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Alternating tillage with conservation agricultural practices in intensive rice (*Oryza sativa* L.)-based cropping systems can improve soil health and increase crop and systems productivity in the Eastern Indo-Gangetic Plains

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ABSTRACT

Available ariable land for agriculture in South Asia's Eastern Indo-Gangetic Plains (EIGP) is decreasing while the population and the demand for food is increasing. Despite this pressure to intensify land use, large tracts of land still remain fallow during the dry season. Making productive use of these lands is essential to increasing farm output while safeguarding food security. One potential part of the solution to this challenge lies in improved land management practices. Conservation agriculture with no or reduced tillage (CA), or alternating tillage where monsoon rice is established with full tillage and dry season crops with reduced or zero tillage (AT), can potentially facilitate improved crop establishment, increase yield, and improve soil health and the resilience of cropping systems. This study was undertaken to evaluate CA, AT and conventional tillage (CT) under double- or triple cropping sequences on loamy soil in a (sub) tropical environment in the EIGP northern Bangladesh. The experiment included six cropping systems (CS) over three consecutive years: CS1, Aman rice (*Oryza sativa* L.) – Boro or winter rice (*Oryza sativa* L.) (R-R); CS2, Aman rice – Wheat (*Triticum aestivum* L.) (R-W); CS3, Aman rice – Maize (*Zea mays* L.)(R-M); CS4, Aman rice - Mung bean (*Vigna radiata* L.) (R-M); CS5, Aman rice – Wheat – Mung bean (R-W-MB); and CS6, Aman rice – Maize – Mung bean (R-M-MB). In CS5 and CS6, mung bean replaced land fallowing after the predominant dry season crop. Maize, but not rice, yields were higher in AT or CA than CT. The R-W-MB and R-M systems had the highest system-level rice equivalent yield. Soil chemical properties, except SOM, total N, and Mn, in the 0–15 cm portion of the soil profile also differed significantly among the systems. Cropping systems had a significant effect on soil penetration resistance up to 30 cm soil depth. The buffering capacity of the soil under these treatments against diurnal temperature variation was also higher under CA followed by AT. These results suggest that AT with CA-based management practices can improve cropping systems level yields and soil properties. These practices can also be be adapted to rice-based farming systems where they can support improved land management and increase systems productivity and soil health. Long-term studies are required across soil types, climates, and socio-economic conditions to extrapolate findings to larger areas of the EGP.

1. Introduction

Cropping systems in South and Southeast Asia comprise a rice crop in the summer, monsoon season followed by either wheat, maize, rice, legumes, oilseeds, or other crops in the dry, winter season, resulting in double cropping systems [1–5]. In many areas, especially in Bangladesh, eastern India, and eastern Nepal Terai located in South Asia's Eastern Indo-Gangetic Plains (EIGP), a third crop of mung bean is also grown [6–10]. Among the various cropping systems, double-cropped rice-rice (R-R), rice-wheat (R-W) and rice-maize (R-M) together cover approximately 75 % of the net cultivable area in the EGP, substantially contribute to food security, and provide metabolizable energy and

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partial protein requirements of low to middle income rural and urban population [4–6,9,11–13].

Existing data reveal that there is a decreasing trend in the availability of extra (new) lands for cropping in the EIGP but there is an increasing trend of lands remaining fallow during the dry season due to extreme climate (excess water in some places and low or no water in other places) as well labour unavailability for cropping [10,14–16]. Hence, there is a need to utilize the existing fallows in the dry season by optimising and intensifying cropping with less water requiring crops such as wheat, maize, mung bean, or mustard [3,9,10,17]. Amongst the various crops, rice, wheat and maize are highly important for food security and their productivity must be increased to meet the increasing food demand of ever-increasing population of Bangladesh and the EIGP. There is also a need to sustainably intensify the current double-cropped areas by including a third crop such as mung bean that requires less water and energy and has potential to improve human nutrition, soil quality, and soil health [6,8,10,18].

Rice-based cropping systems in Bangladesh are practiced with intensive tillage (puddling in rice and repetitive tillage in other crops) and by removing crop residues from the field. Intensive tillage utilizes substantial amounts of non-renewable resources, including water and energy [6,19,20], degrades soil structure and soil organic matter (SOM), and declines soil fertility [21]. Resource-efficient practices such as conservation agricultural-based sustainable intensification (i.e., zero, reduced or strip tillage; full or partial retention of residue; and diversified rotations) are needed to reduce land preparation operations, energy and water requirements, reverse soil degradation, restore soil fertility and soil health, and reduce emissions from cropping [4,5,7,10,20,22–25].

Conservation agriculture (CA) can facilitate crop establishment, ensure timely sowing, increase crop yields and farmers' income, and improve soil physical and chemical properties, while reducing emissions and enhancing system resilience [4,5,8,17,19,26–30]. Results from field experiments in South Asia have shown that CA, or strip-tillage with residue retention, can result in greater yields and profits from dry, winter season non-rice crops compared to monsoon season puddled transplanted rice [4–6,9,10,17,27,31], and farmers' surveys and adoption study also confirm these findings [32]. At the same time, field experiments have also shown that transplanting rice seedlings under unpuddled conditions, especially in the dry season, can save water, energy, labor and overall production cost [20,33,34]. Hence, it can be hypothesized that instead of practicing full (conventional) tillage (CT) to all crops, the monsoon rice crop could be established with full tillage and the dry, winter season crops established with strip tillage with residue retention.

Tillage influences the soil's physical properties, with the most prominent changes in bulk density and penetration resistance [29,35]. Increased bulk density and penetration resistance restrict root growth and reduce yield [36,37]. Studies covering a range of soil types have reported higher bulk density and penetration resistance under no-tillage compared to reduced or full tillage [38,39], while others reported reduced bulk density and penetration resistance under no-tillage [27,40,41]. On the other hand, Licht and Al-Kaisi [42] reported similar soil penetration resistance for strip tillage and zero tillage, but commonly greater than for chisel plow. Other studies showed increasing penetration resistance with increasing depth [38,43]. Licht and Al-Kaisi [42] reported that strip tillage increases soil temperature by 1.2–1.4 °C at the top 5 cm in tilled strips compared to non-tilled areas between the tilled strips. Soil temperature has an inverse relationship with the amount of residue cover [44]. Thus, the increase in soil temperature in strips was due to the influence of surface residue in non-tilled areas by reflecting solar radiation and insulating the soil surface [45,46]. These findings suggest that strip tillage can moderate soil temperature, reduce bulk density and penetration resistance, improve seedbed preparation and seed penetration, improve seed-soil contact and seed germination, and enhance unimpeded root growth.

Tillage also influences soil chemical properties [26]. Yadav et al. [47], Choudhary et al. [41], and Sinha et al. [48] reported higher soil pH under zero tillage compared to conventional tillage. Several workers reported significantly higher soil total N and soil organic carbon (SOC) under zero tillage compared to conventional tillage [40,41,47–49]. Kingery et al. [50] reported that strip tillage results in a more readily mineralizable pool of N. In contrast, Sainju et al. [51] reported no influence of tillage and cropping system on SOC and total N. Based on a literature review, Govaerts et al. [52] reported that in 50 % of cases, the SOC content in zero tillage was higher while in the remaining 50 %, it was either lower than, or had no significant difference from, CT. Strip tillage may, however, lose some SOM to oxidation in the tilled strips where soil temperature is higher than in untilled residue covered inter-row areas [53]. Silgram and Shepherd [54] found that in strip tillage where the straw residue was retained in the non-tilled soil surface, nutrient levels increased in topsoil but decreased in subsoils.

Many studies have reported higher extractable P in zero-tillage compared to conventional tillage [55–57], largely due to reduced mixing of fertilizer P with the soil, resulting in lower P-fixation. Several studies also reported higher extractable K near soil surface in zero tillage compared to conventional tillage, but the effect declined with depth [56–59]. Yadav et al. [47], in contrast, reported a decrease in K in the top 0–15 cm layer under zero tillage compared to conventional tillage for a site in eastern Nepal. Franzluebbers and Hons [56], Du Preez et al. [57], and Govaerts et al. [48] concluded that tillage practice had no significant effect on the concentrations of extractable Fe, Mn and Cu in soil.

Krupnik et al. [20] compared adapted CA (or partial CA) with full CA and CT in terms of energy productivity and GHG emissions in rice-based cropping systems of southern Bangladesh. Hoque et al. [9] compared AT (partial CA) with full CA and CT in terms of crop yields and profitability in rice-based systems of northern Bangladesh. Both studies concluded that partial CA performed similarly to full CA and was superior to CT. To our knowledge, there are few studies evaluating the impacts of full CA with no tillage with residue retention in all crops, or partial CA or alternating tillage with tillage to some crops and no tillage to other crops, compared farmers' practices and CT on soil physical and chemical properties for rice-based cropping systems in the EGP. Relatively little data are available on the effects of these systems when an additional species like mung bean is added to intensify cropping systems and replace fallow land with a crop. An improved understanding of the effects of tillage and crop establishment practices on total cropping systems productivity and soil properties can help devise improved management practices and identify the most productive and sustainable cropping systems for the EGP. Thus, the objective of this study were 1) to evaluate the performance of full conservation agriculture (CA) and alternate tillage (AT) approaches compared to conventional tillage (CT) across different cropping systems, 2) to assess the impact of cropping systems and tillage practices on soil chemical and physical properties in a loamy soils sub-tropical environment, 3) to determine the effects of tillage practices on systems productivity in double- and triple-cropping systems in integration of tillage practices in rice-based agriculture in northern Bangladesh. The above objectives represent a significant rice-growing environment in South Asia for the EGP.

2. Materials and methods

2.1. Site description

A three-year experiment was conducted at research field of the Regional Agricultural Research Station of Bangladesh Agricultural Research Institute (BARI) in Jamalpur (24° 56′ 30.68″ N lat., 89° 55′ 40.39″ E long., 21.6 m ASL) in northern Bangladesh from 2013 to 2016. As per USDA classification, the soil of the experimental site was classified as loam (sand, 47.3 %; silt, 30.0 %; and clay, 22.7 % at 0–15 cm soil layer). Initial (prior to start of the experiment in 2013) soil analysis from

0 to 15 and 15–30 cm soil depths for the experimental site indicated that the soil was slightly acidic to neutral. It had low organic matter, very low total N, low K and B, medium S and Zn, but high P and very high Cu, Fe and Mn. Hoque et al. [9] have provided details of experimental treatments and crop management practices. Here, we briefly provide the relevant details to understand the experimental details.

2.2. Experimental design and treatment details

The experiment was conducted in the split-plot design from rice season of 2013 to mung bean season of 2016. It evaluated six cropping systems (factor A): four double-cropped - CS1, Aman rice – Boro or winter rice (R-R); CS2, Aman rice – Wheat (R-W); CS3, Aman rice – Maize (R-M); CS4, Aman rice- Mung bean (R-MB); and two triple-cropped - CS5, Aman rice – Wheat – Mung bean (R-W-MB); and CS6, Aman rice – Maize – Mung bean (R-M-MB); and three tillage and crop establishment methods (factor B): conventional tillage (CT); alternating tillage (AT); and conservation agriculture (CA).

In CT (the control), the land was prepared by puddling for rice and full tillage for the non-rice crops. The puddling was carried out with repeated tillage under ponding water conditions. For non-rice crops, full tillage was carried out by 2-Wheel tractor on dry soil. The residues of all crops were removed from the field except ≈5 cm of standing crop residue after the harvest of previous crop. In AT (alternating tillage), aman rice was established under puddled conditions the same as in CT, while the winter and spring season crops in all systems, except in R-R, were established with strip-tillage (ST) with residue retention. ST was carried out with a 2-WT operated seeder. In this treatment, boro (winter) rice in the R-R system was established under non-puddled (no-tillage) conditions into the previous anchored crop residues. In CA, both aman and boro rice seedlings were transplanted under non-puddled conditions, while rabi and spring crop seeds were sown and established with ST keeping ≈25 cm of anchored crop residues. The individual treatment of factor A (cropping systems) was assigned using the random techniques within blocks, and factor B was assigned within cropping systems and replicated four times. The main plot size was 20 m × 20 m (400 m^2) and the subplot size was 20 m × 6 m (120 m^2). The detailed crop calendar is presented in Hoque et al. [9].

2.3. Crop management

2.3.1. Planting and fertilizer management

All crops were planted around the dates recommended by the Bangladesh Rice Research Institute (BRRI) for aman and boro rice (15 July and 15 January, respectively) and BARI for maize (15 November), wheat (15 November) and Mung bean (15 February) crops. In double-cropped systems, long-duration rice variety BR-11 was used in the aman season, while long-duration BRRI Dhan-29 was used in boro season, but in a triple-cropped system, a short-duration rice variety BINA Dhan-7 was used in the aman season. In both double- and triple-cropped systems, BARI GOM-26, NK40 (hybrid) and BARI Mung-6 varieties were used respectively for wheat, maize and mung bean. Fertilizer rates for each crop were applied as per the recommendations by BARI, BRRI and Bangladesh Agricultural Research Council (BARC). Fertilizer rates were higher for BR11 and BRRI Dhan-29 compared to BINA Dhan-7. N fertilizer was applied through urea and diammonium phosphate (DAP) in 2–3 splits, P applied through DAP and triple super phosphate (TSP) as basal, K applied through muriate of potash (MoP) in 2 splits, and S was applied through gypsum as basal.

2.3.2. Disease, insects and weed management

Diseases and insect pests in all crops were controlled as and when required based on regular field monitoring and observations of insect pests and/or diseases. No significant arthropod pests or pathogens were found during the experiment. In CT in rice, weeds were suppressed by puddling, and, when necessary, by manual spot weeding; in other crops, they were controlled by manual weeding. For all crops in CA and for winter and spring crops in AT, weeds were controlled by pre- and post-emergence herbicides and, when required, supplemented with spot manual weeding.

2.3.3. Irrigation and water management

Aman rice was grown as a rainfed crop. Hence, no irrigation was applied during the cropping season except for puddling in the second year. In boro rice, under CA and AT, irrigation was applied by alternate wetting and drying technique. In each plot, one perforated PVC pipe (30 cm long; up to 20 cm deep) was installed and daily water level was measured. When the water level was deeper than 15 cm in any of the four replications, irrigation water was applied to a flood depth of 7–10 cm depending on the stage and height of the rice crop. Irrigation was stopped 2 weeks before harvesting.

In maize, depending on seasonal rainfall, up to five irrigations were applied: first at three leaf stage (V3); second, at six leaf stage (V6) after fertilizer banding; third, at V10 after fertilizer banding; fourth, at silking; and, fifth, at grain milking stage. In wheat, in all TCE treatments, a maximum of four irrigations were applied: first, at crown root irrigation (CRI); second, at late tillering; third, at flowering; and, fourth, at milking. Mung bean was grown as rainfed; hence, no irrigation was applied in any year. In all crops, irrigation was not applied when sufficient rainfall occurred around the time of the scheduled irrigation applications.

2.4. Soil measurements

2.4.1. Soil chemical properties

Soil samples were collected from 0 to 30 cm soil depth at 15-cm intervals with a core sampler (inner diameter of 50 mm) prior to the start of the experiment in 2013 and from 0 to 15 and 16–30 cm depths at the completion of the experiment in 2016. Soil samples were analysed for various chemical properties. Soil pH was measured in soil/water (1:2, w/v) using a glass electrode pH meter. Organic carbon was determined by the Walkley and Black oxidation method [60], total N by the micro-Kjeldhal method [61], available phosphorus (P_2O_5), exchangeable potassium (K_2O), available sulphur (S) and zinc (Zn) by a modified Hunter's method [62], and boron (B) was determined colorimetrically by the Azomethine-H method [62,63].

2.4.2. Soil bulk density

Soil bulk density (db) at 0–5, 6–10 and 11–15 cm depths was determined by undisturbed stainless-steel soil cores with 50 mm diameter by 50 mm height dimensions after harvesting of the last crop in respective systems in 2016. Bulk density was determined from the gravimetric weights of cores and from the core volume (58.9 cm^3) after oven drying for 48 h at 105 °C. Average db was determined from four cores for each layer for all depths for all cropping systems and TCE methods.

2.4.3. Soil penetration resistance

A hand-held cone penetrometer (Model: Eijkelkamp, Serial no. 12920283/9, Netherlands) was used to measure soil strength or penetration resistance from soil surface to 45 cm depth (0–45 cm) in 5 cm increments in each TCE treatment at the harvest of the last crop in respective systems in 2016. The penetrometer cone has a 30° apex angle and a base area of 1 cm^2. The apparatus has a mean deviation of ±5 %. Soil strength was measured from four randomly selected places within each plot by manually pressing the penetrometer and the average of four replications in each plot was recorded for statistical analysis. In each plot, measurements were taken when optimum soil moisture was observed. Simultaneously, soil samples from the same depths were also measured for gravimetric soil moisture determination.

2.4.4. Soil temperature

Soil temperature was monitored in each plot during the rabi season was measured at 5 cm measured using a digital soil thermometer (Model: DT801; measurement range: 50 °C to +300 °C; low battery sensation and display). Each observation was taken from the south side of the plot and 1m away from the bund at 6:00 a.m. (morning) and at 2.00 p.m. (afternoon). Temperatures were recorded every day, but weekly averages from sowing (or from transplanting in rice) to harvesting of each crop in rabi season were presented. Due to the frequent occurrence of rain and standing water, soil temperatures were not measured from the aman rice plots, as it was assumed that soil temperature variation could be buffered by standing water. The mean temperatures over three years were presented for analysis and interpretation.

2.5. Crop and system productivity

2.5.1. Rice and wheat

The procedure for the sampling of rice and wheat grain and straw yields was similar. The samples for grain yield estimation were taken from the centre of plots from an area of 18 m^2 in each plot. In CA and AT plots, rice and wheat were harvested at 25-cm height, and in the CT plot at 5-cm height. The harvested rice plants were bundled and left in the field for sun drying. After drying, samples for grain and straw were weighed by a precise balance followed by threshing and weighing of the grains. Concurrently, the grain moisture content readings were taken by a grain moisture meter (Draminski; moisture content range 8–35 %, accuracy 99.5 %). Rice and wheat grain yields were adjusted to 14 % and 12 % moisture content, respectively. Fresh straw dry weight was measured during threshing and then fresh straw sub-samples were dried in an oven for 72 h at 70 °C to a constant weight, and then dry straw weight was determined using a precise balance.

2.5.2. Maize

In maize, in all tillage treatments, grain yield samples from 5-m length in each row from total of six rows (excluding two border rows) in each plot (sampling area/plot, 18 m^2) were selected. All ears (cobs) from the sampling area in each plot were harvested. In the CA and AT plots, maize stover was harvested from above ≈40-cm height. In CT, they were harvested by leaving only ≈5-cm stover height. The ears (with the grain) from each sampling area were thoroughly dried and weighed and grains shelled with a maize hand sheller. A sub-sample of five representative ears was collected for grain moisture determination. Maize grain yield was adjusted to 15.5 % moisture content.

2.5.3. Mung bean

Mung bean yield was measured from an area of 18 m^2 (6.0 m × 3.0 m) and straw yield from a 1 m^2 area. Due to the indeterminate nature of mung bean growth, pods were harvested twice from each plot, and their straw yield was recorded after the second harvest, which typically occurred 14–16 days after the first harvest. Pods were sun-dried and threshed, and grains cleaned and weighed using a precise balance. Grain moisture content was measured using a moisture meter and grain yield was adjusted to 12 % moisture content. In plots where neither pods nor grains were formed nor the pods matured, straw biomass was still recorded from the same 1.0 m^2 at the time of the second picking in other plots. The straw biomass was weighed using a field balance. Sub-samples were dried in an oven for 72 h at 70 °C, and dry weight was recorded after constant weight was achieved.

2.6. Rice equivalent yield (REY) and systems REY

Rice equivalent yield (REY) for the component crops of each cropping system was calculated from the price in BDT ha^{-1} (BDT ha^{-1}) and the yield of component crops was as follows:

$$REY\ (t\ ha^{-1}) = \frac{Grain\ yield\ of\ component\ crop(kg\ ha^{-1}) * price\ of\ respective\ crop(BDT\ kg^{-1})}{price\ of\ rice\ (BDT\ kg^{-1}) * 1000}$$

For calculations of REY, prices of crops used in each cropping system in a respective year, relative to the price of the rice crop, were used. For rice, the prices in 2013-14, 2014-15 and 2014-15 were 15.0, 15.2 and 14.0 taka kg^{-1}. For wheat, the prices in respective years were 22.5, 25.0 and 15.5 taka kg^{-1}; for maize 13.0, 15.5 and 15.5 taka kg^{-1}; and for mung bean they were 60.0, 60.0 and 62.5 taka kg^{-1}, respectively. Rice equivalent yield for each crop and the cropping system (i.e., systems REY or SREY, t ha^{-1}) was determined by summing up the REY of individual crops for each cropping system or TCE treatment. Crops and systems yield data under different cropping systems and tillage and crop establishment methods were presented as a sum of three years to understand the long-term (i.e., cumulative three years) benefits as it would help convince farmers and policy makers.

2.7. Weather information

Weather conditions at the experimental site were variable over three years of experimentation. Rainfall during the rice season (July–Oct) was highest (1130 mm) in 2014 and lowest (830 mm) in 2015 (Fig. 1). Total monthly rainfall in each year varied considerably in the July rainfall varied from 134 to 232 mm and the October rainfall varied from 5 to 146 mm. July rainfall is important for crop establishment of both puddled and non-puddled transplanted rice. In year 2 and 3, there was low rainfall at the end of rice season in October, affecting the rice grain filling. There were, however, less variations in maximum and minimum temperatures across years, with temperatures ranging from 33.0 to 34.7 °C and 22.6 to 28.4 °C, respectively, from July to October. Monthly relative humidity (July–October) varied from 75 to 88 % across years. These data indicate inadequate rainfall, while favorable temperatures are necessary for growing a rainfed rice crop. Rainfall during the rabi season (November–April) across three years was relatively low (100 mm in 2013–2014 to 310 mm in 2014–2015) and was not enough to grow a rainfed crop. The maximum temperature ranged from 24.1 to 32.4 °C in 2014–2015, and from 23.5 to 36.4 °C in 2013–2014, while the minimum temperature ranged from 12.3 to 18.0 °C in 2014–2015 and from 12.2 to 28.7 °C in 2013–2014. Temperatures were always higher in April and May compared to other months. Minimum and maximum temperatures in 2014-15 were higher compared to the other two years, with potential for heat stress and sterility. As expected, relative humidity in winter, rabi season was lower than in rice season.

2.8. Statistical analysis and data presentation

A two-way statistical analysis was undertaken for individual years, with cropping systems (CS) as factor A and tillage and crop establishment methods (TCE) as factor B. The experiment was conducted in a split-plot design, so the analysis was performed using the complete two-factor analysis of variance (ANOVA) in JMP 18 statistical software (V11 software, Buckinghamshire, UK). Since individual years and the

cumulative of three years' results are presented, neither year nor the repeated factor was included in the ANOVA. The ANOVA model was constructed in JMP as follows:

Model effect: CS + TCE + CS × TCE + R + CS × R + TCE × R + CS × TCE × R (residuals).

where CS represents the six cropping systems, TCE is tillage and crop establishment, and R is the number of replications. The model also constituted all possible interaction combinations.

Treatment means were separted using Tukey's honest significant difference (HSD) test at a confidence interval of $p \leq 0.05$ to compare the individuals means of different cropping systems and TCE methods. The graphs and figures were either constructed in MS office excel or Sigma plot using the standard error bars.

3. Results and discussion

Intensive cropping systems in smallholder farming systems require short-to medium-duration crop cultivars and timely planting and harvesting of crops grown in those systems. To maintain sustainable cropping systems, a range of issues related to tillage and residue management practices and soil quality need to be addressed. Although short-duration cultivars reduce the site potential of individual crops, the emphasis or objective in intensive systems is to increase their aggregate or systems yield. To address these issues, TCE practices such as ST with residue retention, or CA with no tillage to one or all crops in cropping systems have shown considerable benefits to small farmers in the EGP [4–6,17,28]. Such technologies are designed to achieve sustainable intensification that can address low yields and soil degradation resulting from CT practices. With these issues in mind, this research was designed to evaluate six rice-based double and triple cropping systems with three TCE practices on a loamy soil in a sub-tropical environment in northern Bangladesh. We measured seasonal and three-year total crop and systems grain productivity, and soil physical and chemical properties. The three-year mean grain yields and economic analysis for individual crops and systems are provided elsewhere [9].

Table 1
Effects of cropping systems and tillage and crop establishment methods on cumulative three-year crop and systems yields in a sub-tropical environment in Bangladesh.

Technology	Monsoon rice yields (sum of three years)	Winter crops rice equivalent yields (sum of three years)	Summer rice equivalent yields (sum of three years)	System rice equivalent yields (sum of three years)
t ha^{-1}				
Cropping systems (CS)				
R-R	14.6a	18.0b	–	32.6d
R-W	14.7a	15.0cd	–	29.8e
R-M	15.1a	25.4a	–	40.5b
R-MB	15.1a	14.3d	–	29.4e
R-W-MB	12.66b	16.1c	12.92	41.7a
R-M-MB	12.54b	25.1a	BMˆ	38.5c
Tillage and crop establishment options (TCE)				
CA	13.51b	19.7a		35.9a
AT	14.27a	19.5a		36.4a
CT	14.57a	17.5b		34.3b
Analysis of variance (p-values)				
CS	<0.001*	<0.001*		<0.001*
TCE	0.002*	<0.001*		<0.001*
CS*TCE	0.912	0.095*		0.006*

Within a column means followed by the same letter are not significantly different (p = 0.05) using Tukey's HST test; BMˆ = mung bean crop was grown but no grain yield harvested; the different cropping systems represents to R-R = rice-rice, R-W = rice-wheat, R-M = rice-maize, R-MB = rice-mung bean, R-W-MB = rice-wheat-mung bean, R-M-MB = rice-maize-mung bean; the different tillage and crop establishment represents to CA = conservation agriculture, AT = alternate tillage, CT = conventional tillage.

3.1. Effects on crop yields and total systems productivity

There was an interaction between the cropping system and tillage options on 3-year cumulative systems rice equivalent yield (SREY, Table 1). Across the systems, CA and AT resulted in 5.0 % higher SREY than CT. The R-W-MB and R-M systems had the highest cumulative SREY (3-yr), with 8.5 t ha^{-1} higher than the dominant, traditional R-R system. The higher cumulative yield from R-W-MB was attributed to the inclusion of mung bean in R-W system. Similar to our findings, Islam et al. (2019) and Dutta et al. [64] for R-M and R-W-MB systems found higher SREY under ZT than CT in the EGP. The R-M system also produced higher yield due to the inclusion of a long-duration rice cultivar and a high yield potential of maize hybrid. The R-M-MB system didn't produce as much yield as R-M due to the use of short-duration rice variety and the inability of mung bean to set grains because of short window that coincided with the onset of the monsoon. However, in contrast to our findings, Rashid et al. [18] demonstrated that R-M-MB could be practiced successfully in clay loam soil in high rainfall areas in northwest Bangladesh if mung bean sowing could be advanced through relay planting in standing maize.

Cropping systems and tillage practices individually influenced monsoon season rice and winter crop yields, but their interaction was non-significant for the former. In contrast, the interaction was significant for two years, except for winter crops in 2014-15 (Table 2). Rice yields were recorded 3.0–7.0 % lower in triple cropping systems (R-W-MB and R-M-MB) than in double cropping systems (R-M, R-W, R-R, R-MB) in all three years. In winter season, maize produced the highest yield among all crops in all three years due to its high yield potential and favorable climate in Bangladesh [2,28]. Wheat yield in the R-W-MB system was observed higher than in the double cropping systems. This could probably be due to the cumulative effect of use of short duration rice cultivar which allowed early planting and the carryover effect of mung bean (a legume crop), though in general one-ton actual wheat yield was lower in year 3 in comparison to year 1 and 2. The results of this study clearly indicated that despite their high market prices wheat and mung bean crops cannot compete with maize or even with winter rice [9]. Both these crops may be cultivated in suitable geography where triple cropping systems are possible under limited irrigation water access from February to May. Conservation agricultural-based practices (CA and AT) had 3.0–6.0 % yield penalty in monsoon rice, whereas CA in winter season recorded 8.0–16 % higher yield gain. Since rice is traditionally grown under soft soil and anaerobic conditions, and in a significantly different growing environment with difficulty in controlling weeds, it performed below its potential in CA. These results for similar rice growing ecologies are consistent with Gathala et al. [28] and Islam et al. [6].

3.2. Effect on soil chemical properties

There was no interaction effect of cropping systems and tillage on any of the soil parameters, however, the individual effect was significant for many parameters (Tables 3 and 4). After three years of experimentation, the chemical soil properties at 0–15 cm soil surface differed significantly among the cropping systems, except SOM, total N and Mn (Table 3). In contrast, at 16–30 cm, significant effects were observed for all parameters except available P, B and Mn and exchangeable K (Table 4). Across tillage treatments, at 0–15 cm soil depth, the soil parameters such as SOM, total N and soil exchangeable K were affected by tillage, but no other parameters. On the other hand, at 16–30 cm soil depth, there was no significant effect of tillage on any of the parameters.

3.2.1. Soil pH

Compared to the initial pH (6.2) at 0–15 cm depth, soil pH decreased to 6.0 in R-W and R-W-MB systems and increased to 6.7 in R-M and R-M-MB systems after three years of experimentation. In contrast, at 16–30 cm, pH decreased only in R-W-MB system (pH 6.6) compared to the

Table 2
Effects of cropping systems and tillage and crop establishment methods on crop yields during three cropping seasons from 2013 to 2015 in a sub-tropical environment in Bangladesh.

Technology	Rice yield (Monsoon season)			Rice equivalent yield (Winter season)			Mung bean (Summer season)		
	2013	2014	2015	2013–14	2014–15	2015–16	2014	2015	2016
					t ha^{-1}				
Cropping systems (CS)									
R-R	4.89 ab	4.96a	4.75 ab	5.75cd	5.61c	6.64c	–	–	–
R-W	4.94 ab	4.93a	4.86 ab	5.71d (3.80)	6.31b (3.85)	3.03f (2.83)	–	–	–
R-M	4.93 ab	5.07a	5.07a	8.04a (9.27)	8.33a (8.50)	9.04b (8.17)	–	–	–
R-MB	5.20a	5.25a	4.64bc	4.59e (1.15)	4.44d (1.13)	5.30d (1.19)	–	–	–
R-W-MB	4.52b	3.97b	4.17d	6.25c (4.16)	6.43b (3.92)	3.45e (3.22)	1.05	1.04	1.04
R-M-MB	4.50b	3.77b	4.27cd	6.98b (8.05)	7.99a (8.14)	10.12a (9.15)	BMˆ	BMˆ	BMˆ
Tillage and crop establishment options (TCE)									
CA	4.62a	4.39b	4.50b	6.46a	6.81a	6.56a			
HY	4.94a	4.73a	4.61 ab	6.40a	6.76a	6.47a			
CT	4.93a	4.86a	4.78a	5.94b	5.94b	5.67b			
Analysis of variance (p-values)									
CS	0.011	<0.001	<0.001	<0.001	<0.001	<0.001			
TCE	0.058	0.003	0.010	<0.001	<0.001	<0.001			
CS*TCE	0.891	0.998	0.706	0.005	0.101	<0.001			

Within a column means followed by the same letter are not significantly different (p = 0.05) using Tukey's HST test; BMˆ = mung bean crop was grown but no grain yield harvested; the different cropping systems represents to R-R = rice-rice, R-W = rice-wheat, R-M = rice-maize, R-MB = rice-mung bean, R-W-MB = rice-wheat-mung bean, R-M-MB = rice-maize-mung bean; the different tillage and crop establishment represents to CA = conservation agriculture, AT = alternate tillage, CT = conventional tillage.

Table 3
Initial (first year) and final (after harvesting of last crop in the respective cropping system in the final year) soil properties at 0–15 cm depth as affected by cropping system and tillage and crop establishment in a sub-tropical environment, Bangladesh.

Source	pH	SOM (g kg^{-1})	Total N (g kg^{-1})	P (μg ml^{-1})	K (meq 100^{-1} ml)	S (μg ml^{-1})	B (μg ml^{-1})	Cu (μg ml^{-1})	Fe (μg ml^{-1})	Mn (μg ml^{-1})	Zn (μg ml^{-1})
Initial	6.2	7.7	0.42	12.88	0.05	10.58	0.14	0.98	36.00	3.78	0.80
Cropping system (CS)											
R-R	6.3 ab	8.7	0.50	10.64b	0.06bc	12.28bc	0.11 ab	1.04c	28.17b	4.49	0.42b
R-W	5.9b	9.5	0.50	14.70 ab	0.06c	17.20a	0.13 ab	1.40 ab	51.38a	6.67	0.71a
R-M	6.2 ab	8.5	0.45	13.73 ab	0.06c	11.83bc	0.14a	1.44a	38.33b	5.06	0.80a
R-MB	6.7a	8.4	0.44	11.07b	0.08 ab	9.88c	0.08b	1.11bc	26.83b	4.39	0.40b
R-W-MB	6.1b	8.6	0.47	15.01a	0.08a	15.12 ab	0.12 ab	0.93c	29.17b	4.74	0.44b
R-M-MB	6.7a	8.6	0.46	13.53 ab	0.08a	9.18c	0.13 ab	1.00c	35.50b	5.79	0.35b
Tillage and crop establishment (TCE)											
CA	6.4	9.3a	0.50a	13.54	0.08a	12.11	0.12	1.12	34.57	5.27	0.52
AT	6.2	8.8 ab	0.46 ab	12.98	0.07b	13.15	0.12	1.19	37.32	5.19	0.51
CT	6.4	8.0b	0.42b	12.83	0.06b	12.48	0.11	1.15	32.80	5.11	0.53
Analysis of variance (*p*-values)											
CS	0.003*	0.433	0.367	0.015	<0.001	<0.001	0.042	<0.001	<0.001	0.074	<0.001
TCE	0.347	0.010	0.002	0.770	0.001	0.579	0.685	0.699	0.345	0.703	0.860
CS × TCE	0.509	0.995	0.991	0.988	0.214	0.731	0.587	0.955	0.241	0.914	0.864

a column means followed by the same letter/no letter are not significantly different (p = 0.05) using Tukey's HST test; the different cropping systems represents to R-R = rice-rice, R-W = rice-wheat, R-M = rice-maize, R-MB = rice-mung bean, R-W-MB = rice-wheat-mung bean, R-M-MB = rice-maize-mung bean; the different tillage and crop establishment represents to CA = conservation agriculture, AT = alternate tillage, CT = conventional tillage.

initial (pH 7.0). There was no change in pH at 0–15 cm under the R-R system. In contrast to our findings, Choudhary et al. [41] didn't find significant differences in pH at 0–15 cm between different cropping systems, including R-W and R-M. Guo et al. [65] reported that higher quantities of crop residues and higher rates of N fertilizer application in intensive cropping systems can contribute to acidification. There was a slight increase in soil pH at 0–15 cm under CA and CT. A decrease in soil pH with a higher amount of crop residues in CA or AT, especially on acidic soils, is expected to contribute to acidification during organic matter decomposition [66]. Our experimental soil was close to neutral but indicated a moderately acidic at 0–15 cm and neutral at 16–30 cm, so a decrease in soil pH under CA was not expected. Sinha et al. (2019) reported a decrease in soil pH at 0–15 cm but not at deeper depths under ZT compared to CT for acidic sites in the EGP.

3.2.2. *Soil organic matter and total N*

At 0–15 cm soil depth, both SOM and total N were not affected by the cropping systems; however, they differed by the TCE (Table 3). At 16–30 cm soil depth, both SOM and total N were affected by the cropping systems, but not by the TCE (Table 4). At 0–15 cm, total N increased in all the six cropping systems, but at 16–30 cm, it remained stable in four systems and decreased in other two systems (R-W and R-M). Consistent with these findings, Choudhary et al. [41] also found differences in SOC at 0–15 cm between R-W and R-M systems. Flooded rice soils can be rich in nutrients and particularly N, helping to maintain SOM and N availability [47,67]. Both SOM and total N at 0–15 cm after three years increased under CA and AT compared to CT, but CT also maintained good level of both SOM and total N in comparison to initial. Soil organic matter remained stable in all TCE, but total N decreased in AT and CT, while it remained stable in CA. Strip tillage (under CA and AT) retained and recycled a higher amount of crop residues compared to CT. Consistent with these findings, Govaerts et al. [52] and Singh et al. [40] also reported higher SOC in ZT compared to CT. ST might have also decreased the organic carbon decomposition by minimizing the

Table 4
Initial and final (after harvest of last crop in the respective cropping system) soil properties at 16–30 cm depth as affected by cropping system and tillage and crop establishment in a tropical environment, Bangladesh.

Source	pH	SOM (g kg^{-1})	Total N (g kg^{-1})	P (μg ml^{-1})	K (meq 100^{-1} ml)	S (μg ml^{-1})	B (μg ml^{-1})	Cu (μg ml^{-1})	Fe (μg ml^{-1})	Mn (μg ml^{-1})	Zn (μg ml^{-1})
Initial	7.0	6.3	0.36	11.34	0.07	9.22	0.11	0.74	28.00	3.18	0.55
Cropping system (CS)											
R-R	6.8 ab	6.7a	0.36 ab	10.31	0.10	8.23bc	0.10	0.84bc	22.44b	3.83	0.36c
R-W	6.9 ab	5.3b	0.28 ab	14.04	0.13	11.83a	0.10	1.11 ab	38.70a	5.08	0.52 ab
R-M	6.9 ab	5.2b	0.27b	13.03	0.08	11.58 ab	0.11	1.20a	29.64 ab	3.88	0.57a
R-MB	7.1 ab	6.6a	0.35 ab	10.31	0.06	9.19abc	0.09	0.82bc	24.92b	4.18	0.36c
R-W-MB	6.6b	6.6a	0.35 ab	12.84	0.13	9.94abc	0.12	0.62c	24.92b	3.98	0.38bc
R-M-MB	7.2a	6.2a	0.38a	12.54	0.07	7.18c	0.13	0.79bc	31.17 ab	8.68	0.27c
Tillage and crop establishment (TCE)											
CA	6.9	6.3	0.36	12.90	0.07	9.38	0.12	0.91	27.90	4.40	0.42
AT	6.9	5.9	0.31	11.43	0.13	9.86	0.10	0.85	30.68	4.43	0.41
CT	6.9	6.2	0.33	12.20	0.09	9.74	0.10	0.93	27.31	5.98	0.41
Analysis of variance (*p*-values)											
CS	0.020	0.025	0.016	0.149	0.676	0.001	0.448	<0.001	<0.001	0.167	<0.001
TCE	0.990	0.663	0.191	0.462	0.345	0.840	0.398	0.649	0.292	0.478	0.961
CS*TCE	0.921	0.925	0.984	0.979	0.372	0.990	0.959	0.571	0.378	0.355	0.664

Within a column means followed by the same letter/no letter are not significantly different (p = 0.05) using Tukey's HST test; the different cropping systems represents to R-R = rice-rice, R-W = rice-wheat, R-M = rice-maize, R-MB = rice-mung bean, R-W-MB = rice-wheat-mung bean, R-M-MB = rice-maize-mung bean; the different tillage and crop establishment represents to CA = conservation agriculture, AT = alternate tillage, CT = conventional tillage.

breakdown of macro-aggregates and thus might have contributed to an increase in SOM and total N at 0–15 cm depth [35,41]. On the other hand, puddling in rice followed by intensive tillage in dry season crops facilitated the organic matter oxidation, resulting in lower SOC and total N in CT [68]. Although there was an increase in SOM and total N in CA and AT at the 0–15 cm compared to CT, it will take at least 5 years to observe a clear trend in SOM change with changes in TCE practices [69].

3.2.3. Soil available P and exchangeable K

After the three cropping cycles, available P and exchangeable K at 0–15 cm soil depth were significantly affected by the cropping systems (Table 3). Amongst the cropping systems, the R-W-MB had the highest available P while R-R and R-MB had the lower values, showing a decreasing trend from the initial value. On the other hand, the soil exchangeable K was slightly increased in all cropping systems, compared to the initial value, with higher values for R-W-MB, R-M-MB and R-MB systems. Across cropping systems, soil available P was not affected by the TCE, but soil exchangeable K was affected, with the highest value for the CA. At 16–30 cm soil depth, the soil available P and exchangeable K were not affected by either cropping systems or TCE (Table 3). The additions of a higher amount of crop residues in the R-M and R-W based systems under CA, and the fact that P is immobile in soil, might have accumulated P in top 0–15 cm under CA compared to CT [1,67]. The increase in soil exchangeable K in all cropping systems and particularly in triple-cropping systems and in CA was due to the addition of a large amount of residues containing high concentrations of K after each crop [70,71].

3.2.4. Soil available S and micronutrients

There were no consistent responses of cropping systems and TCE practices on soil available S or any of the micro-nutrients at 0–15 cm depth. Compared to the initial value, available S at 0–15 cm decreased in R-MB and R-M-MB systems but increased in other systems. Both soil available Zn and B remained unchanged in R-M system but decreased in all other systems. Soil available Cu increased in all cropping systems, except a decrease in R-W-MB, with the highest increase in R-M system (1.44 μg ml^{-1}). Soil available Fe increased in R-M and R-W systems while it decreased in other systems; soil available Mn, however, increased in all systems. At 16–30 cm, available Fe and Mn increased in all cropping systems compared to their initial values, but there were no consistent responses for other micro-nutrients. Soil available S and none of the micro-nutrients were affected by the TCE at any soil depth studied. Consistent with these findings, Franzluebbers and Hons [56], Du Preez et al. [57] and Govaerts et al. [49] concluded that tillage practice had no significant effect on the concentrations of extractable Fe, Mn and Cu in soil. Due to limited evidence on the effects of TCE practices and cropping systems on the availability of micro-nutrients, we suggest further monitoring and measuring of these nutrients under the ST and CA practices in different cropping systems.

3.3. Effect on soil physical properties

3.3.1. Soil bulk density

Bulk density (bd) was not affected by the interaction of cropping systems and TCE, but was significantly affected by the cropping system at 0–5 and 6–10 cm depths, but not at 11–15 cm depth (Table 5). The bulk density at none of the depths was affected by the TCE. At 0–5 cm depth, R-R system had the highest bd (1.42 Mg m^{-3}) while R-W-MB

Table 5
Soil bulk density at three depths after harvesting of the last crop in the respective cropping system in a tropical environment, Bangladesh.

Source	0–5 cm	6–10 cm	11–15 cm
	Mg m^{-3}		
Cropping system (CS)			
R-R	1.42a	1.48a	1.46
R-W	1.40 ab	1.44abc	1.44
R-M	1.40 ab	1.38c	1.45
R-MB	1.40 ab	1.46 ab	1.42
R-W-MB	1.36b	1.38c	1.46
R-M-MB	1.39 ab	1.39bc	1.43
Tillage and crop establishment (TCE)			
CA	1.39	1.42	1.44
AT	1.39	1.42	1.44
CT	1.41	1.43	1.45
Analysis of variance (*p*-values)			
CS	0.017	<0.001	0.371
TCE	0.268	0.649	0.741
CS × TCE	0.973	0.997	0.992

Within a column means followed by the same letter/no letter are not significantly different (p = 0.05) using Tukey's HST test; the different cropping systems represents to R-R = rice-rice, R-W = rice-wheat, R-M = rice-maize, R-MB = rice-mung bean, R-W-MB = rice-wheat-mung bean, R-M-MB = rice-maize-mung bean; the different tillage and crop establishment represents to CA = conservation agriculture, AT = alternate tillage, CT = conventional tillage.

system had the lowest bd (1.36 Mg m^{-3}). For other cropping systems, the bd at 0–5 cm did not differ. Similarly, the R-R system also had the highest bd at 6–10 cm depth (1.48 Mg m^{-3}). On contrary, the R-M, R-M-MB and R-W-MB systems had significantly lower and similar bd. Higher bd in R-R system was due to the soil compaction through the repetitive tillage into standing water (puddling) in both rice crops, as also observed in other studies [1,35,41]. Puddling increases soil bd in rice immediately below the plow layer due to soil aggregate destruction, filling of macropores with fine soil particles, and soil compaction resulting from the use of tillage implements [35,68]. Lower bd in the R-W-MB, R-M-MB, and R-M systems was due to the elimination of puddling, use of ST, and the addition of large quantities of residues, resulting in loose soil with more pore space and improved soil aggregation than in CT and other cropping systems [35,48]].

3.3.2. Soil penetration resistance

The effect of the cropping system on soil penetration resistance (SPR) was significant for 5, 10, 15, 20 and 30 cm soil depths. The effect of TCE was also observed to have a significant effect at depths of 5, 15, and 30 cm. The interaction effect of cropping systems and TCE on soil penetration resistance (SPR), was found non-significant. Across cropping systems and TCE, SPR increased up to 15–20 cm depth and then it decreased to 45 cm depth (Fig. 2). Higher SPR at 10–15 cm compared to 0–10 cm, especially in R-M and R-W systems with or without mung bean, was due to higher bd at those depths (Fig. 3; Table 5). As expected, SPR had a similar response to bd because the soil moisture content at the time of measurement was similar (Sharma and De Datta, 1986). The R-R system had the highest SPR at a depth of 15–20 cm (higher by 21 % compared to R-W and by 15–18 % compared to R-M and R-Mb systems) due to the development of a hard pan caused by continuous puddling [1,68]. Despite lower bd in R-W-MB and R-M-MB systems, they resulted in higher SPR. The reason for this discrepancy is unknown and requires further investigation. At all depths, CT consistently had a higher SPR compared to CA or AT, but the difference was significant only at depths of 5, 15, and 30 cm (higher by 13–15 % and 1–5 % compared to CA and AT, respectively). The higher SPR in CT was due to soil compaction from repetitive tillage and higher bd. On the other hand, CA and AT had less soil compaction and retained residues, resulting in lower bd and lower SPR. These results are consistent with others who have reported positive effects of ZT and residue management on SPR [40,72,73]. In contrast to these findings, Erbach et al. [43] and Unger and Jones [38] reported greater SPR under no tillage compared to minimum tillage or CT in a wheat-sorghum-fallow rotation.

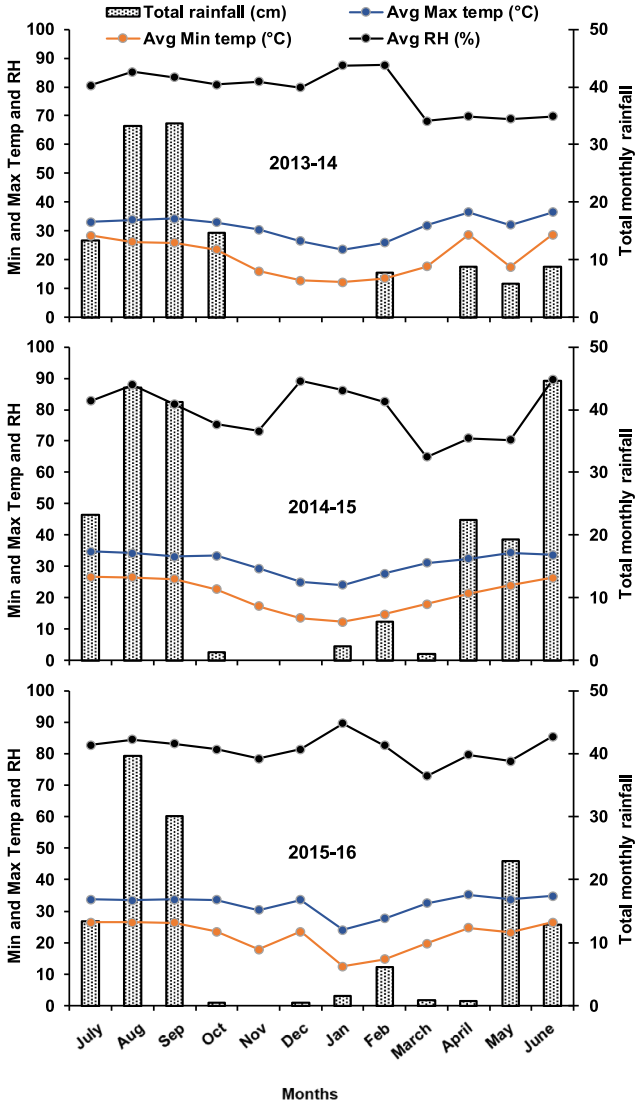


Fig. 1. Weather conditions in the experiment site during three years of experimentation in a sub-tropical environment, Bangladesh (top: 2013–2014; middle: 2014–2015; bottom: 2015–2016).

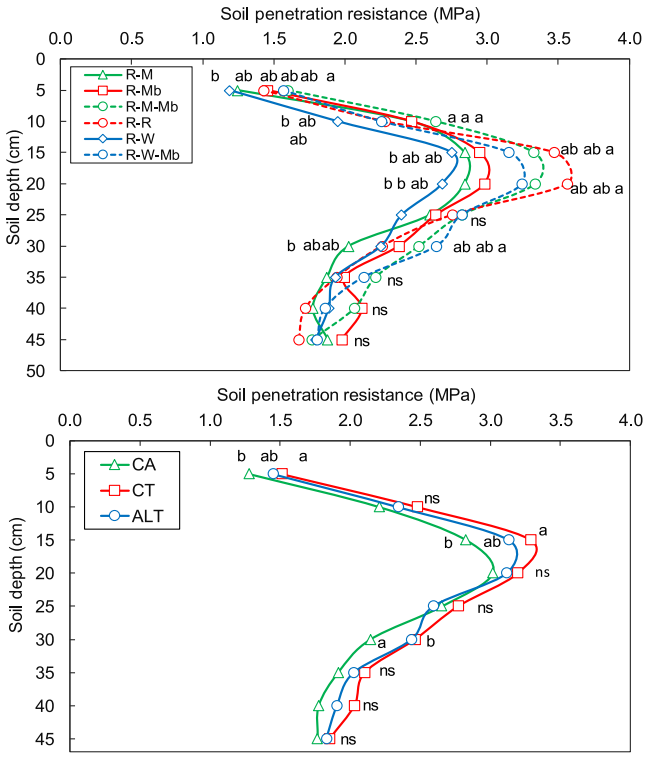


Fig. 2. Effects of cropping system and tillage and crop establishment on soil penetration resistance measured at 5 cm intervals in 0–45 cm depth (data are means of three years for main effects of cropping system and tillage and crop establishment). NS indicates non-significant. CA, AT and CT indicate conservation agriculture, alternate tillage, and conventional tillage, respectively. R-R, R-W, and R-M stand for rice-rice, rice-wheat and rice-maize rotations, while R-MB, R-W-MB and R-M-BM indicate rice-mung bean, rice-wheat-mung bean, and rice-maize-mung bean cropping sequences.

3.3.3. Soil thermal regime

Soil temperatures at 5 cm depth, measured in the morning and in the afternoon during the winter *rabi* cropping season were found to be lowest at planting and crop establishment time in February and were highest at harvest time in May. In wheat and maize, however, the

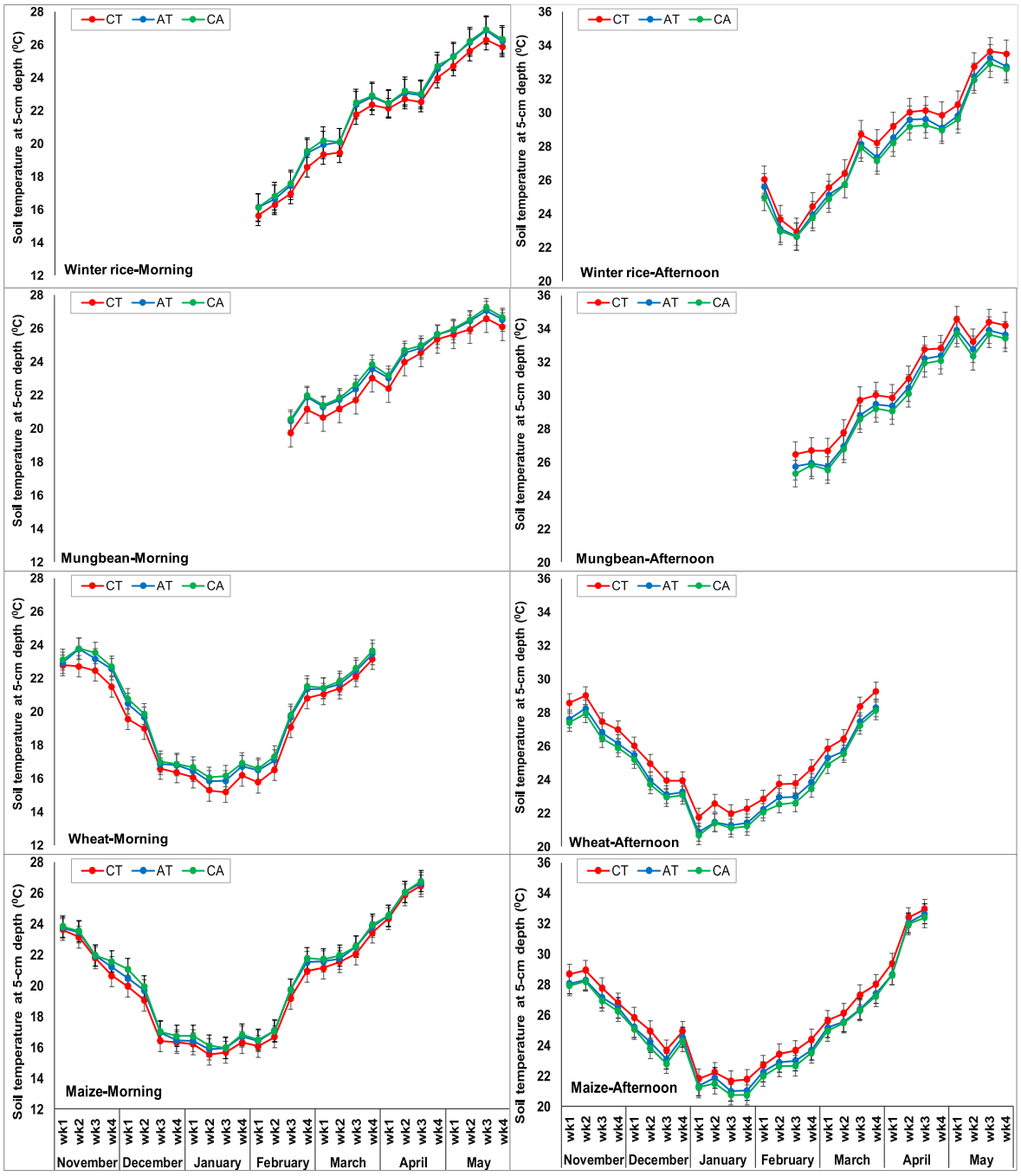


Fig. 3. Effects of cropping system and tillage and crop establishment on weekly soil temperature (5 cm depth) measured in the morning and in the afternoon during the growing season of each crop (data for each crop are means of three years). CA, AT and CT indicate conservation agriculture, alternate and conventional tillage, respectively.

pattern was different, where soil temperatures decreased from planting in the first week of November to mid-to end of January and then increased continuously until harvest at the end of March/April. In all crops, the morning time temperatures were consistently higher in CA followed by AT and then C, while the trends reversed in the afternoon (Fig. 3).

In boro rice, morning time soil temperatures increased from 15.6 °C (first week of February) to 25.9 °C (fourth week of May) in CT and from 16.1 °C (first week of February) to 26.2 °C (fourth week of May) in CA and AT. In the afternoon, however, the temperatures increased from 26.0 to 33.5 °C in CT and from 25.0 to 32.6 °C in CA over the same period. The trend for soil temperatures in mung bean was similar to that for boro rice. CA resulted in higher soil temperatures than CT in the morning, while they were opposite in the afternoon. In wheat, morning time soil temperature at 5 cm depth in CT decreased from 22.8 °C (first week of November) to 15.3 °C (mid-to end of January) and then increased to 23.2 °C (end of March). In CA, the temperatures were higher (23.1 °C in the first week of November to 16.1 °C in mid-January to 23.6 °C in end of March) than that in CT or AT. In the afternoon, soil temperatures over the same periods decreased from 28.6 °C to 22.0 °C and then increased to 29.3 °C in CT and from 27.4 °C to 21.1 °C to 28.1 °C in CA. The trends for morning and afternoon time soil temperatures in maize were similar to that for wheat. In all crops, higher soil temperatures in the morning and lower in the afternoon under CA and

AT with residue retention were due to the insulating (or heating effect) of tilled (and warmer) strips and crop residues in non-tilled areas in the morning and the cooling effect of residues in the afternoon. Such diurnal variations in soil temperatures and warming and cooling effects of residues protected the crops against adverse air temperatures during their growth. It is likely that the maintenance of the previous crops' residues on the soil surface acted as an insulating layer or a blanket over the soil surface and maintained optimal soil thermal regime with lower fluctuation during early crop growth in CA or AT. Similar trends in soil thermal regime were also reported for residue retention plots under R-M systems in NW India [40]. Increasing minimum temperatures when they are below optimal during crop establishment and early crop growth is important for improved seedling emergence and early root growth of winter crops. Licht and Al-Kaisi [42] also reported increase in soil temperature in top 0–5 cm under ST compared to NT or CT, contributing to increase in plant emergence rate index under ST compared to NT. In contrast, decrease in soil temperatures during flowering and grain filling stage will reduce canopy temperatures and help alleviate terminal heat stress in maize and wheat [3,40].

4. Conclusions

Increasing productivity and long-term sustainability of intensive cereal-based cropping systems are essential to provide food and nutrition security to the ever-increasing population of Bangladesh and other countries of South Asia. However, the sustainability of the cereal-based systems depends on the conservation of non-renewable resources such as energy and water and improvement of soil quality and overall soil health. This study demonstrated that CA and AT can result in higher maize but not rice yield. Higher annual system productivities were also found as compared to CT. Amongst the cropping systems evaluated, R-W-MB and R-M can result in the highest system productivity, with the former having the added benefit of occupying unused fallow land within the cropping sequence and intensifying land use. CA and AT can improve soil physical properties, such as lower bulk density and soil compaction, moderate soil temperature, and improve soil chemical properties compared to CT. Our results demonstrate that CA-based management practices can be adapted to most crops in intensive rice-based cropping systems to sustain soil health and increase crop and cropping systems productivity in the EIGP. However, long-term studies are required across various soil types, climates, and socio-economic conditions to evaluate their long-term performance and to extrapolate findings to other and similar areas within Bangladesh and the EGP are also warranted.

CRediT authorship contribution statement

Muhammad Arshadul Hoque: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Mahesh K. Gathala:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jagadish Timsina:** Writing – review & editing, Supervision, Formal analysis. **Md A.T.M. Ziauddin:** Writing – review & editing, Writing – original draft, Supervision. **Mosharraf Hossain:** Writing – review & editing, Supervision, Conceptualization. **Timothy J. Krupnik:** Writing – review & editing, Supervision, Conceptualization.

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.

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Data availability

Data will be made available on request.

References

[1] J. Timsina, D.J. Connor, Productivity and management of rice-wheat cropping systems: issues and challenges, Field Crops Res. 69 (2001) 93–132.
[2] J. Timsina, M.L. Jat, K. Majumdar, Rice-maize systems of south Asia: current status, future prospects and research priorities for nutrient management, Plant Soil 335 (2010) 65–82.
[3] T.J. Krupnik, Z.U. Ahmed, J. Timsina, M. Shahjahan, A.S.M. Alanuzzaman, K. Azahar, A.B.M. Miah, S. Rahman, M.K. Gathala, A. McDonald, Forgoing the fallow in Bangladesh's stress-prone coastal deltaic environments: effect of sowing date, nitrogen, and genotype on wheat yield in farmers' fields, Field Crops Res. 170 (2015) 7–20.
[4] S.K. Magar, J. Timsina, K. Devkota, Wei-li liang, energy and greenhouse gas footprint analysis of conventional and reduced tillage practices in rainfed and irrigated rice-wheat systems, Paddy Water Environ. 20 (2022) 413–427, https://doi.org/10.1007/s10333-022-00902-w.
[5] S.K. Magar, J. Timsina, K. Devkota, Wei-li Liang, N. Rajbhandari, Conservation agriculture for increasing productivity, profitability and water productivity in rice-wheat system of the eastern gangetic plains, Environ. Chall. 7 (2022) 100468, https://doi.org/10.1016/j.envc.2022.100468.
[6] S. Islam, M.K. Gathala, T.P. Tiwari, J. Timsina, A.M. Laing, S. Maharjan, A. K. Chowdhury, P.M. Bhattacharya, T. Dhar, B. Mitra, S. Kumar, P.K. Srivastwa, S. K. Dutta, R. Shrestha, S. Manandhar, S.R. Sherestha, P. Paneru, , Nur-E-Alam Siddquie, A. Hossain, R. Islam, A.K. Ghosh, M.A. Rahman, U. Kumar, K.K. Rao, B. Gérard, Conservation agriculture based sustainable intensification: increasing yields and water productivity for smallholders of the eastern gangetic plain, Field Crops Res. 238 (2019) 1–17.
[7] M.K. Gathala, A.M. Laing, T.P. Tiwari, J. Timsina, S. Islam, A. Chowdhury, C. Chattopadhyay, A.K. Singh, B.P. Batt, R. Shrestha, N.C.D. Barman, B. Gerard, Enabling smallholder farmers to increase productivity while achieving environmental and economic benefits: a meta-analysis of conservation agriculture-based sustainable intensification in the eastern gangetic plains, Renew. Sustain. Energy Rev. 120 (2020) 109645.
[8] M.K. Gathala, A.M. Laing, T.P. Tiwari, J. Timsina, S. Islam, P.M. Bhattacharya, T. Dhar, A. Ghosh, A.K. Sinha, S. Hossain, I. Hossain, S. Molla, M. Rashid, S. Kumar, R. Kumar, B. Chaudhary, S.K. Jha, P. Ghimire, B. Bastola, R.K. Chaubey, B. Gérard, Energy-efficient, sustainable crop production practices benefit smallholder farmers and the environment across three countries in the eastern gangetic plains, south Asia, J. Clean. Prod. 246 (2020) 118982, https://doi.org/10.1016/j.jclepro.2019.118982.
[9] M.A. Hoque, M.K. Gathala, M.M. Hossain, A.T.M.Z. Uddin, T.J. Krupnik, Reduced tillage and crop diversification can improve productivity and profitability of rice-based rotations of the eastern gangetic plains, Field Crops Res. 291 (2023) 108791, https://doi.org/10.1016/j.fcr.2022.108791.
[10] T.J. Krupnik, J. Timsina, K. Devkota, B.P. Tripathi, T. Karki, A. Urfels, Y.K. Gaihre, D. Choudhary, A.R. Beshir, V.P. Pandey, B. Brown, H. Gartaula, S. Shahrin, Y. N. Ghimire, Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems, Adv. Agron. 170 (2021) 155–287.
[11] B.S. Chauhan, G. Mahajan, Sardana, J. Timsina, M.L. Jat, Productivity and sustainability of the rice-wheat cropping system in the indo-gangetic plains of Indian sub-continent: problems, opportunities, and strategies, Adv. Agron. 117 (2011) 315–369.
[12] T.P. Tiwari, M.K. Gathala, S. Maharjan, Informing Policies for Removing Barriers to Scaling Conservation Agriculture Based Sustainable Intensification in the Eastern Gangetic Plains, ACIAR-CIMMYT Joint publication. ACIAR, Canberra, Australia, 2017, p. 63p.
[13] J. Timsina, J. Wolf, N. Guilpart, L. van Bussel, P. Grassini, J. van Wart, A. Hossain, H. Rashid, S. Islam, M. van Ittersum, Can Bangladesh produce enough cereals to meet future demand? Agric. Syst. 163 (2018) 36–44.
[14] M.N. Hasan, M.S. Hossain, M.A. Bari, M.R. Islam, Agricultural Land Availability in Bangladesh, SRDI, Dhaka, Bangladesh, 2013, p. 42.
[15] M.I. Bhuyan, I. Supit, U. Kumar, S. Mia, F. Ludwig, The significance of farmers' climate change and salinity perceptions for on-farm adaptation strategies in the south-central Coast of Bangladesh, J. Agric. Food Res. 16 (2024) 101097.

[16] M.M. Rahman, M.R. Ali, M.M. Oliver, M.A. Hanif, M.Z. Uddin, Tamim-Ul-Hasan, K. K. Saha, M.H. Islam, M. Moniruzzaman, Farm mechanization in Bangladesh: a review of the status, roles, policy, and potentials, J. Agric. Food Res. 6 (2021) 100225.
[17] S. Marahatta, S.K. Sah, A. Mcdonald, J. Timsina, K.P. Devkota, Improving soil health and crop productivity through conservation agriculture and nitrogen management in rice-mustard-maize systems, Field Crops Res. 325 (2025) 109825, https://doi.org/10.1016/j.fcr.2025.109825.
[18] M.H. Rashid, J. Timsina, N. Islam, Effect of tillage and residue management on productivity, profitability and soil fertility for the irrigated rice-maize-mung bean systems of south Asia, J. Crop Improv. (2019) 683–710, https://doi.org/10.1080/15427528.2019.1661056.
[19] M.K. Gathala, J. Timsina, M.S. Islam, T.J. Krupnik, T.R. Bose, N. Islam, M. M. Rahman, M.I. Hossain, Harun-Ar-Rashid, A.K. Ghosh, M.M.K. Hasan, M. A. Khayer, M.Z. Islam, T.P. Tiwari, A.J. McDonald, Productivity, profitability, and energetics: a multi-criteria and multi-location assessment of farmers' tillage and crop establishment options in intensively cultivated environments of south Asia, Field Crops Res. 186 (2016) 32–46, https://doi.org/10.1016/j.fcr.2015.11.008.
[20] T.J. Krupnik, M.K. Hossain, J. Timsina, M.K. Gathala, T. Sapkota, S. Yasmin, M. Shahjahan, F. Hossain, A. Kurishi, A.A. Miah, B.M.S. Rahman, A.J. McDonald, Adapted conservation agricultural practices can increase energy productivity and lower yield-scaled greenhouse gas emissions in coastal Bangladesh, Front. Agronomy 4 (2021), https://doi.org/10.3389/fagro.2022.829737.
[21] R. Lal, Tillage effects on soil degradation, soil resilience, soil quality, and sustainability, Soil Till. Res 27 (1993) 1–8, https://doi.org/10.1016/0167-1987(93)90059-X.
[22] P.R. Hobbs, Conservation agriculture: what is it and why is it important for future sustainable food production? J. Agric. Sci. 145 (2007) 127–137, https://doi.org/10.1017/S0021859607006892.
[23] FAO, Save and Grow: a Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production, United Nations Food and Agriculture Organization, Rome, 2011, p. 102.
[24] J.N. Pretty, T.G. Benton, Z.P. Bharucha, L.V. Dicks, C.B. Flora, H.C.J. Godfray, et al., Global assessment of agricultural system redesign for sustainable intensification, Nat. Sustain. 1 (2018) 441–446, https://doi.org/10.1038/s41893-018-0114-0.
[25] J. Dixon, M.F. Rola-Rubzen, J. Timsina, J. Cummins, T.P. Tiwari, Socioeconomic impacts of conservation agriculture based sustainable intensification (CASI) with particular reference to south Asia, in: Y. Dang, R. Dalal, N.W. Menzies (Eds.), No-till Farming Systems for Sustainable Agriculture: Challenges and Opportunities, Springer International Publishing Switzerland, 2020, pp. 377–394, https://doi.org/10.1007/978-3-030-46409-7_22.
[26] N. Verhulst, B. Govaerts, E. Verachtert, A. Castellanos-Navarrete, M. Mezzalama, P. Wall, J. Deckers, K.D. Sayre, Conservation agriculture, improving soil quality for sustainable production systems? in: R. Lal, B.A. Stewart (Eds.), Advances in Soil Science: Food Security and Soil Quality CRC Press, Boca Raton, FL, USA, 2010, pp. 137–208.
[27] M.K. Gathala, V. Kumar, P.C. ShaR-Ma, Y.S. Saharawat, H.S. Jat, M. Singh, A. Kumar, M.L. Jat, E. Humphreys, D.K. Sharma, S. Sharma, J.K. Ladha, Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the north-western indo-gangetic plains of India, Agric. Ecosyst. Environ. 177 (2013) 85–97, https://doi.org/10.1016/j.agee.2013.06.002.
[28] M.K. Gathala, J. Timsina, M.S. Islam, M.H. Rashid, A.K. Ghosh, T.J. Krupnik, T. P. Tiwari, A. McDonald, Conservation agriculture-based tillage and crop establishment options can maintain farmers' yield and increase profits in south asia's rice-maize systems: evidence from Bangladesh, Field Crops Res. 172 (2015) 85–98, https://doi.org/10.1016/j.fcr.2014.12.003.
[29] V. Kumar, M.K. Gathala, Y.S. Saharawat, R. Kumar, M.L. Jat, D. Krishna, A. Mishra, Effect of tillage and crop establishment methods on yield, profitability, and soil physical properties under a rice–wheat rotation in the indo–gangetic plains: in (chapter 3, in: N. Verhulst, J. Herrera, A. Yahyaoui, B. Govaerts (Eds.), Compendium of Deliverables of the Conservation Agriculture Course, D.F.: CIMMYT, Mexico, 2012, pp. 1851–1862, https://doi.org/10.2136/sssaj2010.0362, 75(5).
[30] R.K. Jat, T.B. Sapkota, R.G. Singh, M.L. Jat, M. Kumar, R.K. Gupta, Seven years of conservation agriculture in a rice–wheat rotation of eastern gangetic plains of south Asia: yield trends and economic profitability, Field Crops Res. 164 (2014) 199–210, https://doi.org/10.1016/j.fcr.2014.04.015.
[31] O. Erenstein, V. Laxmi, Zero tillage impacts in India's rice–wheat systems: a review, Soil Till. Res. 100 (2008) 1–14, https://doi.org/10.1016/j.still.2008.05.001.
[32] A. Keil, A. D'Souza, A. McDonald, Zero-tillage is a proven technology for sustainable wheat intensification in the eastern indo-gangetic plains: what determines farmer awareness and adoption? Food Secur. 9 (2017) 723–743.
[33] M.E. Haque, R.W. Bell, M.A. Islam, M.A. Rahman, Minimum tillage unpuddled transplanting: an alternative crop establishment strategy for rice in conservation agriculture cropping systems, Field Crops Res. 185 (2016) 31–39, https://doi.org/10.1016/j.fcr.2015.10.018.
[34] M.A. Hossen, M.M. Hossain, M.E. Haque, R.W. Bell, Transplanting into non-puddled soils with a small-scale mechanical transplanter reduced fuel, labour and irrigation water requirements for rice (Oryza sativa L.) establishment and increased yield, Field Crops Res. 225 (2018) 141–151, https://doi.org/10.1016/j.fcr.2018.06.009.
[35] M.K. Gathala, J.K. Ladha, V. Kumar, Y.S. Saharawat, V. Kumar, P.K. ShaR-Ma, Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice−wheat rotation, Soil Sci. Soc. Am. J. 75 (2011) 1851–1862, https://doi.org/10.2136/sssaj2010.0362.
[36] R.L. Croissant, H.F. Schwartz, P.D. Ayers, Soil compaction and tillage effects on dry bean yields, J. Prod. Agric. 4 (1991) 461–464, https://doi.org/10.2134/jpa1991.0461.
[37] K.K. Singh, T.S. Colvin, D.C. Erbach, A.Q. Mughal, Tilth index: an approach to quantifying soil tilth, Trans. ASAE 35 (1992) 1777–1785. DOI: 10.13031/2013.28797) @1992.
[38] P.W. Unger, O.R. Jones, Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum, Soil Till. Res. 45 (1998) 39–57, https://doi.org/10.1016/S0167-1987(97)00068-8.
[39] J. Lampurlanes, C. Cantero-Martinez, Soil bulk density and penetration resistance under different tillage and cop management systems and their relationship with barley root growth, Agron. J. 95 (2003) 526–536, https://doi.org/10.2134/agronj2003.0526.
[40] V.K. Singh, Yadvinder-Singh, B.S. Dwivedi, M.K. Singh, M.L. Jat, R.P. Mishra, M. Rani, Soil physical properties, yield trends and economics after five years of conservation agriculture-based rice-maize system in north-western India, soil till, Res. 155 (2016) 133–148.
[41] M. Choudhary, H.S. Jat, A. Datta, A.K. Yadav, T.B. Sapkota, S. Mondal, R.P. Meena, P.C. ShaR-Ma, M.L. Jat, Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems, Appl. Soil Ecol. 126 (2018) 189–198, https://doi.org/10.1016/j.apsoil.2018.02.027.
[42] M.A. Licht, M. Al-Kaisi, Strip-tillage effect on seedbed soil temperature and other soil physical properties, Soil Till. Res. 80 (2005) 233–249, https://doi.org/10.1016/j.still.2004.03.017.
[43] D.C. Erbach, J.G. Benjamin, R.M. Cruse, M.A. Elamin, S. Mukhtur, C.H. Choi, Soil and corn response to tillage with paraplow, Trans. ASAE 35 (1992) 1347–1354.
[44] J.K. Radke, Managing early season soil temperatures in the northern corn belt using configured soil surfaces and mulches, Soil Sci. Soc. Am. J. 46 (1982) 1067–1071.
[45] W.R. van Wijk, W.E. Larson, W.C. Burrows, Soil temperature and the early growth of corn from mulched and unmulched soil, Soil Sci. Soc. Am. Proc. 23 (1959) 428–434.
[46] K.J. Shinners, W.S. Nelson, R. Wang, Effects of residue-free band width on soil temperature and water content, Trans. ASAE 37 (1993) 39–49.
[47] G.S. Yadav, R. Datta, S.I. Pathan, R. Lal, R.S. Meena, S. Babu, A. Das, S. N. Bhowmik, M. Datta, P. Saha, P.K. Mishra, Effects of conservation tillage and nutrient management practices on soil fertility and productivity of rice (Oryza sativa L.)–Rice system in northeastern region of India, Sustainability 9 (2017) 1816, https://doi.org/10.3390/su9101816.
[48] A.K. Sinha, A. Ghosh, T. Dhar, P.M. Bhattacharya, B. Mitra, S. Rakesh, P. Paneru, S. R. Shrestha, S. Manandhar, K. Beura, S. Dutta, A.K. Pradhan, K.K. Rao, A. Hossain, H.N. Siddquie, M.S.S.H. Molla, A.K. Chaki, M.K. Gathala, M.S. Islam, R.C. Dalal, D. S. Gaydon, A.M. Laing, N.W. Menzies, Trends in key soil parameters under conservation agriculture-based sustainable intensification farming practices in the eastern ganga alluvial plains, in: Soil Res, vol. 57, CSIRO Publishing, 2019, pp. 883–897, https://doi.org/10.1071/SR19162.
[49] B. Govaerts, K.D. Sayre, K. Lichter, L. Dendooven, J. Deckers, Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems, Plant Soil 291 (2007) 39–54, https://doi.org/10.1007/s11104-006-9172-6.
[50] W.L. Kingery, C.W. Wood, J.C. Williams, Tillage and amendment effects on soil carbon and nitrogen mineralization and phosphorus release, Soil Tillage Res. 37 (1996) 239–250.
[51] U.M. Sainju, Z.N. Senwo, E.Z. Nyakatawa, I.A. Tazisong, K.C. Reddy, Soil carbon and nitrogen sequestration as affected by long-term tillage, cropping systems, and nitrogen fertilizer sources, Agric. Ecosyst. Environ. 127 (2008) 234–240.
[52] B. Govaerts, N. Verhulst, K.D. Sayre, J. Dixon, L. Dendooven, Conservation agriculture and soil carbon sequestration: between myth and farmer reality, Crit. Rev. Plant Sci. 28 (2009) 97–122, https://doi.org/10.1080/07352680902776358.
[53] N.L. Morris, P.C.H. Miller, J.H. Orson, R.J.F. Williams, The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review, Soil Till. Res. 108 (2010) 1–15, https://doi.org/10.1016/j.still.2010.03.004.
[54] M. Silgram, M. Shepherd, The effects of cultivation on soil nitrogen mineralisation, Adv. Agron. 65 (1999) 267–311, https://doi.org/10.1016/S0065-2113(08)60915-3.
[55] J.H. Edwards, C.W. Wood, D.L. Thurlow, M.E. Ruf, Tillage and crop-rotation effects on fertility status of a hapludult soil, Soil Sci. Soc. Am. J. 56 (1992) 577–1582.
[56] A.J. Franzluebbers, F.M. Hons, Soil-profile distribution of primary and secondary plant available nutrients under conventional and no tillage, Soil Till. Res. 39 (1996) 229–239, https://doi.org/10.1016/S0167-1987(96)01056-2.
[57] C.C. Du Preez, J.T. Steyn, E. Kotze, Long-term effects of wheat residue management on some fertility indicators of a semi-arid plinthosol, Soil Till. Res. 63 (2001) 25–33, https://doi.org/10.1016/S0167-1987(01)00227-6.
[58] R. Lal, T.J. Logan, N.R. Fausey, Long-term tillage effects on A mollic ochraqualf in north-west Ohio. 3. Soil nutrient profile, Soil Till. Res. 15 (1990) 371–382, https://doi.org/10.1016/0167-1987(90)90110-Y.
[59] I. Ismail, R.L. Blevins, W.W. Frye, Long-term no-tillage effects on soil properties and continuous corn yields, Soil Sci. Soc. Am. J. 58 (1994) 193–198, https://doi.org/10.2136/sssaj1994.03615995005800010028x.
[60] A. Walkley, A. Black, An examination of the degtjareff method for deteR-Mining soil organic matter and proposed modification of the chromic acid titration method, Soil Sci. 37 (1934) 29–38, https://doi.org/10.1097/00010694-193401000-00003.

[61] M.C. Jackson, Soil Chemical Analysis, Prentice Hall incorporation Eaglewood Cliffs, New York, 1958, p. 498.
[62] A.H. Hunter, Laboratory and greenhouse techniques for nutrient survey to determine the soil amendments required for optimum plant growth, in: Soil Fertility Evaluation Implementation Project. N.C, N.C, State University, Raleigh, 1972.
[63] J. Sippola, R. Ervio, Determination of boron in the soils and plants by the Azomethine-H method, Finnish, Chem. Lett. 4–5 (1977) 138–140.
[64] S.K. Dutta, A. Laing, S. Kumar, S. Shambhavi, S. Kumar, B. Kumar, D.K. Verma, A. Kumar, R.G. Singh, M. Gathala, Sustainability, productivity, profitability and nutritional diversity of six cropping systems under conservation agriculture: a long term study in eastern India, Agric. Syst. 207 (2023) 103641.
[65] J.H. Guo, X.J. Liu, Y. Zhang, J.L. Shen, W.X. Han, W.F. Zhang, P. Christie, K. Goulding, P.M. Vitousek, F.S. Zhang, Significant acidification in major Chinese croplands, Science 327 (2010) 1008–1010.
[66] R.C. Dalal, P.A. Henderson, J.M. Glasby, Organic matter and microbial biomass in a vertisol after 20 yr of zero tillage, Soil Biol. Biochem. 23 (1991) 435–441, https://doi.org/10.1016/0038-0717(91)90006-6.
[67] F.N. Ponnamperuma, The chemistry of submerged soils, Adv. Agron. 24 (1972) 29–96, https://doi.org/10.1016/S0065-2113(08)60633-1.
[68] P.K. Sharma, S.K. De Datta, Physical properties and processes of puddle rice soils, Adv. Soil Sci. 5 (1986) 139–178.
[69] R. Alvarez, A review of nitrogen fertiliser and conservation tillage effects on soil organic carbon storage, Soil Use Manag. 21 (2005) 38–52.
[70] J. Timsina, V.K. Singh, K. Majumdar, Potassium management in rice–maize systems in south Asia, J. Plant Nutr. Soil Sci. 176 (2013) 317–330, https://doi.org/10.1002/jpln.201200253.
[71] B. Singh, Y. Singh, P. Imas, X. Jian-Chang, Potassium nutrition of the rice-wheat cropping system, Adv. Agron. 81 (2004) 203–259, https://doi.org/10.1016/S0065-2113(03)81005-2.
[72] R. Bhattacharya, S. Kundu, S.C. Pandey, K.P. Singh, H.S. Gupta, Tillage and irrigation effects on crop yields and soil properties under the rice-wheat system in the Indian himalayas, Agric. Water Manag. 95 (2008) 993–1002, https://doi.org/10.1016/j.agwat.2008.03.007.
[73] S. Saha, D. Chakraborty, A.R. Sharma, R.K. Tomar, S. Bhadraray, U. Sen, U. K. Behera, T.J. Purakayastha, R.N. Garg, N. Kalra, Effect of tillage and residue management on soil physical properties and crop productivity in maize-indian mustard system, Agric. Sci. 80 (2010) 679–685.