled rice seedling transplantation might increase opportunities for crop intensification and enable rice to fit in the CA system.

The 8th World Congress of Conservation Agriculture Declaration (2021) advocated for transformation of paddy rice systems into CA systems with legumes and cover crops. As stated by Kar et al. (2021), the adoption of minimum soil disturbance plus crop residue retention and diversification of the rice-wheat cropping system with the inclusion of pulses may lead to a greater sustainability of the CA system through increased SOC accumulation and lower C input to maintain soil health (Bell et al., 2019). Most progress in CA has been made in large-scale commercial agriculture based on mechanized farming principles which are not yet adopted widely in rice-based cropping systems in Asia (Kassam et al., 2015). By contrast with the large amount of research conducted on CA in temperate climates with a single crop per year, fewer studies have been conducted in the tropics and subtropics with intensive rice-based cropping systems based on no-till cropping systems adapted to local conditions and needs (Pittelkow et al., 2015). Though recent studies on CA were conducted in rice-based cropping system in the Indo Gangetic Plain (IGP) (Jat et al., 2014; Bhatt et al., 2021, 2022), rice were established in those studies following dry direct seeding method, SRI method and machine transplanting method. None of the studies used the popular manual rice transplanting method of South Asia for establishment of rice in CA plots. Dry direct seeding rice establishment method is not applicable in places particularly in medium high land and medium low land due to early inundation of these rice fields. Thus, a follow-up study two years after completion of field trials revealed that no local farmers had continued CA-based practices mainly due to high weed pressure, lack of land leveling, inaccessibility of rice transplanting machines, and lack of ZT service providers (Magar et al., 2022). In addition, researchers in the IGP of South Asia often report the practice as CA even when zero or reduced tillage is only practiced for a single crop, or without considering the other two CA principles- residue retention and crop rotation for the on-farm implementation of CA (Magar et al., 2022).

The recently developed non-puddled transplanting system for rice (Islam et al., 2010; Haque et al., 2016; Bell et al., 2019; Salahin et al., 2021) involves strip tillage (ST), irrigation to saturate and soften the soil for 18–24 h and then transplanting seedlings in the strips. Minimum tillage can slow the breakdown of plant residues and reduce the release of mineralized inorganic forms of N (Hobbs et al., 2008; Kassam et al., 2009; Alam et al., 2020b). Very recently, it was observed that CA practices in Eastern Gangetic Plains with non-puddled rice based cropping system have altered the N cycling by reducing the level of mineral N available to plants in the early growing season but increasing soil total N (0–10 cm) and plant N uptake (Alam et al., 2020b). While synchronising N availability with crop demand increases N use efficiency of crops, no data are available to assess the requirement for N fertilizer for crop species under continuous CA in intensive rice-based cropping systems. In this study, we hypothesized that the conversion of a rice-based cropping system to CA with non-puddled ST rice establishment along with high crop residue retention can increase the N fertilizer requirement.

Thus, the present study was designed to examine whether strip tillage with low or high residue retention alters N requirement of crops or the land equivalent ratio, profitability and soil carbon stock in a rice-wheat-mungbean sequence under subtropical humid climatic condition.

## 2. Materials and methods

### 2.1. Experimental site and soil

The experiment was conducted on an Aeric Haplaquept soil at the Bangladesh Agricultural University (BAU) farm, Mymensingh, Bangladesh ($24^0$ 43.407′ N, $90^0$26.22′ E) for nine consecutive years from the monsoon rice of 2012 until summer mungbean of 2021. The experimental site is classed as medium-high land on Non-calcareous Dark Grey Floodplain soil in the Brahmaputra Floodplain agroecological zone (FAO/UNDP, 1988). The soil (0–15 cm) was silt loam (110 sand:760 silt:130 clay, g $kg^{-1}$) with bulk density (core sampler method) 1.58 Mg $m^{-3}$, pH(1:2.5 soil: water) 6.92, Walkley & Black organic carbon 13.2 g $kg^{-1}$, total N (Kjeldahl N) 1.2 mg $g^{-1}$, Olsen P 12.6 mg $kg^{-1}$, $NH_4OAc$ exchangeable K 0.12 cmol $kg^{-1}$ and $CaCl_2$extractable S 14.6 mg $kg^{-1}$. Soil analysis was done following the methods outlined by Page et al. (1982). The region has a sub-tropical humid climate and is characterized by hot and humid summers and cool winters with mean annual rainfall of about 2400 mm, 80% of which falls between May and September (Supplementary Fig. 1).

### 2.2. Treatments and design

The 3-way factorial experiment was laid out in a split-split-plot design with three replications. The three factors consisted of two soil disturbance levels - strip tillage (without puddling of soil for rice establishment)(ST) and conventional tillage including puddling of soil for rice crops (CT); two residue retention levels- farmer's practice with low (15%) retention and high retention (30% for rice and wheat and 100% for mungbean), and five annual N rates (117, 156, 195, 234 and 273 kg N $ha^{-1}$ $yr^{-1}$ representing 60%, 80%, 100%, 120% and 140% of the recommended N fertilizer doses (RFD). The RFD was based on existing recommendations for those crops (BARC, 2012): 75 kg N $ha^{-1}$ for rice, 100 kg N $ha^{-1}$ for wheat and 20 kg N $ha^{-1}$ for mungbean. Tillage methods were assigned to main-plots and sub-plots represented low and high residue retention, sub-sub plots represented five N rates. The size of the individual sub-sub plot was 7 m × 7 m.

### 2.3. Crop management

Land preparation was started in the third week of July for cultivation of monsoon-season (T. Aman) rice (*Oryza sativa*), the last week of November for cultivation of wheat (*Triticum aestivum*), and the last week of March for mungbean (*Vigna radiata*). For T. Aman rice establishment, in CT plots, soils flooded with 5–6 cm standing water were puddled with four rotary tillage passes by a 2-wheel tractor (2WT) mounted rotary tiller before the transplanting of rice seedlings; and in the case of ST, 4–6 cm wide and 5–6 cm deep tilled zones with 20 cm row spacing were made using a Versatile Multi-crop Planter (VMP). The ST plots were then flooded overnight for softening the soils in strips, and the rice seedlings were transplanted (Haque et al., 2016) in the strips manually.

In CT plots, four full cross rotary tillage passes with a 2-wheel tractor (2WT) were used for field preparation to sow wheat and mungbean. In the case of ST,4–6 cm wide and 5–6 cm deep tilled zones were prepared (that preserved about75- 80% of untilled soil) by2WT-mounted VMP with a row spacing of 20 and 30 cm for wheat and mungbean, respectively. After land preparation, 30-day old healthy rice seedlings raised in the seedbed were transplanted manually at three seedlings per hill with a spacing of 20 × 20 cm in both ST and CT plots. Wheat and mungbean were sown in lines by the 2WT-mounted VMP at a row spacing of 20 cm and at seed rates of 120 and 30 kg ha$^{-1}$, respectively, for wheat and mungbean both in ST and CT plots. The seeding depth was maintained at 3–4 cm using the depth-control roller of the VMP. Rice cv. BRRIdhan 49 was grown as a rainfed crop during July to November (Kharif season) followed by wheat (cv. BARI gom 25) during the dry November to March (Rabi season) and mungbean (cv. Binamung 8) during April to June (pre-kharif season) (Fig.S1). The same crop rotation was replicated for nine consecutive years totaling 27 crops in sequence.

For rice, urea was applied in three splits - 50% N as basal (during final land preparation), 25% N at 30 days (tiller stage) and 25% N at 50 days after transplanting (panicle initiation stage). For wheat, urea was added in three equal splits at 0, 25 and 50 days after sowing (DAS). However, all the urea was applied as a single basal application during final land preparation for mungbean. The other nutrients were applied at sowing at 10 kg P, 30 kg K, 10 kg S and 2 kg Zn ha$^{-1}$for rice, 20 kg P, 60 kg K, 10 kg S, 2 kg Zn and 1.5 kg B ha$^{-1}$for wheat, and 20 kg P, 30 kg K and 10 kg S ha$^{-1}$ for mungbean. The full amounts of P, K, S, Zn and B and basal rates of N were applied in the strips for ST and broadcast for CT during final land preparation for all the crops. In case of top dressing, N fertilizers were broadcast in all treatments. The sources of added nutrients were urea for N, triple superphosphate (TSP) for P, muriate of potash (MoP) for K, gypsum for S, zinc sulfate heptahydrate ($ZnSO_4$. 7 $H_2O$) for wheat and mungbean or zinc oxide (ZnO) for rice, and boric acid ($H_3BO_3$) for boron.

Non-selective herbicide, glyphosate, was sprayed over the field at 1.85 kg a.i. ha$^{-1}$ 2–3 days before transplanting of rice seedlings and sowing of wheat and mungbean seed both in ST and CT. In addition, for rice, pretilachlor (post-emergence) was used at 450 g ha$^{-1}$ 5–7 days after transplanting only in ST. Following local practice, hand weeding was practiced on all plots (both for ST and CT) if there was a weed infestation particularly for rice and wheat. Insecticide, Brifar 5 G was applied 50 DAS for wheat, diazinon 60EC was sprayed 3 times for mungbean (36, 48 and 59 DAS) to control insect attack and insecticides ‘Brifer 5 G’ and ‘Cidial 5 G’ were used to control insect attack for rice, principally stem borer.

Irrigation was provided for wheat firstly during the crown root initiation stage and secondly at the flowering stage. Around 35–40 mm irrigation was applied for wheat. Rice was dependent on rainwater; however, the rice fields were irrigated one day before the final land preparation if there was not sufficient water to make the soil soft for easier transplanting. No irrigation was provided for mungbean as there was periodical rainfall during this period.

### 2.4. Soil analysis for bulk density, organic carbon and microbial biomass carbon

The effects of tillage systems, residue levels and N rates on bulk density, total N, organic C, C stock and microbial biomass C of surface soil (0–15 cm) were assessed after harvest of the 23rd crop (wheat). In each plot, soil samples were collected from 15 locations (4 samples on strip or row and the rest between strip or row) by means of an auger (Ø 2.5 cm) from 0 to 15 cm depth. The samples after bulking were air-dried, ground, and passed through a 2-mm sieve. The soil organic carbon (SOC) was determined by the wet oxidation method (Walkley and Black, 1934).

Soil carbon stock was calculated by consideration of SOC for a soil layer and its bulk density. Bulk density was determined by core sampler method taking samples from 15 spots of each plot.

(Blake and Hartge, 1986). Soil microbial biomass carbon (MBC) was determined by $CHCl_3$ fumigation extraction method (Wu et al., 1990) which assumes an extraction efficiency coefficient of 0.45.

### 2.5. Harvesting

Rice and wheat were harvested manually at full maturity from three randomly selected quadrats of 1 m$^2$ from each plot to record their yields. Mungbean pods were harvested twice by hand picking at 2-week intervals when the pods attained maturity. Rice and wheat straw were harvested at 15% and 30% of plant height while mungbean stover was retained in split plots at 0 or 100%. The grain yields of rice, wheat and mungbean were reported at 14%, 12% and 12% grain moisture, respectively. The straw samples (15% and 30%) from the selected quadrats were returned to the field after recording the data.

### 2.6. Nutrient use efficiency

The N use efficiency (NUE) in the present study was estimated in terms of relative agronomic efficiency ($AE_N$) and partial factor productivity of N ($PFP_N$). The relative $AE_N$ refers to the increase in grain yield from addition of nitrogen, expressed as kg grain increase kg$^{-1}$ N applied (modified after Dobermann, 2005):

$$AE_N = \frac{GY_{NA} - GY_{NC}}{N_R}$$

where $GY_{NA}$ represents grain yield (kg ha$^{-1}$) obtained from N addition, $GY_{NC}$ represents grain yield (kg ha$^{-1}$) from N control (here 60% RDF) and $N_R$ indicates rate of nutrient added. Partial factor productivity of N ($PFP_N$) is a measure of efficiency of input use. It is the ratio of grain yield to the quantity of N applied, expressed as kg grain kg$^{-1}$ N applied (Dobermann, 2005),

$$PFP_N = \frac{GY_{NA}}{N_R}$$

### 2.7. Land equivalent ratio, economic and statistical analysis

Land equivalent ratio (LER) was calculated by the following formula slightly modified from Begum and Kader (2018):

$$LER = \frac{1}{3} \times (\frac{Y_{a1}}{Y_{b1}} + \frac{Y_{a2}}{Y_{b2}} + \frac{Y_{a3}}{Y_{b3}})$$

Where, $Ya_1$, $Ya_2$ and $Ya_3$ = Yield of rice, wheat and mungbean in tillage, residue and N treatments, respectively, while $Yb_1$, $Yb_2$ and $Yb_3$ = Yield of rice, wheat and mungbean in control treatments, respectively. Here, CT, LR and 60% RFD N were considered as control treatments for tillage, residue and N management, respectively.

The labour required to complete each operation (land preparation, irrigation, and herbicide or insecticide application) in a particular treatment plot was recorded and converted to person-days ha$^{-1}$ considering 8 h as equivalent to one person-day and the daily labour wage was Taka 400 (1US$ = 85 Tk) per person day$^{-1}$(Bangladesh Government wage rate). The prices of urea, TSP, MoP, gypsum, zinc sulphate and boric acid were 16, 22, 15, 10, 180 and 700 Tk kg$^{-1}$based on the Government fixed fertilizer price (for urea, TSP and MoP) and local market price. Each of the treatments of the experiment was evaluated based on total variable cost, gross return, and gross margin. Total variable cost was calculated considering the land preparation, labour, seed, fertilizer, irrigation, herbicide, fuel cost for threshing. Gross return was calculated by multiplying the amount of produce by its corresponding price at harvest. Gross margin was calculated by subtracting variable cost from gross return.

A quadratic yield response function was fitted to N fertilizer response data using Excel, 2016. Model coefficients were used to determine N rates for 100% and 95% of maximum yield goal following Watkins et al. (2010).

Data were statistically analyzed by MSTAT-C statistical software program (Michigan State University, USA). Three-way ANOVA based on a split-split plot design and Duncan's multiple range test (DMRT) (Gomez and Gomez, 1984) were used to assess significant differences in the mean crop yield, and SOC (carbon stock and microbial biomass carbon) due to tillage methods, residue retentions and N rates.

## 3. Results

### 3.1. Crop yield

There were no significant interactions between tillage systems, residue levels and N rates on crop yield for the first six years; thereafter for the last three years the two-way interaction effects (Tillage × N and Residue × N) were significant. The main and the interaction effects are presented in Supplementary Tables S1 and S2.

The grain yield of rice did not vary significantly between ST and CT until 2017–2018 and thereafter the ST plot yield was significantly higher than that of CT plot yield showing 4.59–5.49 t ha$^{-1}$ ST yield against 4.08 – 4.82 t ha$^{-1}$ CT yield (Table S1). Similarly, the mean rice yield did not differ significantly between levels of residue retention for the first six years and then in 2018–19, 2019–20 and 2020–21 the yield in HR plots was remarkably higher than that in LR. For N applications, the rice grain yield increased significantly with the N rates up to the highest yield (4.70–5.83 t ha$^{-1}$) at 90 kg N ha$^{-1}$ (120% RFD-N), then declined (4.56–5.28 t ha$^{-1}$) at 105 kg N ha$^{-1}$ (140% N rate), but the yields for the two highest N rates were not significantly different; the lowest yield was always recorded with 60% RFD-N rate (45 kg N ha$^{-1}$).

Strip tillage increased wheat yield relative to CT, but only after three years (Table S1). Similarly, the wheat yield response was higher for HR retention compared to LR in the last five years. Applying N at 120 kg N ha$^{-1}$ and 140 kg N ha$^{-1}$ produced higher yields (3.51–4.00 t ha$^{-1}$ and 3.30 – 3.92 t ha$^{-1}$, respectively) than 100% N-rates (3.38–3.42 t ha$^{-1}$) but their yields were not significantly different from each other. The 60% RFD-N rate (60 kg N ha$^{-1}$) produced the lowest wheat yield.

Seed yield of mungbean in ST plots (0.7–1.62 t ha$^{-1}$) was significantly higher than that of CT plots (0.5–1.14 t ha-$^{1}$) in every year (Table S1). The mungbean yield across the years also significantly increased due to HR (0.6–1.50 t ha$^{-1}$) compared to LR (0.5–1.26 t ha$^{-1}$). With regards to N fertilizer application, the mungbean yield had increased in some years with increasing N rates up to 24 kg ha$^{-1}$ (120% RDF) and in some years the yield reached its peak at the highest N rate (28 kg N ha$^{-1}$, 140% RDF); the yields at 24 and 28 kg N ha$^{-1}$ were statistically identical, but superior to other N rates.

The interaction effects of tillage or residue and N rate on rice yield were significant in the last three years i.e. year-7, year-8 and year-9 (Table S2). Then ST plots at every N rate produced significantly higher rice yield than CT plots (Table S3). The highest rice yield was recorded with 90 and 105 kg N ha$^{-1}$(120% and 140% RFD N rate) for ST system. The significant interaction of tillage and residue indicates that ST with HR gave significantly higher system yield over CT with LR in 2018–2019 and over both CT and ST with LR in 2019–2020 (Table S2). Similarly, in wheat, the ST practice and HR retention accompanied with N application at any N rate demonstrated higher yield compared to CT and LR, respectively. Mungbean yield increased by 0.1–0.4 t ha$^{-1}$ with high residue retention under ST, while there was no significant effect of residue retention under CT system. Nevertheless, all the rates of N application had greater effect on mungbean yield under ST compared to CT effect on rice and wheat yields over the years. Thus, adoption of ST and HR retention with 120% RFD N application produced the best yield for all crops.

### 3.2. Land equivalent ratio

Land equivalent ratio increased significantly in ST over CT for all the years except 2014–2015. (Tables 1 and 2). Similarly, LER increased significantly (0.15–0.33 unit) in HR treatment over LR only from 2017 to 2018 and continued the same trend till 2020–2021. The effects of N treatments on LER was significant from the beginning of the experiment. However, the highest LER was calculated in 120% rate of N application with ST (Table 2). Interaction of N fertilizer with crop residue retention followed the same trend with the highest LER in 120% rate of N application with HR (Table 2).

### 3.3. Economic performances

The ST practice gave higher gross margin over CT practice in all years (Table 3). The gross margin due to adoption of ST varied from 1700 US$ ha$^{-1}$yr$^{-1}$ to 2,780US$ ha$^{-1}$yr$^{-1}$. The annual gross margin due to ST over 9 years' was 57.2% higher than CT practice. The average annual gross margin was 26.4% higher with HR. For N fertilization, the annual gross margins due to 60%, 80%, 120% and 140% RDF relative to 100% RDF were-32.3%, − 15.7%, 13.4% and 11.9%, respectively. In the rice-wheat-mungbean cropping system, the gross margin increased up to the highest rates (120% and 140%) of N application, producing the highest gross margins with values of 2470 and 2440 US$ ha$^{-1}$, respectively.

### 3.4. Nutrient use efficiency

There is substantial increase in relative $AE_N$ for rice and mungbean in ST plots compared to CT plots (Table 4a). The values of relative $AE_N$ for rice, wheat and mungbean in CT plots ranged from 11.7 to 20.3 (17.9 ± 4.1), 13.3–22.5 (17.4 ± 3.8) and 23.2–49.8 (38.4 ± 11.2) kg grain increase for each kg N application while the corresponding relative $AE_N$ ranges for the three crops in ST plots were 16.7–27.5 (21.7 ± 4.5), 11.5–18.7 (16.5 ± 3.4) and 31.3–56.4 (46.2 ± 10.8) kg grain. Higher

**Table 1**

Long-term tillage, residue and nitrogen effects on land equivalent ratio in a rice-wheat-mungbean cropping system during 2012–13–2020–21.

| Till/ Res/N | **Land equivalent ratio** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2012–13 | 2013–14 | 2014–15 | 2015–16 | 2016–17 | 2017–18 | 2018–19 | 2019–20 | 2020–21 |
| **Tillage** | | | | | | | | | |
| ST | 1.21a | 1.17a | 1.07 | 1.20a | 1.14a | 1.23a | 1.28a | 1.21a | 1.79a |
| CT | 1.00b | 1.00b | 1.00 | 1.00b | 1.00b | 1.00b | 1.00b | 1.00b | 1.00b |
| **Residue** | | | | | | | | | |
| HR | 1.06 | 1.11 | 1.10 | 1.11 | 1.08 | 1.29a | 1.33a | 1.22a | 1.15a |
| LR | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00b | 1.00b | 1.00b | 1.00b |
| **N rate (kg N ha$^{-1}$yr$^{-1}$) *** | | | | | | | | | |
| 117 | 1.00d | 1.00c | 1.00d | 1.00d | 1.00d | 1.00d | 1.00d | 1.00d | 1.00d |
| 156 | 1.27c | 1.15b | 1.19c | 1.19c | 1.11c | 1.05c | 1.12c | 1.27c | 1.12c |
| 195 | 1.38b | 1.20ab | 1.30b | 1.36b | 1.33b | 1.15b | 1.29b | 1.50b | 1.23b |
| 234 | 3.49a | 1.23ab | 1.33b | 1.45b | 1.38b | 1.40a | 1.47a | 1.68a | 1.44a |
| 273 | 1.40b | 1.26a | 1.44a | 1.59a | 1.49a | 1.34a | 1.42a | 1.56b | 1.29b |

CT = Conventional tillage, ST = Strip tillage, LR = Low residue, HR = High residue

* 117, 156, 195, 234 and 273 kg N ha$^{-1}$ yr$^{-1}$ represent 60%, 80%, 100%, 120% and 140% of the recommended fertilizer dose for N, respectively.

Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.

**Table 2**
Interactions of tillage × nitrogen and residue× nitrogen on land equivalent ratio during 2018–2021.

| Tillage × Nitrogen | Land equivalent ratio | | | Residue × Nitrogen | Land equivalent ratio | | |
|---|---|---|---|---|---|---|---|
| | 2018–19 | 2019–20 | 2020–21 | | 2018–19 | 2019–20 | 2020–21 |
| **CT × N1** | 1.00 g | 1.00 g | 1.00j | LR × N1 | 1.00 f | 1.00e | 1.00e |
| **CT × N2** | 1.13 f | 1.29 f | 1.30i | LR × N2 | 1.11e | 1.34d | 1.15d |
| **CT × N3** | 1.41e | 1.52e | 1.64 h | LR × N3 | 1.07ef | 1.53c | 1.27c |
| **CT × N4** | 1.48d | 1.73d | 1.85 f | LR × N4 | 1.45c | 1.68c | 1.46b |
| **CT × N5** | 1.47d | 1.61e | 1.73 g | LR × N5 | 1.40 cd | 1.57c | 1.32c |
| **ST × N1** | 1.35e | 1.27 f | 2.49e | HR × N1 | 1.34d | 1.28d | 1.23c |
| **ST × N2** | 1.51d | 1.58e | 2.74d | HR × N2 | 1.38d | 1.60c | 1.30c |
| **ST × N3** | 1.67c | 1.86c | 3.03c | HR × N3 | 1.64b | 1.83b | 1.44b |
| **ST × N4** | 2.03a | 2.09a | 4.05a | HR × N4 | 1.80a | 2.03a | 1.68a |
| **ST × N5** | 1.93b | 1.94b | 3.44b | HR × N5 | 1.76a | 1.89b | 1.45b |
| **F-Test** | * * | * * | * * | | * * | * * | * * |

* * indicate $p < 0.05$.
Within a column, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.
CT = Conventional tillage, ST = Strip tillage, LR = Low residue, HR = High residue
N1 = 60% RFD, N2 = 80% RFD, N3 = 100% RFD, N4 = 120% RFD, N5 = 140% RFD
RFD means recommended fertilizer dose for N which was 75 kg/ha for rice, 100 kg/ha for wheat and 20 kg for mungbean.

average relative $AE_N$ was calculated for rice and mungbean in ST plots than CT while it was reversed for wheat. For rice, relative $AE_N$ declined with the increase of N rate in CT plots while it increased up to 120% RFD in ST plots then declined. For wheat, it increased up to 100% RFD in CT plots and 120% RFD in ST plots (except 100% RFD) before declining. However, for mungbean, it declined with the increase of N rate in CT plots while it increased up to 120% RFD in ST plots then declined. For LR, the relative $AE_N$ values for rice, wheat and mungbean varied from 10.5 to 19.7 (16.3 ± 4.4), 11.2–25.3 (18.6 ± 5.8) and 25.9–44.3 (34.7 ± 9.3) kg grain increase for each kg N application while the values with HR were 11.7–24.5 (21.1 ± 6.3), 11.1–19.0 (14.7 ± 4.9) and 24.5–40.7 (35.6 ± 7.5) kg grain, respectively. Higher average relative $AE_N$ was calculated for rice and mungbean in HR plots than LR while it was reverse for wheat. For LR, though relative $AE_N$ did not show a consistent trend in general, it declined with the increase of N application (except 100% RFD) for all the three crops. In contrast, it increased up to 120% RFD in HR plots for all the three crops. Among the three crops, mungbean had the highest agronomic efficiency of N irrespective of tillage, residue retention and N rates treatments.

The estimated PFP values for the three crops (rice, wheat and mungbean) in CT plots were 45.5–90.5, 23.8–37.8 and 28.1–38.4 kg grain for 1 kg N application while the respective PFP values in ST plots varied from 52.6 to 100.5, 27.5–48.8 and 46.5–66.9 kg grain (Table 4b). The average PEP values were calculated 12%, 22% and 69% higher for rice, wheat and mungbean, respectively in ST plots than CT plots. Concerning residue retention, the PFP values for rice, wheat and mungbean in LR plots ranged between 43.0 and 86.2, 23.3 and 35.8, and 34.8 and 46.7 kg grain per kg N applied, and in HR plots were 21%, 15% and 33% higher for rice, wheat and mungbean, respectively. For all cases, 140% RDF recorded the highest PFP value while 60% RDF had the lowest. Rice among the three crops had the highest PFP of N.

### 3.5. *Crop response curve*

The mean crop yield (y) in the last three years (2018–2021) for N treatments under CT and ST fitted well using the quadratic equation, $y = a + bx + cx^2$; the $R^2$values being highly significant (Fig. 1). The equations were developed using measured data from within the range 60–140% of RDF-N rate which is 45–105 kg N ha$^{-1}$ for rice, 60–140 kg N ha$^{-1}$ for wheat and 12–28 kg N ha$^{-1}$ for mungbean. This crop response curve suggests that the rice yield from both CT and ST plots responded positively to N application showing its peak at 120% RFD-N rates and then declined at higher N rate (140% RFD). These yield trends were equally true for the other two crops in sequence - wheat and mungbean.

The optimum N rate for rice and mungbean for ST practice at 100% maximum yield goal appears to be higher than that for CT practice showing 88–105 kg N ha$^{-1}$ (99.3 ± 9.8) vs 66–103 (89.0 ± 20.1) kg N ha$^{-1}$ for rice, 100–139 (125.0 ± 21.7) kg N ha$^{-1}$ vs 118–140 (132.0 ± 12.2) kg N ha$^{-1}$ for wheat and 24–28 (25.3 ± 2.3) kg N ha$^{-1}$ vs 23–25 (24.0 ± 1.1) kg N ha$^{-1}$ for mungbean over the last three years. However, no significant differences in optimum N rate for 100% maximum yield goal between CT and ST treatments were found for rice ($P = 0.23$, paired t-test), wheat ($P = 0.33$, paired t-test) and mungbean ($P = 0.27$, paired t-test). The maximum yield of rice, wheat and mungbean (100% yield goal) for ST increased by 15–18%, 15–21% and 32–176% compared to CT for rice, wheat and mungbean, respectively (Table S3) while the optimum N requirement increased mainly for rice by 2–33% and mungbean by 4–12% (Table S4). A decrease in optimum N requirement was observed for wheat.

However, when the yield level was set at 95% of maximum yield goal, the predicted N requirements were 66–87 (79.7 ± 11.8) kg N ha$^{-1}$ for ST vs 56–79 (65.3 ± 12.1) kg N ha$^{-1}$ for CT in rice, 91–120 (101.3 ± 22.5) kg N ha$^{-1}$ for ST vs 76–119 (110.0 ± 16.5) kg N ha$^{-1}$ for CT for wheat and 20–26 (23.7 ± 3.2) kg N/ha for ST vs 22 kg N ha$^{-1}$ for CT for mungbean over the last three years (Table 5). Again the differences between CT and ST were not significant for rice ($P = 0.14$, paired t-test), wheat ($P = 0.19$, paired t-test) and mungbean ($P = 0.46$, paired t-test).

On the other hand, a significant reduction ($P < 0.01$, pair t test) in N requirement was observed in ST plots when the yield goal was the same as for optimum yield goal of CT. The fertilizer N requirement in ST (for 100% maximum yield goal of CT) declined to 48–68 kg N ha$^{-1}$ (vs 66–103 kg N ha$^{-1}$) for rice, 54–93 kg N ha$^{-1}$ (vs 118–140 kg N ha$^{-1}$) for wheat and 8–13 kg N ha$^{-1}$ (vs 23–25 kg N ha$^{-1}$) for mungbean over the last three years (Table S4). The optimum N requirement in ST also showed decline relative to CT ($P < 0.01$) if the yield goal was set at 95% maximum yield of CT. Optimum N requirement calculated was 42–61 kg N ha$^{-1}$ (vs 56–79 kg N ha$^{-1}$) for rice, 48–86 kg N ha$^{-1}$ (vs 76–119 kg N ha$^{-1}$) for wheat and 7–13 kg N ha$^{-1}$ (vs 22 kg N ha$^{-1}$) for mungbean over the last three years (Table S4).

### 3.6. *Soil bulk density, nitrogen and carbon*

Effects of all interactions (tillage × residue, tillage × N and residue × N) were significant on all forms of carbon while there was no significant interaction in respect of soil bulk density and total N content (Table 6).

The highest organic C as well as the highest C stock was observed in ST with the high crop residue retention. The microbial biomass C exhibited similar trend with organic C as well as C stock which all decreased in the order: ST-HR > ST-LR > CT-HR > CT-LR. The C stock ranged from 21.5 to 30.5 t ha$^{-1}$ and the microbial biomass C from 156 to 240 mg kg$^{-1}$ over the tillage × residue interactions (Table 6).

Concerning tillage × N interactions, the highest values for organic C,

**Table 3**

Effects of tillage methods, residue retention and N rates on economic return in a rice-wheat-mungbean cropping system during 2012–13–2020–21.

| Tillage/ Residue / N rate | Variable cost \vskip5\hfill \hbox\rot90 {(1000 US $ ha$^{-1}$yr$^{-}$) | Gross return (1000 US $ ha$^{-1}$yr$^{-}$) | | | | | | | | | | Gross margin (1000 US $ ha$^{-1}$ yr$^{-}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2012–13 | 2013–14 | 2014–15 | 2015–16 | 2016–17 | 2017–18 | 2018–19 | 2019–20 | 2020–21 | **Mean** | 2012–13 | 2013–14 | 2014–15 | 2015–16 | 2016–17 | 2017–18 | 2018–19 | 2019–20 | 2020–21 | **Mean** |
| **Tillage** | | | | | | | | | | | | | | | | | | | | | |
| CT | 1.55–1.71 | 3.03 | 2.9 | 2.81 | 3.46 | 3.63 | 3.22 | 3.11 | 3.32 | 2.89 | **3.15** | 1.48 | 1.35 | 1.26 | 1.83 | 2.00 | 1.59 | 1.40 | 1.61 | 1.18 | **1.52** |
| ST | 1.27–1.40 | 3.36 | 3.15 | 2.97 | 4.11 | 4.11 | 4.11 | 3.87 | 3.93 | 3.94 | **3.73** | 2.09 | 1.88 | 1.70 | 2.78 | 2.78 | 2.78 | 2.47 | 2.53 | 2.54 | **2.39** |
| **Residue** | | | | | | | | | | | | | | | | | | | | | |
| LR | 1.41–1.55 | 3.33 | 2.94 | 2.8 | 3.66 | 3.80 | 3.31 | 2.99 | 3.32 | 3.20 | **3.26** | 1.92 | 1.53 | 1.39 | 2.18 | 2.32 | 1.83 | 1.44 | 1.77 | 1.65 | **1.78** |
| HR | 1.41 | 3.50 | 3.11 | 2.98 | 4.04 | 4.08 | 4.14 | 3.99 | 4.05 | 3.70 | **3.73** | 2.09 | 1.70 | 1.57 | 2.56 | 2.60 | 2.66 | 2.44 | 2.50 | 2.15 | **2.25** |
| * **RDF –** kg N ha$^{-1}$ yr$^{-1}$ | | | | | | | | | | | | | | | | | | | | | |
| 117 | 1.37 | 2.61 | 2.66 | 2.41 | 3.00 | 3.23 | 3.15 | 2.88 | 2.68 | 2.98 | **2.85** | 1.24 | 1.29 | 1.04 | 1.63 | 1.86 | 1.78 | 1.51 | 1.31 | 1.61 | **1.48** |
| 156 | 1.39 | 3.28 | 3.04 | 2.75 | 3.49 | 3.51 | 3.32 | 3.21 | 3.32 | 3.13 | **3.23** | 1.89 | 1.65 | 1.36 | 2.10 | 2.12 | 1.93 | 1.82 | 1.93 | 1.74 | **1.84** |
| 195 | 1.41 | 3.62 | 3.18 | 2.92 | 3.94 | 4.05 | 3.62 | 3.59 | 3.91 | 3.46 | **3.59** | 2.21 | 1.77 | 1.51 | 2.53 | 2.64 | 2.21 | 2.18 | 2.50 | 2.05 | **2.18** |
| 234 | 1.43 | 3.78 | 3.29 | 3.02 | 4.20 | 4.25 | 4.28 | 4.09 | 4.36 | 3.83 | **3.90** | 2.35 | 1.86 | 1.59 | 2.77 | 2.82 | 2.85 | 2.66 | 2.93 | 2.40 | **2.47** |
| 273 | 1.44 | 3.58 | 3.26 | 3.15 | 4.57 | 4.53 | 4.07 | 3.96 | 4.11 | 3.67 | **3.88** | 2.14 | 1.82 | 1.71 | 3.13 | 3.09 | 2.63 | 2.52 | 2.67 | 2.23 | **2.44** |

CT = Conventional tillage, ST = Strip tillage, LR = Low residue (15% retention), HR = high residue (30% retention)

* 117, 156, 195, 234 and 273 kg N ha$^{-1}$ yr$^{-1}$ represent 60%, 80%, 100%, 120% and 140% RDF-N, respectively.

Variable cost ((1000 US $ ha$^{-1}$yr $^{-}$): For CT: 2012–15: 1.55, 2015–18: 1.63, 2018–21: 1.71; For ST: 2012–15: 1.27, 2015–18: 1.33, 2018–21: 1.40;

For LR: 2012–15: 1.41, 2015–18: 1.48, 2018–21: 1.55

C stock and microbial C were recorded with ST and 100–140% of the recommended N rate (Table 6). At every N rate, the effect of ST was higher than that of CT. The C stock increased from 23.4 t ha$^{-1}$ (CT-N1) to 30.7 t ha$^{-1}$ (ST-N5) and the microbial biomass C from 155 mg kg$^{-1}$ (CT-N1) to 242 mg kg$^{-1}$ (ST-N4). For residue × N interactions, the HR with all N fertilizer rates except the 60% RFD had higher values for all forms of C (Table 6).

## 4. Discussion

### 4.1. The dynamic response of crop yield to tillage and residue retention

Rice yield was comparable between the CT and ST systems for the first six years i.e. 2012–2018 and thereafter the ST yielded 13% higher than the CT yield. In years 7–9, the positive yield responses to ST were consistent indicating that on this soil the benefits of ST for rice take many crops to become manifest. Hence, in the following analysis we focus on the effects of tillage and residue retention on crop responses to N fertilizer in the last three years.

In recent study, no yield reduction of rice was reported in non-puddled transplanted plots from the initial year of CA management (Haque et al., 2016; Bell et al., 2019; Salahin et al., 2021). Puddling of soil is not essential for rice growth and yield (Singh et al., 2001), and there was no yield reduction of non-puddled transplanted or direct-seeded rice compared to the puddled one (Aggarwal et al., 1995; Humphreys et al., 1996). By contrast, previous reports suggest that the transition from CT to no-till decreased yield in early years until increases in soil C, aggregate stability, and available water capacity developed (Six et al., 2002; Kumar et al., 2012). From a global meta-analysis, Pittelkow et al. (2015) concluded that no-tillage system was the 4th most influential variable, with a lag period of several years (5 + years) occurring before no-till yields matched CT yields. The meta-analysis was done on global dataset covering 63 countries representing 50 crops (rice, wheat, maize, oilseeds, legumes, etc.). While the positive yield response in non-puddled rice took six years in the present study, the response of mungbean to both ST and increased crop residue retention occurred throughout the study (2012–2021). Possible reasons for the benefit of ST and increased residue retention on mungbean yield are discussed below. Wheat was intermediate in its response to ST, taking three years for yield to increase significantly due to ST practice over CT. This result indicates that ST is more beneficial to dryland crops (wheat, mungbean) than to wetland rice, similar to the observation made by Pittelkow et al. (2015), but over time the changes in soil properties can also benefit rice.

### 4.2. Tillage and residue retention effects on land equivalent ratio

The LER in ST significantly exceeded that with CT practice for all the years except 2014–2015 due to much higher yield (LER) of mungbean in ST system throughout the experimental period except 2014–2015 and also higher yield (LER) of wheat and rice in ST system from year-4 and year-7 onwards, respectively (Tables S1 and S2). Mungbean yield in ST increased by 66, 40% and 14% in year-1, year-2 and year-3, respectively, but not in ST in 2014–2015. However, thereafter (2015–2021), the yield of wheat and rice increased in ST over CT in addition to mungbean from year-4 and year-7, respectively, thus LER increased significantly in ST over CT. A recent global meta-analysis (Pittelkow et al., 2015) also concluded that legumes performed better under no-till system while among the cereals, wheat yield was less negatively impacted by no-till practices relative to the results reported for rice. Indeed, increased crop yield following adoption of CA was mainly attributed to two mechanisms: firstly, through conservation of soil moisture and regulating soil temperature and secondly, through an improvement of soil health particularly through SOC build-up, soil nitrogen and soil structure improvement (Alam et al., 2018, 2020b). In this experiment, rice was cultivated during rainy season when soil remained flooded throughout the rice growing period. Therefore, high

**Table 4**
Nitrogen use efficiency (NUE) in terms of agronomic efficiency (AE) and partial factor productivity (PFP) of N (3 years' average result, 2018–2021).

| | (a)Agronomic Efficiency of N ($AE_N$) | | | | | | |
|---|---|---|---|---|---|---|---|
| Tillage × Nitrogen | $AE_N$ (kg grain increase kg$^{-1}$ N applied) | | | Residue × Nitrogen | $AE_N$ (kg grain increase kg$^{-1}$ N applied) | | |
| | Rice | Wheat | M. bean | | Rice | Wheat | M. bean |
| **CT × N1** | – | – | – | LR × N1 | – | – | – |
| **CT × N2** | 20.2 | 16.2 | 49.8 | LR × N2 | 19.7 | 25.3 | 44.3 |
| **CT × N3** | 20.3 | 22.5 | 42.1 | LR × N3 | 15.2 | 19.8 | 27.5 |
| **CT × N4** | 19.3 | 17.6 | 38.3 | LR × N4 | 19.7 | 17.9 | 41.0 |
| **CT × N5** | 11.7 | 13.3 | 23.2 | LR × N5 | 10.5 | 11.2 | 25.9 |
| **ST × N1** | – | – | – | HR × N1 | – | – | – |
| **ST × N2** | 20.7 | 18.1 | 51.3 | HR × N2 | 23.8 | 9.9 | 38.1 |
| **ST × N3** | 22.0 | 17.7 | 45.9 | HR × N3 | 24.5 | 18.9 | 38.9 |
| **ST × N4** | 27.5 | 18.7 | 56.4 | HR × N4 | 24.4 | 19.0 | 40.7 |
| **ST × N5** | 16.7 | 11.5 | 31.3 | HR × N5 | 11.7 | 11.1 | 24.5 |
| | (b)Partial Factor Productivity of N ($PFP_N$) | | | | | | |
| **Tillage × Nitrogen** | $PFP_N$ (kg grain kg$^{-1}$ N applied) | | | **Residue × Nitrogen** | $PFP_N$ (kg grain kg$^{-1}$ N applied) | | |
| | **Rice** | **Wheat** | **M. bean** | | **Rice** | **Wheat** | **M. bean** |
| **CT × N1** | 90.5 | 37.8 | 34.6 | LR × N1 | 86.2 | 39.3 | 46.7 |
| **CT × N2** | 73.0 | 32.4 | 38.4 | LR × N2 | 69.6 | 35.8 | 46.1 |
| **CT × N3** | 62.4 | 31.7 | 37.6 | LR × N3 | 57.8 | 31.5 | 39.0 |
| **CT × N4** | 54.9 | 27.7 | 36.4 | LR × N4 | 53.0 | 28.6 | 43.9 |
| **CT × N5** | 45.5 | 23.8 | 28.1 | LR × N5 | 43.0 | 23.3 | 34.8 |
| **ST × N1** | 100.5 | 48.8 | 66.9 | HR × N1 | 103.6 | 47.6 | 67.2 |
| **ST × N2** | 80.6 | 41.1 | 63.0 | HR × N2 | 83.7 | 38.2 | 59.9 |
| **ST × N3** | 69.1 | 36.4 | 58.5 | HR × N3 | 72.0 | 36.1 | 55.9 |
| **ST × N4** | 64.0 | 33.7 | 61.6 | HR × N4 | 64.0 | 33.3 | 53.9 |
| **ST × N5** | 52.6 | 27.5 | 46.5 | HR × N5 | 51.1 | 26.8 | 42.8 |

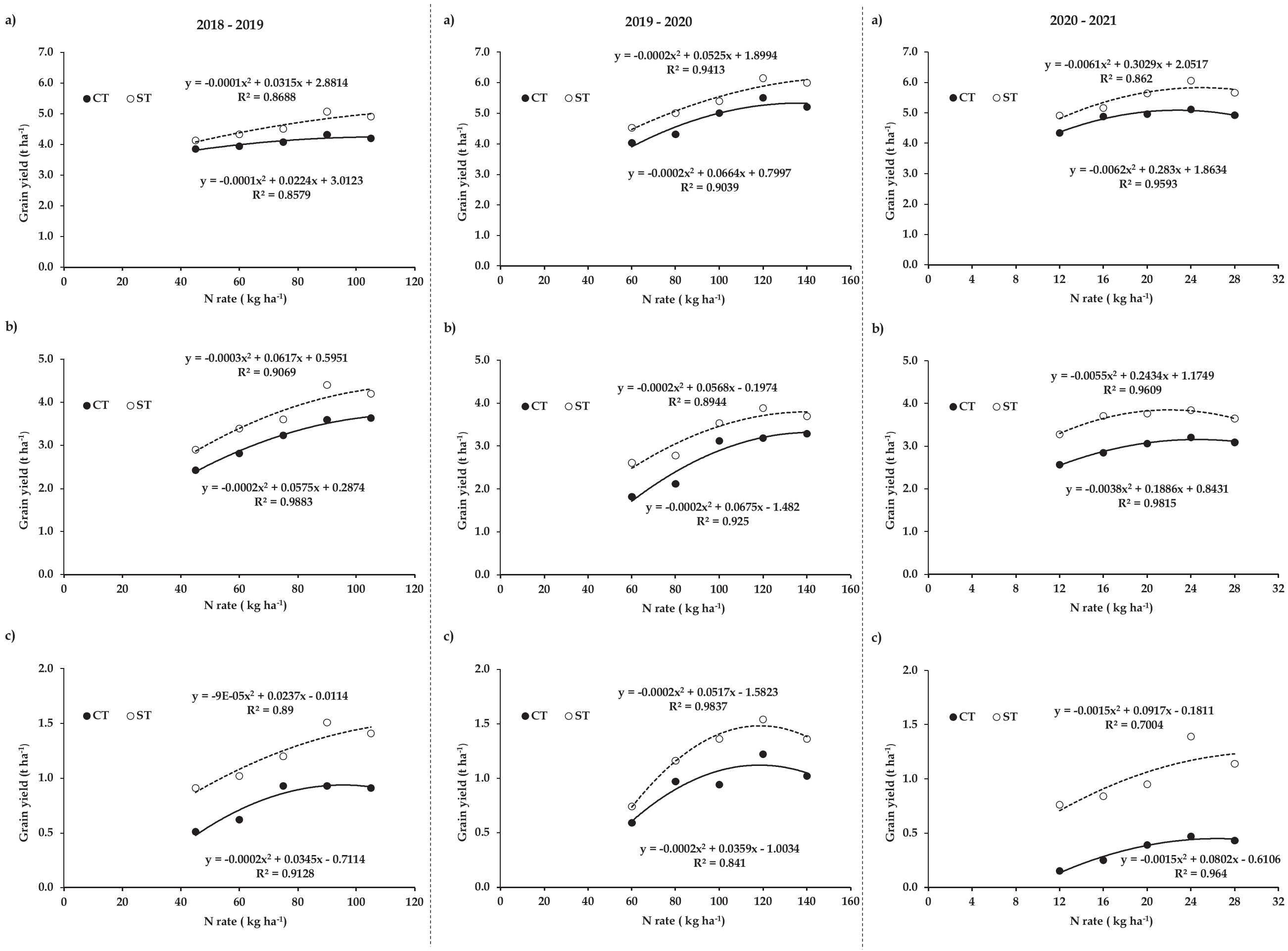

**Fig. 1.** Response of rice (a), wheat (b) and mungbean (c) yield in three consecutive years as a function of N rates under two tillage systems (ST- strip tillage; CT-conventional tillage). Values are means of four replicates.

**Table 5**

Optimum N requirement (kg N $ha^{-1}$) of rice, wheat and mungbean in conventional tillage (CT) and strip tillage (ST) plots in different years. Values derived from Fig. 1.

| Year | N requirement in CT | | | N requirement in ST | | | N requirement in ST at maximum yield of CT | | |
|---|---|---|---|---|---|---|---|---|---|
| | Rice | Wheat | M. bean | Rice | Wheat | M. bean | Rice | Wheat | M. bean |
| **100% of maximum yield** | | | | | | | | | |
| 2018–2019 | 103 | 140 | 24 | 105 | 139 | 24 | 53 | 93 | 13 |
| 2019–2020 | 98 | 138 | 23 | 105 | 136 | 24 | 68 | 92 | 13 |
| 2020–2021 | 66 | 118 | 25 | 88 | 100 | 28 | 48 | 54 | 8 |
| **95% of maximum yield** | | | | | | | | | |
| 2018–2019 | 61 | 119 | 22 | 87 | 119 | 25 | 42 | 85 | 13 |
| 2019–2020 | 79 | 120 | 22 | 86 | 109 | 20 | 61 | 86 | 13 |
| 2020–2021 | 56 | 91 | 22 | 66 | 76 | 26 | 43 | 48 | 7 |

**Table 6**

Interaction effects of tillage practices, residue retention and nitrogen fertilization on bulk density, total N, organic C, C stock and microbial biomass C in a rice - wheat - mungbean cropping system at 0–15 cm soil depth (after 23rd crop).

| Tillage × Residue × Nitrogen | Bulk density (g $cm^{-3}$) | Total N (g $kg^{-1}$) | Organic C (%) | Carbon stock (t $ha^{-1}$) | Microbial biomass C (mg $kg^{-1}$) |
|---|---|---|---|---|---|
| **Tillage × Residue interactions** | | | | | |
| CT-LR | 1.30 | 1.1 | 1.1c | 21.5c | 156 d |
| CT-HR | 1.28 | 1.1 | 1.4 b | 26.9 b | 175c |
| ST-LR | 1.30 | 1.5 | 1.4 b | 27.3 b | 198 b |
| ST-HR | 1.27 | 1.5 | 1.6 a | 30.5 a | 240 a |
| **F-test** | **NS** | **NS** | * | * | * |
| **Tillage × Nitrogen interactions** | | | | | |
| CT × N1 | 1.30 | 1.1 | 1.2c | 23.4 d | 155 d |
| CT × N2 | 1.29 | 1.1 | 1.2c | 23.2 d | 163 cd |
| CT × N3 | 1.28 | 1.3 | 1.2c | 23.0 d | 158 d |
| CT × N4 | 1.29 | 1.3 | 1.3 bc | 25.1 cd | 151 d |
| CT × N5 | 1.30 | 1.5 | 1.3 bc | 25.4 cd | 199 b |
| ST × N1 | 1.29 | 1.3 | 1.4 b | 27.1 b | 197 b |
| ST × N2 | 1.29 | 1.3 | 1.4 b | 27.1 b | 223 ab |
| ST × N3 | 1.28 | 1.4 | 1.5 ab | 28.8 ab | 227 ab |
| ST × N4 | 1.28 | 1.4 | 1.6 a | 30.7 ab | 242 a |
| ST × N5 | 1.29 | 1.5 | 1.6 a | 31.0 a | 205 b |
| **F-Test** | NS | NS | * | * | * |
| **Residue × Nitrogen interactions** | | | | | |
| LR × N1 | 1.30 | 1.2 | 1.3c | 25.4c | 165 e |
| LR × N2 | 1.30 | 1.2 | 1.3c | 25.4c | 183 cde |
| LR × N3 | 1.29 | 1.3 | 1.3c | 25.1c | 159 e |
| LR × N4 | 1.30 | 1.3 | 1.4 b | 27.3c | 170 de |
| LR × N5 | 1.31 | 1.5 | 1.4 b | 27.5c | 206 abc |
| HR × N1 | 1.28 | 1.3 | 1.5 ab | 28.8 ab | 187 bcde |
| HR × N2 | 1.27 | 1.2 | 1.5 ab | 28.6 ab | 203 abc |
| HR × N3 | 1.26 | 1.4 | 1.5 ab | 28.4 ab | 226 a |
| HR × N4 | 1.27 | 1.4 | 1.6 a | 30.5 a | 223 ab |
| HR × N5 | 1.28 | 1.5 | 1.6 a | 30.7 a | 198 abcd |
| **F-Test** | NS | NS | * | * | * |

Within a column for each interaction, the mean values followed by the same letter are not significantly different at the 0.05 level of probability by DMRT.

[*] , $p < 0.05$; NS = Not significant.

rainfall during monsoon (wet) season in this humid region nullified the beneficial effect of soil moisture conservation and soil temperature regulation under CA management (Hobbs et al., 2008; Farooq et al., 2011; Pittelkow et al., 2015) leaving no differences on measured rice yield in initial 6 years. Soil health improvement in rice soil through better aggregation, aeration and water movement is also nullified in the initial years as the soil remained oversaturated almost throughout the rice growing period. Improvement of soil health associated with SOC buildup occurs slowly as was observed in this experiment too. Significant difference in SOC was observed after 6 years but still no significant difference was observed for soil total N. Thus, there was no significant difference in rice yield between two tillage treatments for the first 6 years.

### 4.3. *Tillage and residue effects on economic benefits*

The most consistent benefit under ST was due to increased profit arising from lower input costs coupled with higher earnings from output sales. The lower input cost in ST was associated with decreased land preparation costs (water, labor and energy savings) (Haque et al., 2016; Bell et al., 2019). Similarly, Saharawat et al. (2010), Pittelkow et al. (2012), Jat et al. (2019) and Salahin et al. (2021) reported that ST did not impede transplanting of rice seedlings rather it reduced the land preparation cost and time, crop establishment period and irrigation cost, and increased the gross margin of rice relative to CT. With HR management, increased crop yield led to higher gross margin. The ST practice increased gross margin over CT practice, and similarly HR management exhibited higher gross margin compared to LR management. The improved economic performance of ST systems is an important factor for farmer adoption, and decreased farm labour requirements may be particularly influential in South Asia due to the shortage of labour in rural areas (Haque et al., 2016).

### 4.4. *Tillage and residue effects on N requirement*

The effect of N application on crops was significant from the first crop. However, the interaction effect of tillage or residue on N fertilizer responses only became significant after 6 years. The crop yield or system yield (3 crops combined) increased with increasing rates of N application, but after 6 years during 2018–2021, the crop yield declined at 140% N rate. Hence, after 9 years of CA practice, the 120% RDF-N rate (90 kg N $ha^{-1}$ for rice, 120 kg N $ha^{-1}$ for wheat and 24 kg N $ha^{-1}$ for mungbean) combined with ST and HR management produced the highest yield and hence the demand for N uptake.

The positive response of crop yield to higher N rates in ST than the recommendation (100% N rate) under HR retention over the years more likely due to higher N demand resulted from the improvement of soil health. Significant increase in SOC and increasing trend of soil total N in ST support this hypothesis (Table 6). Increase in SOC and total N in ST soils in a rice-based cropping system similar to our experimental set up was reported by Alam et al., (2018, 2020b). Interestingly, calculated optimum N requirement in ST plots did not increase substantially relative to the CT plot, contrasting to yield increase. This might be due to better recycling or plant recovery of soil N in ST plots. Higher N use efficiency and microbial biomass in ST plots support this finding. Based on crop yield and N demand, we calculate that ST plot requires 33–47 kg additional N per year to achieve 100% maximum yield goal or 31–44 kg additional N per year for the 95% maximum yield goal. However, since the additional N requirement in ST plot calculated from crop response curve was much lower than the above-mentioned figures, we conclude that ST soil supplied this additional N through more efficient N cycling or root uptake. Since both $NH_4$-N and $NO_3$-N levels as well as their sum in standing water of rice field were higher in CT compared to ST system (data not shown), it is possible that N was more susceptible to loss through volatilization and denitrification in the case of CT than with ST (Huda et al., 2016), although there was no evidence of lower $NH_3$

volatilization with ST under rice crops (Uddin et al., 2021). Alam et al. (2020b) suggested that there was better synchronization between crop N demand and soil N supply under CA practice in a rice-based cropping system would lead to higher N use efficiency.

Lundy et al. (2015) reported from a recent meta-analysis that yield declines related to the implementation of no-tillage are more sensitive to the rate of N fertilization in tropical/subtropical than in other regions. In contrast, Jat et al. (2012) reported that increasing N application minimized potential yield reductions associated with adoption of no-tillage corn production both in drier (silt loam soil) and humid climates (fine textured soils), however, the tillage effect appeared to be independent of N management. Very recently, Cao et al. (2021) observed that N addition decreased SOC mineralization of forest soils but increased that of paddy soils. There are reports that N addition reduces SOC mineralization (Guo et al., 2017; Hu et al., 2017; Zhu et al., 2018), produces no effects (Micks et al., 2004; Allison et al., 2008) and even increases SOC mineralization (Huang et al., 2011; Zhao et al., 2019).

Even though fertilizer N demand increased in ST, due to higher yield than CT, its N use efficiency was higher particularly for rice and mungbean. The NUE in ST plots were increased up to 120% RFD. Indeed, the ST system compared to CT had a 50–90% reduction in N requirement when yield goal is fixed at the maximum CT yield. This suggests more efficient use of N fertilizer and of soil N. Higher microbial biomass in ST plot suggests greater turnover of soil N for crop uptake. Mungbean grown before the rice crop was well-nodulated particularly in ST plots and high residue retention plots (data not shown) which may indicate greater input of symbiotically-fixed N in the ST crop sequence. The inclusion of leguminous crops in the crop rotation, potentially contribute N to the system for subsequent crops and reducing the probability of N-related NT/CT yield interactions (Pittelkow et al., 2015). However, the greater demand for N due to higher yield in ST would be expected to increase the N requirement with the advancement of time. The crop response curve as a function of N (described in Section 3.5) indicates that the N requirement in ST practice needs to be increased by about 10% for achieving soil fertility improvement of rice-based CA practice in Bangladesh.

### *4.5. Tillage and residue effects on soil carbon*

After 8 years of cropping, soil accumulated more organic C in ST (28.9 t ha$^{-1}$) than CT (24.2 t ha$^{-1}$) and in HR (28.7 t ha$^{-1}$) than LR (24.4 t ha$^{-1}$). Similarly, there was a higher MBC (microbial carbon) in ST (219 mg kg$^{-1}$) than CT (166 mg kg$^{-1}$), and HR (208 mg kg$^{-1}$) than LR (177 mg kg$^{-1}$). Choudhary et al. (2018) also reported higher soil organic carbon and also MBC in ZT than in CT and in HR than LR in Indo-Gangetic Plains under a cereal cropping system.

The C stock (0–15 cm) in the present study increased from 21.5 to 30.5 t ha$^{-1}$due to the combined effects of strip tillage and high crop residue retention after 8 years (Table 6). A considerable amount of SOC accumulation under ST management with high residue retention might be attributed to firstly an increase in OC and N in particulate organic matter and better soil aggregation hence physical protection of soil organic matter (SOM) (Kader et al., 2010). Secondly, redistribution of SOC within the soil profile results in SOC enrichment in the surface layer under ST (Luo et al., 2010). Thirdly, increase in net plant productivity as well as root based C exudates and root biomass (Virto et al., 2012). Fourthly, decline in soil respiration due to less soil disturbance (Kainiemi et al., 2015). Fifthly, promotion of fungal-based microbial community that helps C sequestration more than the bacterial-based microbial community (Six et al., 2006; Haddaway et al., 2017). The initial soil C stock (before start of the experiment) was 25.7 t ha$^{-1}$, thus the increment was equivalent to 0.15–0.6 Mg C ha$^{-1}$ yr$^{-1}$. Retention of crop residues after no or minimum tillage or on raised beds in rice-wheat systems has increased SOM in South Asia (Anon, 2008). Lemma et al. (2021) using the Day Cent model reported that the conservation management with rainfed cropping systems (sorghum, millet, corn, etc.) increased SOC in Southern Ethiopia under a tropical climate by 0.34–9.71 Mg C ha$^{-1}$ over 30 years (1991–2020) when compared to conventional practices. Similarly, Begum et al. (2018) calculated SOC sequestration of 0.67 t $CO_2$-eq. ha$^{-1}$ year$^{-1}$under reduced tillage management with high crop residue retention by using Day Cent model for wetland paddy soil in Bangladesh under sub-tropical humid climate, which is nearly 10% higher than SOC under baseline management.

Strip tillage accompanied with higher N than the recommended N rate increased all forms of soil C. The N application increased soil C stock, with the values of 27.9 t ha$^{-1}$for 120% N and 28.2 t ha$^{-1}$ for 140% N application against 25.9 t ha$^{-1}$ due to 100% N supplement. It also increased the microbial C. Several studies have reported increased SOC with increased N fertilization rates (Studdert and Echeverria, 2000, 2018). Lemma et al. (2021) reported that the combination of 50–75% CR (crop residue), NT (no-till), and 32 kg N ha$^{-1}$ fertilization provided the highest SOC sequestration over 30 years with rates equivalent to 0.27–0.32 Mg C ha$^{-1}$ yr$^{-1}$. Unlike the study by Alam et al. (2020b) on a silty clay soil and an intensive rice-based crop rotation which showed increased soil total N after 5 years, the present study showed no significant increase in soil N after 8 years.

## 5. Conclusions

The CA research in intensively cultivated rice-based cropping systems in South Asia focused on zero-till wheat, and less on zero-till (non-puddled) rice: indeed many studies lacked a complete CA system approach due to inadequate technology for rice establishment. The recent development of strip tillage and transplanting of rice on non-puddled soil facilitates the rice system-based study of CA in this region. Adding to a growing body of literature, our results demonstrate that strip tillage of rice is feasible in silty floodplain soil of Bangladesh without any yield penalty for the first 6 years, and subsequently with 12.5–13.9% yield increase. Moreover, mungbean and wheat yields in the cropping sequence benefitted from the first and third year onwards, respectively, after the adoption of ST and increased residue retention resulting in a significant increase in land equivalent ratio, gross return and gross margin. Adoption of ST practice increased the SOC stock and crop N use efficiency but only marginally increased N fertilizer requirement to achieve the higher yield potential.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108636.

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