Improvement of cereal-based cropping systems following the principles of conservation agriculture under changing agricultural scenarios in Bangladesh

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Abstract

In the Eastern Gangetic Plains of Bangladesh, the cropping systems are predominantly rice based, having large yield gaps in farmers' fields because of poor management practices adopted by farmers. The increasing scarcity of resources (water, labor and energy) and production costs further make the rice-based cropping system less sustainable and less profitable. We hypothesized that integrating the best compatible cropping patterns accompanied by best management practices into the portfolio of farmers' own technologies would improve system productivity, resource use efficiency and economic profitability. To test this hypothesis, we evaluated four cropping system scenarios (S1–S4) designed to be adapted to current and future drivers of agricultural changes and varying from each other in best management practices (BMPs) and conservation agriculture (CA) principles (tillage and crop establishment, residue management, and crop rotation). Four cropping system scenarios were (i) current farmers' practice (S1), (ii) BMPs with conventional tillage and farmers' crop rotation (S2), (iii) BMPs with reduced tillage and farmers' crop rotation (S3), and (iv) BMPs with reduce or zero tillage and crop diversification. Scenario 2 alone compared with S1 increased system productivity (24–33%), total water productivity (16–50%) and net economic returns (85–169%), and decreased specific energy (11–17%). The combination of BMPs in S2 with reduced tillage and manual or mechanical transplanting (S3) did not further increase yield and save water. Crop diversification with potato in place of Boro rice and intensification with maize or mungbean in between Boro and Aman rice (S4) yielded 1.9–3.7 times higher net economic returns than S1. But this could be a risky rotation because of its vulnerability to uncertain rainfall during the season and fluctuating market price of potato. Results of a three-year study indicated that

farmers' productivity and economic returns can be improved by BMPs, which not only increase crop yields but also improve the efficiencies of resources such as water and energy.

Keywords: Best management practices; Crop diversification; Cropping system intensification; Resource management; Resource use efficiency

1. Introduction

In South Asia, rice, wheat and maize are the major cereal crops grown often in rotation with non-cereal crops such as potato, mustard and legumes (Balasubramaian et al., 2012). Among them, rice and wheat provide the staple food for hundreds of millions of people. Maize is mainly a feed crop but it is also a food crop in many poverty-stricken areas, especially in the hilly areas. These crops greatly influence the livelihoods and health of the urban and rural poor in these regions. Cereal production needs to increase by about 2% per annum over the next four decades to ensure food security in South Asia (Ray et al., 2013). National mean yields of these cereals in South Asia are below global averages except for maize in Bangladesh, and large yield gaps of about 50% or more exist (Balasubramaian et al., 2012). Since there is little or no scope for expanding the area under cultivation in South Asia, further intensification of land use together with increases in crop productivity and production are the options to meet the growing demand.

In Bangladesh, rice is the major staple food crop grown on 80% of the cultivated land area sometimes in rotation with other crops, contributes 19.6% to the gross domestic product (GDP) and provides employment for 63% of the country's population (Gumma et al., 2012). Bangladesh has increased rice production 1.8 times during the last 20 years with almost no increase in rice area (FAO, 2012). However, because of the continuous increase in population, rice demand is

projected to be 56% higher in 2050 than in 2001 and demand for other dominant cereals such as maize and wheat is projected to be more than 10 times and twice, respectively in 2050 (Mukherjee et al., 2011).

Cropping patterns in Bangladesh are largely rice-based, comprising rice–non-rice crops (34% of rice area), rice–rice–non-rice crops (37% of rice area), rice–rice (21% of rice area), rice–rice–rice (6% of rice area) and rice alone (2% of rice area) (Gumma et al., 2012). The major non-rice crops in these cropping systems are wheat, potato, maize, pulses, oilseeds and jute. Rice is mostly established by transplanting seedlings into puddled soil, and the field is kept continuously flooded for much of the growing season. Non-rice crops are established into dry soil prepared by intensive dry tillage. These conventional practices of land management and crop establishment are labor and water intensive which are becoming scarce and expensive resulting in sharp increases in cost of cultivation (Kumar and Ladha, 2011). In addition, the national average rice yield is much lower than what has been achieved by researchers and progressive farmers. In 2010, national average was 4.3 Mg ha⁻¹ (FAO 2012) which is far below the reported yields of 8–10 Mg ha⁻¹ in the dry season (Boro) and 5–6 Mg ha⁻¹ in the wet season (Aman) (BRRI 2010). This yield gap in farmers' fields is mainly due to the differences in management practices adopted by farmers and researchers. The causes of large rice yield gap are classified into two broad categories: (i) biotic factors such as poor-quality seeds and seedlings, insects, diseases, weeds and rodents, and (ii) abiotic factors such as poor management of nutrients and water. However, a large portion of this yield gap remains unexplained.

The development and understanding of appropriate practical technologies to bridge the yield gap are critical for meeting the future rice demand with less inputs (i.e. water, labor, agro-chemicals). There is a need of highly productive, resource efficient and sustainable crop rotations

and management practices that are adapted to the changes in agricultural, socioeconomic and climatic environment. Integrating the appropriate crop rotation accompanied by BMPs and CA into the portfolio of farmers' own technologies are crucial for maximizing productivity and economic benefits to the farmers (Ladha et al., 2009).

Systematic studies integrating BMPs with CA in the key cropping systems adapted to the changes within and outside of agricultural environment are lacking in the region. Such studies are important for extrapolation to broader geographical levels. Therefore, a production-scale field trial guided by key scenarios of agricultural environment was designed and established in four locations in the key agro-ecosystems of South Asia. Recently, the responses of various management practices in the rice–wheat system, which is predominant in two major agro-ecosystems (western and central) of the Indo-Gangetic Plains (IGP) were reported (Gathala et al., 2013; Laik et al., 2014). However no systematic studies have been carried out in the Eastern IGP which is home to the world's highest rural population density. Cropping patterns are largely rice-based with large potential of intensification and diversification and therefore is envisioned to supply future demand of food grains. As part of this comprehensive study, here we report the performance of rice–rice rotation during the three years, at Gazipur, Bangladesh, a part of the Eastern IGP. Using a range of indicators related to yield, economics, and input (water, labor, energy) usages and their use efficiencies, four scenarios involving options of land preparation, crop establishment, resource management practices, and crop diversification were evaluated.

2. Materials and methods

2.1 Experimental site and seasons

The study was conducted at the experimental farm of the Bangladesh Agricultural Research Institute (BARI) in Gazipur, Bangladesh (23°59'01" to 23°59'02.2" N and 90°24'08" to

90°24'12.6" E). The experiment was established in 2009 as a production-scale trial with a long-term perspective of at least 10 years involving four rice-based cropping systems. The climate of Gazipur is hot subhumid with total annual (December–November) rainfall during the study period was 1309 mm in 2009-10, 1829 mm in 2010-11 and 1359 mm in 2011-12. The lowest mean monthly minimum and the highest mean monthly maximum temperatures during three years were as follows: 2009-10, 11.21°C in January and 35.13°C in April, respectively; 2010-11, 10.31°C in January and 33.10°C in May, respectively; and 2011-12, 12.96°C in January and 34.31°C in May (Fig. 1). Crop production was distributed across the three seasons common in the country: Rabi, also called Boro (November to March); pre-monsoon Kharif-1, also called Aus (April to June); and monsoon Kharif-2, also called Aman (July to October). The trial began in Boro 2009-10.

The basic soil physical and chemical characteristics of the experimental field measured prior to the establishment of the experiment are given in Table 1. Prior to the start of the trial, a cover crop of puddled transplanted rice was grown to promote soil uniformity. We measured total biomass of cover crop by sampling 10 m² at each of 20 places uniformly distributed in entire field and found no significant differences. After the harvest of the cover crop, the entire field was laser-leveled and divided into three blocks separated by a 1.5-m walkway and each block was subdivided into four plots each measuring 35 m × 41 m separated by earthen bunds (0.6 m wide and 0.3 m high).

2.2 Experimental design and treatments

Four cropping system treatments referred to as scenarios (S) were designed based on different drivers of agricultural change (Table 2). The scenarios varied from each other in tillage, crop establishment, residue management, crop rotation and other management practices. Treatments

referred to as scenarios 1–4 (S1, S2, S3 and S4) were assigned to individual plots and replicated thrice in a randomized complete block design. Scenario details involving crop management and various field activities are provided in Tables 2 and 3, respectively.

2.2.1 Scenario 1(business as usual–farmers’ practice)

This scenario represents current farmers’ practices of crop rotation, crop varieties and management (tillage and crop establishment, and residue), which were based on an on-farm survey conducted in 263 farmers’ fields during 2006-08 in the neighboring area.

Rice (Boro)–fallow (Aus)–rice (Aman) was the crop rotation because it is the predominant cropping pattern covering more than 80% of the cultivated area in the region. In both seasons (Boro and Aman), rice was grown by transplanting four to six seedlings per hill in puddled soil prepared by intensive wet tillage. Boro rice was irrigated but Aman rice was rainfed. Rice was harvested manually at or near ground level, leaving 5–10 cm standing biomass from the ground which was incorporated during land preparation of the next crop.

2.2.2 Scenario2 (best management practices with conventional tillage)

Scenario 2 was designed to increase productivity, input use efficiency and profitability of the rice (Boro)–fallow (Aus)–rice (Aman) crop rotation through the use of BMPs. Rice was manually transplanted into puddled and leveled soils prepared by three to four passes of a power tiller followed by two passes of the power tiller. At harvest, 30 cm standing rice biomass was incorporated during land preparation of the next crop.

2.2.3 Scenario 3 (best management practices with reduced tillage)

Similar to S2, S3 had the objective of increasing productivity, input use efficiency and profitability of the rice (Boro)-fallow (Aus)-rice (Aman) crop rotation through the use of BMPs. In addition some components of CA was included to specifically address shortages of labor and water.

Intensive wet tillage (puddling) was avoided by transplanting in non-puddled soil. At harvest, 30 cm standing biomass was left and incorporated during land preparation of the next crop. Boro rice was transplanted manually and Aman rice with a mechanical transplanter into reduced-till non-puddled soils. In Boro, soils prepared by one to two passes of a power tiller operated seeder (PTOS) in dry condition and prior to transplanting water applied. In Aman, soils prepared by two passes of a power tiller in wet condition.

2.2.4 Scenario 4 (crop diversification with best management practices and reduced to zero tillage)

This scenario was designed for water- and labor-scarce environments to improve system productivity and profitability through diversified cereal-based cropping systems with BMPs and CA. In this scenario, the crop rotation was potato (Boro)–relay maize (or mungbean) (Aus)–rice (Aman). In 2011, maize failed to grow because of untimely and excessive rainfall. In 2012, mungbean instead of maize was grown after the harvest of potato. Rice was transplanted into reduced-till non-puddled soils prepared by one to two passes of a power tiller in wet condition. Transplanting was done manually in 2010 and 2011 and with a mechanical transplanter in 2012. Potato was planted manually into soils prepared with reduced tillage (four to five passes of a power tiller followed by two passes of laddering) while maize and mungbean were sown with zero tillage (ZT). At harvest, 30 cm standing rice biomass was left and incorporated during land preparation of the next crop and full residues of non-rice crops were retained on soil surface.

2.3 Best management practices (BMPs)

The BMPs used in this study were based on recommended management practices for rice by BRRI (BRRI, 2007) and for potato, maize and mungbean by BARI (BARI, 2004), which include (a) suitable cultivar/variety of a particular crop and scenario based on yield and growth duration, (b) certified seeds and seed treatment with fungicide to prevent seed-borne diseases, (c) improved

174 raised bed or mat nursery for rice to produce robust, healthy young seedlings, (d) applying adequate
175 nutrients in a nursery to enrich seedlings with nutrients and to minimize transplanting shock, (e)
176 optimum seedling age for rice (less than 40 days in Boro and less than 30 days in Aman), (f)
177 planting two to three seedlings per hill at 20 × 20 cm spacing, (g) efficient water management by
178 alternate wetting and drying (AWD) method allowing the water level to drop to 15 cm below the
179 soil surface at the time of irrigation, (h) weed control by pre-emergence herbicide followed by need-
180 based hand weeding for rice, and only hand weeding for non-rice crops, (i) applying adequate
181 nutrients at the right time and following site-specific nutrient management (SSNM) principles to
182 ensure high yields, and (j) need-based pest management to control pests and diseases. Full details of
183 the practices in each scenario are provided in Table 3.

184 For machine transplanting, iron frames having 10 units (each of 58 cm × 28 cm × 2.5 cm)
185 arranged side by side in two rows were used to raise the seedlings. The iron frames were placed
186 on a polythene sheet spread on properly leveled ground. Each frame was filled with 2.0-cm-
187 depth soil mixture prepared by mixing finely ground soil and decomposed cow dung at a 70:30
188 ratio. Pre-germinated seeds at the rate of 140 g tray⁻¹ (120 g dry seeds per tray) were sown
189 uniformly on the soil surface covered with a thin layer of soil, and watered. Subsequently,
190 irrigation was applied twice a day to ensure uniform germination and seedling growth. Twelve-
191 to 14-day-old seedlings were transplanted. The mechanical transplanter used was a 4-row
192 transplanter transplanting at 30-cm fixed row spacing and adjustable hill spacing within 14-17
193 cm.

194 *2.4 Soil sampling and analysis*

195 Before imposing the experimental treatments, baseline soil samples were collected from three
196 locations in each of the four grids measuring 20.5 m × 17.5 m in each plot at 0–15-cm and 15–30-

cm soil depths using an augur of 5-cm diameter. Each of the four corners of each plot had one grid. The depth-wise soil samples from each grid cell of a plot were composited, air-dried, ground to pass through a 2-mm sieve and stored in a plastic jar until analysis. The soil samples were analyzed for pH, electrical conductivity (EC), total carbon (TOC; SSM Analyzer Shimadzu), total N (TN Analyzer Shimadzu), Bray P (Bray and Kurtz, 1945) and 1N neutral NH_4OAC -extractable K (by flame emission spectrophotometer). Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962). The textural class was determined by the United States Department of Agriculture (USDA) system.

2.5 Data measurement and calculation

The human labor used in all operations and management practices, amounts of all inputs and outputs, electrical energy used for irrigation, input-output prices, wage rate for labor and machinery rent were recorded for each plot.

2.5.1 Crop yield estimation

Grain and straw yields of rice, grain and stover yields of maize, tuber and shoot yields of potato and grain and shoot yields of mungbean were determined by manually harvesting five areas (one from each of four grid cells and one from the middle of the plot) in each plot at physiological maturity. Each harvest area was 6 m² for rice and 12 m² for each of maize, potato and mungbean. Grain yields of rice, maize and mungbean were adjusted to 14%, 14% and 12% moisture content, respectively. Potato yields were reported as tuber fresh weight in Mg ha⁻¹. Fresh straw/stover/shoot weight was recorded from each harvest area, and 200 g of fresh subsample was oven-dried to a constant weight. Straw/stover/shoot yield was calculated on a dry-weight basis (oven-dried constant weight). The amount of crop residues retained and

incorporated in each season was recorded and reported. All the biomass measured was reported in Mg ha⁻¹.

The grain and tuber yields of non-rice crops were converted into rice equivalent yield (REY) using the following equation to compare the productivity of different crops and total system productivity of the different scenarios:

$$REY (Mg^{-1}) = \frac{\text{Non - rice crop yield (Mg ha}^{-1}) \times \text{Farmgate price of non - rice crop (\$ Mg}^{-1})}{\text{Farmgate price of rice (\$ Mg}^{-1})} \quad (1)$$

In the equation, the farm-gate price was the local market price at harvest time.

2.5.2 Water measurement and water productivity calculation

In the experimental area, all the plots were connected by a 5-cm polyvinyl chloride (PVC) pipeline installed on the bunds on one side of each plot with an outlet to the plot at the center for precise water application and measurement. The PVC pipeline was connected to a tube well with a water meter fitted in the outlet pipe. A non-return valve (NRV) was installed in the pipeline at the tube-well delivery outlet link to the pipeline supplying the experimental fields to avoid any water loss within and between irrigations. Each outlet to the plot had a water-tight butterfly valve to ensure that only one plot was irrigated at a time.

Water meter readings (m³) were recorded at the start and at the end of each irrigation to determine the amount of water applied per irrigation in each plot. The amount of irrigation water applied was calculated as water depth (mm) using the following equations:

$$\text{Irrigation water (m}^3 \text{ ha}^{-1}) = \frac{\text{Final water meter reading (m}^3) - \text{Initial water meter reading (m}^3)}{\text{Plot area (m}^2)} \times 10000 \quad (2)$$

$$\text{Irrigation water (mm)} = \frac{\text{Irrigation water (m}^3 \text{ ha}^{-1})}{10} \quad (3)$$

The total amount of water applied (input water) was calculated by summing irrigation water (mm) and rainfall (mm). Rainfall data were recorded from an automated weather station (Spectrum Technologies) installed in the experimental area.

The productivity of irrigation (WP_I) and total water (WP_{I+R}) was calculated using the following equations:

$$WP_I \text{ (kg grain m}^{-2} \text{ of irrigation water)} = \frac{\text{Grain yield (kg ha}^{-1}) / \text{irrigation water (mm)}}{10} \quad (4)$$

$$WP_{I+R} \text{ (kg grain m}^{-2} \text{ of irrigation water + rainfall)} = \frac{\text{Grain yield (kg ha}^{-1}) / [(\text{irrigation water} + \text{rainfall}) \text{ (mm)}]}{10} \quad (5)$$

To compare different crops and cropping systems, the water productivity of non-rice crops was calculated based on their REY.

2.5.3 Energy calculation

The energy equivalent was calculated for each input (seed, fertilizer, irrigation water, pesticides, fuel, electricity, machinery use and labor) and output (economic yield [grain and tuber] and crop residue [straw, stover, shoot]) by multiplying by a respective energy value provided in Table 4. Fuel consumption was recorded during each field operation, which includes land preparation, transplanting and harvesting. The energy usage in irrigation was calculated from the amount of total irrigation water and electricity consumption. The total energy input (EI) and output (EO) were computed by summing the energy equivalents of all the inputs and outputs. Specific energy (SE) was calculated by using the following equations (Moraditochae, 2012):

$$SE (MJ Kg^{-1}) = \frac{EI (MJ ha^{-1}) \text{ in crop production}}{\text{Economic and residue yields } (Kg ha^{-1})} \quad (6)$$

2.6 Economic analysis

The economic analysis was done considering total variable costs (TVC) of crop production and gross returns (GR). The variable costs included human labor, machinery (power tiller, transplanter and reaper) rent and the cost of production inputs (seed, fertilizer, pesticides, fuel and electricity). The cost of human labor used for tillage, seedling raising, transplanting or planting, irrigation, fertilizer and pesticide application, weeding, harvesting and threshing of crops was calculated by multiplying the person-days ha^{-1} required for an operation by wage rate. The amount of labor and time (h) required to complete a particular field operation in each plot was recorded and was expressed as person-days ha^{-1} , considering 8 h to be equivalent to 1 person-day. Irrigation cost was calculated by multiplying total electricity used for irrigation (kWh) by the fixed charges of electricity per unit as enforced by the Rural Electrification Board (REB), Bangladesh. The costs of inputs such as seed, fertilizer, pesticides and fuel were calculated based on prevailing market prices. Gross returns were calculated by multiplying the economic yields of crops by the farm-gate price at harvest time. Net returns (NR) were calculated as the difference between GR and TVC ($NR = GR - TVC$). The cropping systems' returns were calculated by adding the net returns of all crops harvested within a cropping year for a particular scenario. The benefit-cost ratio (BCR) was calculated by dividing gross returns by TVC ($BCR = GR/TVC$). All the economic data were converted to US\$ using the exchange rate

during the cropping season or year. The prices of inputs, outputs, wage rate and exchange rate of US\$ to Bangladeshi taka are presented in Table 5.

2.7 Data analysis

Data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedures of the Statistical Analysis System (SAS Institute, 2001). The Tukey protected least significant difference test at $P < 0.05$ level was used to test the differences between the scenario means. The scenario $\times$ year interaction effects were always significant for all parameters except GR, NR and BCR for both Boro rice or potato and Aman rice.

3. Results and discussion

3.1 Weather

Boro rice received insufficient rainfall and hence largely depended on irrigation, but with high solar radiation. During transplanting to harvesting (late January to early May), Boro rice had 49–50 mm, 281–291 mm and 233–234 mm of rainfall in the first, second and third year, respectively (Table 6). In Boro, first year had lower rainfall but relatively higher solar radiation than second and third years. Maize (late January to late May) also received insufficient rainfall of less than 300 mm in first and third years, and slightly more than 500 mm in second year. In the second year, 40% of the total rainfall of 517 mm occurred at 80–85 days after planting of maize, resulting in waterlogging and crop failure. During the Aman rice-growing period (mid-July to late November), total rainfall was 788 mm, 1006 mm and 474–630 mm in the first, second and third year, respectively. In the third year, the total amount of rainfall varied among the scenarios (490 mm in S1, 599 mm in S2, 630 mm in S3 and 474 mm in S4) because of variable transplanting dates during 19 July to 1 August and shorter field duration by 35 days in S4 compared with S1–S3. Earlier transplanted rice having similar growth duration in S1–S3

received more rainfall. Although rice was transplanted earlier in S4, it received the lowest amount of rainfall because of early harvest of the shorter-duration variety. The transplanting dates were also variable during 21 to 29 July in the first year and 23 July to 6 August in the second year but this did not influence the total amount of rainfall because it was the same within these periods in both years. The rice variety used in S4 was 20 days early maturing in the first and second year, which also did not affect the total amount of rainfall. Despite high rainfall in the second year, irrigation was required at the booting/flowering stage because of unfavorable rainfall pattern (data not shown). Irrigation was also required in the third year at booting/flowering stage.

3.2. Crop and cropping system yield

3.2.1. Boro rice, rice equivalent yield of potato and Aman rice

Boro rice yields in S1–S3 and rice equivalent yield (REY) of potato in S4 ranged from 4.9 to 6.6 and 7.1 to 9.9 Mg ha⁻¹, respectively, across years (Table 7). Boro rice yields in S2 and S3 were always similar but significantly higher than in S1 and lower than REY of potato in S4. Compared to S1 (farmers' practice), the average Boro rice yields of S2 and S3 were 28% higher in the first year, 20% higher in the second year and 14% higher in the third year. Among the years and across scenarios, the rice yields of Boro were higher in the first year than in the second and third years by 0.2–0.7 Mg ha⁻¹ and 0.2–0.4 Mg ha⁻¹, respectively, which was likely related to the low solar radiation in the second and third years compared to the first year (Table 6). The REY of potato in S4 was higher by 94% than in S1 and by 51% than the average yield of S2 and S3 in the first year. The corresponding increases of REY of potato were 44% and 20% in the second year and 71% and 50% in the third year. In the second year, despite the highest potato yield (17.7 Mg ha⁻¹), the REY of potato was the lowest (7.1 Mg ha⁻¹) because of the low potato

price (Table 5). The lowest actual potato yield in the third year (14.8 Mg ha^{-1}) was due to infestation of late blight disease but its REY was higher than in the second year because of the low rice price in the third year (Table 5). In general, Aman rice yields were 5–28% lower than those of Boro. Like Boro, Aman rice in scenarios 2–4 yielded 11–48% higher than in S1. Scenarios 2 and 3 with only a difference in tillage intensity (conventional puddling in S2 vs reduced tillage, no puddling in S3) did not result in yield differences. This is expected because puddling effects are known to last for a few seasons though the effects on resource use and economics are expected to be different. On average across three years and two scenarios (S2 and S3), rice yields increased by 21% in Boro and by 30% in Aman. These results demonstrate the significant potential of the integration of BMPs in farmers' portfolio to increase rice productivity in the Eastern IGP similar to Northwestern IGP and Central IGP (Ladha et al., 2009; Gathala et al., 2013; Laik et al., 2014).

3.2.2. *Maize or mungbean (rice equivalent)*

In scenario 4, maize was planted as a relay crop with potato in the first and second years, and mungbean was planted after the harvest of potato in the third year. In the first year, maize produced good yield but, in the second year, maize plants suffered at 85–91 days after planting (DAP) because of waterlogging from heavy rainfall, resulting in no harvest. In the second year, total rainfall during 85–91 DAP of maize was 5.6 times higher than in the first year. Maize and its REY were 9.2 Mg ha^{-1} and 5.2 Mg ha^{-1} , respectively in the first year, and of mungbean and its REY were 0.7 Mg ha^{-1} and 2.1 Mg ha^{-1} , respectively in the third year (Table 7). Normally, farmers leave fields fallow between the two main crops (Boro and Aman) because of the uncertainty associated with rainfall as experienced in our study in the second year when maize failed because of excess rainfall in April. Therefore, we shifted to mungbean, a shorter-duration

crop (70 d), which allowed planting in February and harvesting by early April when rainfall is normally negligible.

3.2.3. Cropping system

On a cropping-year basis, total REY of the four cropping systems ranged from 8.4 to 20.0 Mg ha⁻¹ across scenarios and years (Table 7). System REY in S2 and S3 were similar but 24–33% higher than in S1. In S4, REY further increased by 72% in the first year and by 43% in the third year than the mean of S2 and S3. These increases in REY were due to substitution of Boro rice by potato, and inclusion of maize in first year and mungbean in second year as Aus crop in between potato and Aman. In second year, REY in S2, S3 and S4 were similar when maize as summer crop failed (Table 6). The low potato price at harvest in second year also contributed to low REY system yield in S4. These results highlight that intensification of rice–rice rotation with non-rice crops is a key to pushing the frontiers of system productivity (Gathala et al., 2013; Laik et al., 2014). However, establishment as well as growing of non-rice crops in summer season could be a challenge is very difficult due to un-predictable rainfall which starts in April and increases thereafter. The fluctuating price of potato at harvest can also put the farmers at some risk of growing potato instead of Boro rice. Selection of suitable non-rice crops which can fit in the agricultural environment as well in existing market scenarios during Boro and summer seasons is important to maximize the benefits.

3.3. Water application and water productivity

3.3.1. Water application

In general, the Boro season received insufficient rainfall during December to March (8 mm in the first year, 122 mm in the second year and 13 mm in the third year) and largely depended on irrigation. Irrigation water application varied from 578 to 1247 mm to rice in S1–S3 and from

120 to 202 mm to potato in S4 across years (Table 8). Irrigation input to Boro was highest in the first year, which declined by 373–520 mm across S1–S3 in the third year. Although the time trend of total input (irrigation + rainfall) was similar in three years in Boro, a gradual reduction in input from the first year to the third year was due to higher total rainfall (average of 200 mm per year) in the latter two years. The irrigation water applied in S2 and S3 was similar, suggesting that avoiding tillage did not result in any more water savings than that of puddling or wet tillage. However, this may change with time because of expected changes in soil percolation associated with changes in soil physical condition (Jat et al., 2009). On average, S2 and S3 had 18–27% lower irrigation inputs than S1 across three years, with significant differences in the second and third years. Substitution of Boro rice with potato in S4 reduced water input by an average of 6-fold (780 mm). Aman rice, which is primarily rainfed, obtained much of its water requirement from rain, which ranged from 474 to 1006 mm in three years (Table 6). Although the first year had lower rainfall than the second year during Aman, no irrigation input was required due to a favorable rainfall pattern (Fig. 1). Despite higher total rainfall in the second year than in the first year, the second year required irrigation input in all scenarios, ranging from 56 to 111 mm. In Aman year 3, the rainfall was lowest of three years but it was fairly spread across the season (Fig. 1).

The majority of water input to the fields in Boro was irrigation, while in Aman rainfall was the dominant source of water input. Further, the results demonstrated that BMPs and CA (S2–S4) resulted in significant reduction in irrigation water inputs.

3.3.2. Water productivity

In all three years, the WP_1 of potato (as REY) ($4.9\text{--}7.1\text{ kg m}^{-3}$) in S4 was 6–12 times higher than that of Boro rice in S1–S3 (Table 9). The WP_1 of Boro rice in S1–S3 ($0.4\text{--}1.0\text{ kg m}^{-3}$) was

similar in the first and third years, and, in the second year, it was similar in S2 and S3. In year 2, WP_I of S2 and S3, was 1.0 compared to 0.6 WP_I of S1. The WP_I of the cropping system in S1–S3 was similar (0.8–1.7 kg m⁻³) but significantly lower than that of S4 across years (6.0–12.9 kg m⁻³).

The WP_{I+R} of Boro rice in S1–S3 was similar (0.4–0.7 kg m⁻³) and significantly lower than that of potato (3.9–6.4 kg m⁻³ as REY) in S4 across years. The WP_{I+R} of the cropping systems in S2 and S3 (0.5–0.7 kg m⁻³) was always similar but significantly higher than in S1 by 0.1–0.2 kg m⁻³ and lower than in S4 by 0.4–1.2 kg m⁻³.

3.4. Economic analysis

The TVCs of Boro in S1–S3 were similar and were US\$1078–1134 ha⁻¹, US\$1001–1064 ha⁻¹ and US\$908–928 ha⁻¹ in the first, second and third year, respectively, which were significantly lower than those of potato (US\$2030–US\$2400) in S4 (Table 10). On average of three years, S4 had 123% higher TVCs than S1–S3, which was largely due to the 18–33 times higher cost of potato seed compared with rice and associated increases in fertilizer inputs. Across scenarios, TVC in Aman rice in years 1 and 2 were 16–32% lower than with Boro rice, but in year 3, Aman rice in S2 had higher TVC (US\$976) than Boro rice (US\$924) which was largely contributed by irrigation cost. Compared to S1, TVC of Aman rice was higher in S2 and S4 in year 1, higher in S2 in year 2 and higher in S2–S4 in year 3. This was likely because of the increased fertilizer and crop establishment costs in the first and second year and increased fertilizer, crop establishment and insect and disease control costs in the third year. Despite similar fertilizer costs in S2 and S3, the TVCs of S3 were always lower than in S2 because of the lower crop establishment cost in S3 resulting from machine transplanting. The TVCs of maize in S4 were US\$808 ha⁻¹ in year 1, US\$341 ha⁻¹ in year 2. In year 2, though maize failed, it incurred US\$341 TVCs. On a system

basis, across years, S4 had the highest TVCs, ranging from US\$3068 to US\$4059 ha⁻¹, which is largely driven by the higher cost of potato cultivation. In year 1, the system cost in S1-S3 was not different but in years 2 and 3, the cost was higher in S2 than other scenarios.

The gross and net returns (GRs and NRs) and benefit-cost ratio (BCR) of crops and cropping systems are presented in Table 11. The GRs, NRs and BCR of three years were averaged because of non-significant year-by-scenario interactions. Despite the highest costs, GRs were also the highest in S4 because of high potato yield and economic value as a cash crop. Gross returns in S4 were US\$1167–1442 ha⁻¹ higher than those of S1–3. Gross returns of Boro rice in S2 and S3 were similar but they were 20–22% higher than in S1. Gross returns of Aman rice were 39%, 34% and 25% higher in S2, S3 and S4, respectively, than in S1. These differences among scenarios were largely due to differences in yields. On a system basis, S1 had the lowest GRs of US\$2312 ha⁻¹, US\$2128 ha⁻¹ and US\$1882 ha⁻¹ in the first, second and third years, respectively. System GRs of S2, S3 and S4 were 26%, 25% and 139% higher, respectively, than in S1 in the first year and the corresponding increases were 33%, 30% and 79% in the second year and 27%, 22% and 100% in the third year.

In the Boro season, the NRs of potato in S4 and rice in S2 and S3 were similar, ranging from US\$392 to US\$487 ha⁻¹, which were 2.1–2.7 times significantly higher than those of S1 (Table 11). In Aman, the highest NRs (US\$423 ha⁻¹) were in S3, which were significantly higher by US\$267 ha⁻¹ than S1 and by US\$108 ha⁻¹ to US\$100 ha⁻¹ than S2 and S4, respectively. System NRs in year 1 was higher in S4 (US\$1486 ha⁻¹) than S1 but not different than S2 (US\$ 966 ha⁻¹) and S3 (US\$996 ha⁻¹). In year 1, maize contributed US\$ 1340 ha⁻¹ to the system NRs. The NR from maize in year 2 was negative (–US\$341 ha⁻¹), which was shown in parenthesis in Table 11. This negative NR of maize resulted system NRs of US\$336 ha⁻¹ in S4 in year 2. However, we did

not include the TVC and NRs of maize in year 2 in analysis. In year 2, the net returns in S2-S4 ranged from US\$ 677-US\$ 1046 ha⁻¹ which was significantly higher than S1. In year 3, the net returns of US\$ 699 ha⁻¹ in S4 was significantly higher than S1 and S2 but not different from S3. Mungbean contributed by US\$486 ha⁻¹ to the NRs in year in S4.

The BCR was similar in S2 and S3 (1.5) and higher than in S1 and S4 (1.2) in Boro rice and potato crops, and in Aman rice it was highest in S3 (1.6) (Table 11). At a systems level in the first year, the BCR in S2–S4 (1.4–1.5) was significantly higher than S1 (1.2). In the second year, the BCR of S2 and S3 was similar (1.5–1.6), but significantly higher than in S1 and S4. In the third year, S3 had the significantly highest BCR (1.4), followed by S2 (1.3) and S1 and S4 (1.2).

The results of economic analysis of different scenarios across years suggest that the integration of BMP and CA in farmers' management practices is a potential option to increase the economic returns of the rice–rice system by 1.8–3.0 times than those of the farmers' practice with a BCR of 1.3–1.5. Similar economic returns have been reported from rice–wheat rotations on Northwestern and Eastern IGP of India (Gathala et al 2013; Liak et al 2014) Although the substitution of Boro rice with potato and inclusion of maize or mungbean in the rice–rice system also resulted in 1.9–3.7 times higher NRs than with the farmers' practice, it is not economically attractive as the BCR is 1.2 in both the second and third years. This is because uncertain rainfall during Aus and fluctuating marker price of potato.

3.5. Energy inputs and efficiency

Total energy inputs across years and scenarios in Boro rice and potato (24679 MJ ha⁻¹ to 35834 MJ ha⁻¹) were generally twice to that in Aman rice (10056 MJ ha⁻¹ to 24010 MJ ha⁻¹) (Table 12). In Boro rice, input energy was similar in the four scenarios in the first year but differed significantly in the second and third years. Compared with S1, it was 14% and 7% lower

in S3 but 5% and 6% higher in S4 in the second and third years, respectively. The lower energy uses in S3 were largely due to reduced tillage and the higher uses in S4 were because of potato requiring relatively more energy in seed, fertilizer and labor. By contrast, the energy inputs in Aman rice varied among scenarios in all years, and were higher in S3 than in S1, S2 and S4 by 75%, 8% and 55%, respectively, in the first year; and by 86%, 36% and 77%, respectively, in the second year. In the third year, S3 was similar to S2 but higher than S1 and S4 by 62% and 7%, respectively. The higher energy use in S3 in Aman rice was largely due to machine transplanting and associated fuel cost. On a systems basis, S4 had the highest energy use in the first and third year, and in the second year this was highest in S3. Energy used for the system in S4 (53650 MJ ha⁻¹) was 15% higher than in S1 and similar to that in S2 and S3 in the first year. In the third year, energy use in S4 (44925 MJ ha⁻¹) was 21% higher than in S1, and 9% higher than in both S2 and S3. In the second year, the energy used for the system in S3 (49544 MJ ha⁻¹) was 16% more than in S1 but 6% and 10% more than in S2 and S4, respectively.

The specific energy (SE) of crops and cropping systems varied significantly across years, except of Aman rice in the third year (Table 12). In Boro rice and potato, SE was highest (5.4–7.1 MJ kg⁻¹) in S1 and lowest (1.8–1.9 MJ kg⁻¹) in S4 and this was significantly different from S2 and S3 (4.4–5.1 MJ kg⁻¹). However, S2 and S3 were similar across years. Despite the high input energy in S4, the lowest SE was due to high potato yield. In Boro rice, significantly lower SE in S2 and S3 than in S1 suggests that both S2 and S3 are more energy efficient than S1.

In Aman rice, SE was similar in S2 and S3 (3.3–3.7 MJ kg⁻¹), which was significantly higher than in scenarios 1 and 4 in the first year. In the second year, it was highest in S3 (4.7 MJ kg⁻¹), followed by S1, S2 and S4. In the third year, despite higher input energy in S2, S3 and S4 than in S1, the similar SE in all scenarios suggests that S2, S3 and S4 are more energy efficient than S1.

The SE of the cropping system followed a similar trend as in Boro rice and potato. The results demonstrate that the integration of BMPs and CA options in farmers' management practices has the potential to save input energy as well as make rice production more energy efficient.

4. General discussion

This three-year study used production-scale plots simulating farmer field conditions to evaluate four scenarios involving current and futuristic cropping patterns and resource management practices. A set of key parameters was used to quantify crop productivity, economic costs and returns, water productivity and energy balance. Scenario 1, the farmers' existing cropping patterns and management practices, was used as the baseline to compare S2 to S4 comprising BMPs and suitable CA components to address emerging constraints such as scarcity of labor and water and the rising cost of production. On an annual basis, S2 and S3 had 2.3–2.8 Mg ha⁻¹ more crop yields and US\$233–587 ha⁻¹ more economic returns than S1. Higher returns resulted largely from increases in crop productivity but also through increasingly higher efficiencies of water and energy usages. In the E-IGP with heavy-textured soils, we experienced difficulties in practicing zero tillage and drill-seeding, which are the key components of CA. The heavy and unpredictable rainfall during crop establishment in soil with relatively more clay and silt make drill operation difficult for seeding. There is also a risk of complete failure of seed germination due to flooding. Existing rice varieties which are selected for transplanting in puddled soil lack ability to germinate under anaerobic condition and suffer in an aerobic soil with high bulk density. Therefore, we tried transplanting under non-puddled (reduced tillage) conditions in S3. However, neither rice yields nor input usages differed between S2 and S3, suggesting that reduced tillage was not adequate enough to make large changes in yield and input usages, at least in the first three years. On the other hand, crop diversification, reduced tillage,

and partial residue mulch in S4 resulted in significantly higher system performance. Compared to S1, annual crop productivity increased by 3.2–10.6 Mg ha⁻¹, total water productivity by 0.6–1.3 kg grain m⁻³, water and economic returns by US\$331–1090 ha⁻¹. The energy balance was also highly positive as shown by significantly lower (2.1–3.3 MJ kg⁻¹ ha⁻¹) specific energy in S4. This clearly demonstrates the role of crop diversification in the E-IGP of Bangladesh. However, the selection of an alternative crop is crucial. There are important considerations such as rainfall pattern, and price volatility of the produce. Our research highlights the need of more longer-term cropping systems research to identify compatible alternative crops to increase farmers' profitability while preserving the resource base. There is also a need for breeding and selection of a rice plant type suitable for direct seeding after zero tillage in heavy-textured soils.

Acknowledgments

We acknowledge the Bill & Melinda Gates Foundation (BMGF) and United States Agency for International Development (USAID) for their funding this research through a project titled “Cereal Systems Initiative for South Asia” (CSISA). We are grateful to the Bangladesh Agricultural Research Institute (BARI) for providing experimental land for establishing the research platform. We are extremely grateful to the director general of the Bangladesh Rice Research Institute and director general of BARI for their continued support to conduct this research at the research platform.

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Table 1

Initial soil properties at 0–15-cm and 15–30-cm soil depths in an experimental field at BARI farm, Gazipur, Bangladesh.

Soil properties	0–15 cm [†]		15–30 cm [†]	
	Range	Mean $\pm$ S.D. [‡]	Range	Mean $\pm$ S.D. [‡]
Clay (%)	19–39	28 $\pm$ 5	23–40	32 $\pm$ 5
Silt (%)	40–66	54 $\pm$ 7	40–62	51 $\pm$ 5
Sand (%)	11–25	18 $\pm$ 3	13–25	17 $\pm$ 3
Soil texture	Silt loam – silty clay loam		Silt loam – silty clay loam	
pH (1:1 soil:water)	4.4–5.6	4.8 $\pm$ 0.3	4.4–6.4	5.1 $\pm$ 0.4
EC (dS m ⁻¹) (1:1 soil:water)	0.1–2.0	0.5 $\pm$ 0.5	0.1–1.9	0.5 $\pm$ 0.6
Total carbon (%)	0.7–1.4	1.1 $\pm$ 0.2	0.5–1.2	0.7 $\pm$ 0.2
Total nitrogen (%)	0.06–0.18	0.09 $\pm$ 0.02	0.03–0.15	0.07 $\pm$ 0.02
Available P (mg kg ⁻¹)	2.3–28.1	8.7 $\pm$ 6.1	1.3–13.2	4.1 $\pm$ 2.4
Exchangeable K (mg kg ⁻¹)	30–273	80 $\pm$ 41	29–409	79 $\pm$ 60
Particle density (g cm ⁻³)	2.3–2.7	2.5 $\pm$ 0.1	2.3–2.6	2.5 $\pm$ 0.1

[‡]S.D., standard deviation.

[†]In each depth the ranges and means were determined from 48 observations

Table 2

Descriptions of cropping systems scenarios examined in replicated production plots at Gazipur, Bangladesh

Features	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Business-as-usual–farmers’ practice	Best management practice (BMP) with conventional tillage	BMP with reduced tillage	BMP with crop diversification and reduced or zero tillage
Drivers of change	None	Need for increased cereal production and farmers’ income	Need for increased cereal production and farmers’ income in the face of increasing scarcity of labor, water, and energy and soil degradation	Need for diversification and increased cereal production and farmers’ income in the face of increasing scarcity of labor, water, and energy and soil degradation
Crop rotation	Rice–fallow–rice	Rice–fallow–rice	Rice–fallow–rice	Potato–maize–rice [¶] Potato–mungbean–rice [†]
Tillage	Conventional tillage–puddling (CT-Pd)	CT-Pd	Reduced tillage non-puddled (RT-nonPd)	Reduced tillage for potato Zero tillage for maize and mungbean RT-nonPd for rice
Crop establishment	Transplanted manually	Transplanted manually	Transplanted in Aman by machine and in Boro manually	Rice transplanted in 2012 by machine and in other years manually Potato, maize, and mungbean planted in line manually
Harvesting and threshing	Manually	Manually	Manually in 2010 and by machine in 2011 and 2012	Manually in 2010 and 2011 and by machine in 2012
Residue management	Incorporated 5 - 10-cm standing rice biomass	Incorporated 30-cm standing rice biomass	Incorporated 30-cm standing rice biomass	Incorporated 30-cm standing rice biomass, and full residues of potato, maize, and mungbean retained on surface

[¶]Crop rotation in 2009-10 and 2010-11.

[†]Crop rotation in 2011-12.

Table 3

Field activities and crop management practices for (a) Boro rice/potato/maize/mungbean, (b) Aman rice in different scenarios.

Activity/operation	Scenario 1	Scenario 2	Scenario 3	Scenario 4
(a) Boro rice/potato/maize/mungbean				
Crop	Rice	Rice	Rice	Potato (P), maize (M), mungbean (Mb)
Cultivar	BRRI dhan28	BRRI dhan28	BRRI dhan28	Diamond (P) NK 40 (M) BARI mung 6 (Mb)
Seeds and seedling nursery management				
Seeds	Farmers' seeds	Certified seeds	Certified seeds	Certified seeds
Seed treatment	None	Treated with fungicide at 3 g bavistine kg ⁻¹ seed	Treated with fungicide at 3 g bavistine kg ⁻¹ seed	Treated with fungicide at 3 g bavistine kg ⁻¹ seed
Seedbed	Flat bed	Raised (improved) seedbed	Raised (improved) seedbed	Not applicable (NA)
Seed rate (kg ha ⁻¹ of seedbed)	1500	1000	1000	NA
Land preparation				
Power tiller	4–5 passes	3–4 passes	1–2 passes	4–5 passes (P) Zero till (M and Mb)
Power tiller with wooden plank for land levelling	1 pass	2 passes	None	2 passes (P)
Date sown on nursery				
2009-10	27 Nov. 2009	7 Dec. 2009	7 Dec. 2009	NA
2010-11	27 Nov. 2010	26 Nov. 2010	26 Nov. 2010	NA
2011-12	28 Nov. 2011	27 Nov. 2011	27 Nov. 2011	NA
Date transplanted/planted				
2009-10	24 Jan. 2010	14 Jan. 2010	14 Jan. 2010	6 Dec. 2009 (P) 21 Jan. 2011 (M)
2010-11	16 Jan. 2011	31 Dec. 2010	1 Jan. 2011	11 Nov. 2010 (P) 23 Jan. 2011 (M)
2011-12	17 Jan. 2012	2 Jan. 2012	2 Jan. 2012	16 Nov. 2011 (P) 15 Feb. 2012 (Mb)
Seed rate (kg ha ⁻¹ of main field)	45	30	30	1614 (P) 20 (M) 30 (Mb)
Planting density (hill m ⁻²) or spacing (cm)	20 - 23	25	25	60 × 25 (P) 60 × 25 (M) 30 × continuous (Mb)
Water management	Irrigated, water applied at 5–6-cm depth when no standing water in the field without	Irrigated, water applied at 3–4-cm depth following AWD method	Irrigated, water applied at 3–4 cm depth following AWD method	Pre-sown irrigation followed by 2 irrigations in 2009-10 and 1 irrigation in 2010-11 and 2011-12

	any soil crack			(P). 1 irrigation in 2009-10 (M) and no irrigation for Mb
Fertilizer application (kg ha ⁻¹)				
2009-10				
N-P-K-S-Zn-B at 0 DAT	0-18-32-12-0-0	0-20-65-10-2-0	0-20-65-10-2-0	80-54-185-18-4-1 (P)
N topdress	51 at 33 DAT 69 at 45 DAT 35 at 61 DAT	45 at 16 DAT 50 at 33 DAT 45 at 48 DAT	45 at 17 DAT 50 at 33 DAT 45 at 48 DAT	80 at 35 DAP (P) 38 at 30 DAP (M) 38 at 55 DAP (M)
K topdress	0	20 at 48 DAT	20 at 48 DAT	0
2010-11				
N-P-K-S-Zn-B at 0 DAT	0-18-32-12-0-0	0-13-23-11-2-0	0-13-23-11-2-0	80-54-185-18-4-1 (P)
N topdress	51 at 23 DAT 69 at 44 DAT 35 at 67 DAT	42 at 22 DAT 63 at 39 DAT 65 at 61 DAT	42 at 16 DAT 63 at 33 DAT 65 at 55 DAT	80 at 42 DAP (P) 38 at 30 DAP (M) 38 at 55 DAP (M)
K topdress	0	16 at 61 DAT	16 at 55 DAT	0
2011-12				
N-P-K-S-Zn-B at 0 DAT	0-18-32-12-0-0	0-13-23-11-2-0	0-13-23-11-2-0	117-32-127-23-6-1 (P)
N topdress	51 at 25 DAT 69 at 50 DAT 35 at 65 DAT	44 at 26 DAT 59 at 49 DAT 59 at 65 DAT	44 at 26 DAT 59 at 49 DAT 59 at 65 DAT	58 at 32 DAP (P) No fertilizer for Mb
K topdress	0	16 at 65 DAT	16 at 65 DAT	0
Crop residue recycled from previous season (Mg ha ⁻¹)	0	0	0	0
2009-10	0.4	1.6	1.8	1.7
2010-11	0	1.4	1.7	1.4
2011-12				
Weed control				
Pre-emergence herbicide application (0.99 L a.i. ha ⁻¹)	0	Pendimethalin (Panida 33 EC) at 5-6 DAT	Pendimethalin (Panida 33 EC) at 5-6 DAT	0
Hand weeding (no.)	3 in all years	3 in 2009-10 1 in 2010-11 2 in 2011-12	3 in 2009-10 1 in 2010-11 3 in 2011-12	1 time in 2009-10 (P) 1 in 2010-11 (P) 2 in 2011-12 (P)
Insect and disease control				
Pesticide application				
2009-10	Carbofuran (Furadan 5G) at 0.5 kg a.i. ha ⁻¹ at 32 DAT	Cartap (Cidan 4G) at 0.556 kg a.i. ha ⁻¹ at 28 DAT and 48 DAT	Cartap (Cidan 4G) at 0.556 kg a.i. ha ⁻¹ at 28 DAT and 48 DAT	Sulphur (Kumulus DF) at 1.6 kg a.i. ha ⁻¹ at 45 DAP and 56 DAP (P)
2010-11	Carbofuran (Furadan 5G) at 0.5 kg a.i. ha ⁻¹ at 32 DAT	Cartap (Suntap 50SP) at 0.7 kg a.i. ha ⁻¹ at 58 DAT and 85 DAT	Cartap (Suntap 50SP) at 0.7 kg a.i. ha ⁻¹ at 53 DAT and 79 DAT	Sulphur (Kumulus DF) at 1.6 kg a.i. ha ⁻¹ at 35 DAP (P)
2011-12	Cartap (Suntap 50SP) at 0.7 kg a.i. ha ⁻¹ at 56 DAT	Cartap (Suntap 50SP) at 0.7 kg a.i. ha ⁻¹ at 55 DAT	Cartap (Suntap 50SP) at 0.7 kg a.i. ha ⁻¹ at 55 DAT	Chlorpyrifos (Dursban 20EC) at 1.47 l ha ⁻¹ at 43 DAP, sulphur (Kumulus DF) at 1.6 kg a.i. ha ⁻¹ at 27 DAP and 41

				DAP (P)
Date harvested 2009-10	24 Apr. 2010	30 Apr. 2010	1 May 2010	25 Feb. 2010 (P) 1 June 2010 (M)
2010-11	6 May 2011	4 May 2011	4 May 2011	15 Feb. 2011 (P) NA (M)
2011-12	7 May 2012	7 May 2012	6 May 2012	14 Feb. 2012 (P) 20 Apr. 2012 (Mb)
(b) Aman rice				
Cultivar	BR 11 in 2010 and BRRI dhan49 in 2011 and 2012	BRRI dhan49	BRRI dhan49	BINA 7 in 2010 and 2011, BRRI dhan56 in 2012
Seeds and seedling nursery management				
Seeds	Farmers' seeds	Certified seeds	Certified seeds	Certified seeds
Seed treatment	None	Treated with fungicide at 3 g bavistine kg ⁻¹ seed	Treated with fungicide at 3 g bavistine kg ⁻¹ seed	Treated with fungicide at 3 g bavistine kg ⁻¹ seed
Seedbed	Flat bed	Raised (improved) seedbed	In trays	Raised (improved) seedbed in 2010 and 2011. In 2012, same as scenario3
Seed rate (kg ha ⁻¹ of seedbed)	1500	1000	6739–8086	1000 in 2010 and 2011 6739–8086 in 2012
Land preparation				
Power tiller	4–5 passes	3–4 passes	1–2 passes	1–2 passes
Power tiller with wooden plank for levelling	1 pass	2 passes	None	None
Date sown on nursery				
2010	5 July	1 July	8 July	1 July
2011	26 June	24 June	14 July	30 June
2012	25 June	25 June	7 July	7 July
Date transplnted/planted				
2010	29 July	22 July	21 July	24 July
2011	6 Aug.	23 July	26 July	25 July
2012	1 Aug.	23 July	19 July	20 July
Seed rate (kg ha ⁻¹ of main field)	49	35	19	35 in 2010 and 2011, 19 in 2012
Planting density (hill m ⁻²)	20-23	25	20	25in 2010 and 2011 20in 2012
Water management	Rainfed – no irrigation applied in 2010 and 2012, irrigation applied at booting in 2011.	Supplemental irrigation applied following AWD method. No irrigation required in	Supplemental irrigation applied following AWD method. No irrigation required	Supplemental irrigation applied following AWD method. No irrigation required

		2010. In 2011 and 2012, irrigation applied at booting and flowering stage.	in 2010. Irrigation applied at early tillering, booting, and flowering stage in 2011 and at booting and flowering stage in 2012	in 2010 and 2012. Irrigation applied at booting stage in 2011.
Fertilizer use (kg ha ⁻¹)				
2010				
N-P-K-S-Zn at 0 DAT	0-0-0-0-0	0-16-16-8-2	0-16-16-8-2	0-16-16-8-2
N topdress	34 at 18 DAT 39 at 31 DAT	20 at 15 DAT 45 at 34 DAT 45 at 50 DAT	20 at 17 DAT 45 at 37 DAT 45 at 58 DAT	20 at 8 DAT 45 at 20 DAT 45 at 35 DAT
K topdress		0	0	0
2011				
N-P-K-S-Zn at 0 DAT	0-0-0-0-0	0-10-24-0-0	0-10-24-0-0	0-0-0-0-0
N topdress	34 at 23 DAT 39 at 41 DAT 0	22 at 12 DAT 51 at 45 DAT 51 at 53 DAT	22 at 12 DAT 51 at 51 DAT 51 at 62 DAT	22 at 10 DAT 51 at 45 DAT 51 at 53 DAT
K topdress	0	17 at 53 DAT	17 at 62 DAT	17 at 53 DAT
2012				
N-P-K-S-Zn at 0 DAT	0-0-0-0-0	0-10-24-0-4	0-10-24-0-4	0-10-24-0-4
N topdress	34 at 27 DAT 39 at 46 DAT	22 at 10 DAT 29 at 26 DAT 42 at 42 DAT	22 at 14 DAT 29 at 30 DAT 42 at 48 DAT	22 at 13 DAT 48 at 27 DAT 29 at 46 DAT
K topdress	0	17 at 42 DAT	17 at 48 DAT	13 at 46 DAT
Crop residue recycled from previous season (Mg ha ⁻¹)	1.5	2.2	2.6	0.3 (P) 4.3 (M)
2010	0	1.6	1.4	1.6
2011	1.6	2.0	1.9	1.6
2012				
Weed control				
Pre-emergence herbicide application (0.99 a.i. l ha ⁻¹)	0	Pendimethalin (Panida 33 EC) at 3–5 DAT 2 in all 3 years	Pendimethalin (Panida 33 EC) at 3–5 DAT 2 in 2010 3 in each of 2011 and 2012	Pendimethalin (Panida 33 EC) at 3–5 DAT 2 in each of 2010 and 2011 3 in 2012
Hand weeding (no.)	2 in 2010 1 in 2011 2 in 2012			
Insect and disease control				
Pesticide application 2010	No insecticide	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 21 DAT and Cartap at 0.556 kg a.i. ha ⁻¹ at 52 DAT	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 22 DAT and Cartap at 0.556 kg a.i. ha ⁻¹ at 55 DAT	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 18 DAT and Cartap at 0.556 kg a.i. ha ⁻¹ at 56 DAT
2011	No insecticide	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 20 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 35 DAT	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 19 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 32 DAT	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 18 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 34 DAT
	Thiamethoxam	Carbofuran at 0.5 kg	Carbofuran at 0.5	

2012	(20%) + Chloraniliprole (20%) (Virtako 40WG) at 0.015 + 0.015 kg a.i. ha ⁻¹ at 35 DAT	a.i. ha ⁻¹ at 26 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 43 DAT Tebuconazole (Folicur 25 EC) at 0.125 l ha ⁻¹ at 49 DAT	kg a.i. ha ⁻¹ at 20 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 35 DAT Tebuconazole (Folicur 25 EC) at 0.125 l ha ⁻¹ at 50 DAT	Carbofuran at 0.5 kg a.i. ha ⁻¹ at 20 DAT and Cartap at 0.7 kg a.i. ha ⁻¹ at 35 DAT Tebuconazole (Folicur 25 EC) at 0.125 l ha ⁻¹ at 50 DAT
Date harvested				
2009-10	22 Nov. 2010	14 Nov. 2010	17 Nov. 2010	26 Oct. 2010
2010-11	22 Nov. 2011	15 Nov. 2011	26 Nov. 2011	30 Oct. 2011
2011-12	11 Nov. 2012	11 Nov. 2012	17 Nov. 2012	21 Oct. 2012

Table 4

Energy equivalent of inputs and outputs used in energy calculation.

Particulars	Unit	Energy equivalent (MJ unit ⁻¹)	References
<i>A. Inputs</i>			
1. Human labor	H	0.2014	Bala and Hussain, 1992
2. Machinery	H	62.7	Erdal et al., 2007; Singh et al., 2002; Singh, 2002
3. Diesel fuel	L	56.31	Erdal et al., 2007; Singh et al., 2002, Singh, 2002
4. Chemical fertilizers	kg		
(a) Nitrogen (N)		66.14	Esengun et al., 2007; Yilmaz et al., 2005
(b) Phosphate (P)		28.5	Esengun et al., 2007; Yilmaz et al., 2005
(c) Potassium (K)		13.4	Esengun et al., 2007; Yilmaz et al., 2005
(d) Zinc (Zn)		8.4	Pimentel, 1980; Argiro et al., 2006
5. a. Granular pesticides	kg	120	Canakci et al., 2005; Mandal et al., 2002; Singh, 2002
b. Liquid pesticides	L	102	Gopalan et al., 1978; Binning et al., 1983
6. Water for irrigation	m ³	1.02	Acaroglu and Aksoy, 2005
7. Seed (maize)	kg	15.1	Gopalan et al., 1978; Binning et al., 1983
8. Seed (paddy)	kg	14.57	Bala and Hussain, 1992
9. Seed (potato tuber)	kg	3.6	
10. Seed (mungbean)	kg	25	Ozkan et al., 2004
11. Electricity	kWh	3.6	Woolley, S. Edexcel IGCSE Physis Revision Guide. Pearson Education. p. 49
<i>B. Outputs</i>			
1. Grain paddy	kg	14.57	Bala and Hussain, 1992
2. Grain maize	kg	15.1	Gopalan et al., 1978; Binning et al., 1983
3. Grain mungbean	kg	14.7	Ozkan et al., 2004
4. Potato tuber	kg	3.6	Ozkan et al., 2004
5. Rice straw /mungbean residue/maize stover/potato residue	kg	12.5	Ozkan et al., 2004

Table 5

Price of major inputs and outputs used for economic analysis.[¶]

Item	Boro rice or potato			Maize or mungbean		Aman rice		
	2009-10	2010-11	2011-12	2010	2012	2010	2011	2012
Inputs								
Farmer rice seed (US\$ kg ⁻¹)	0.39	0.42	0.46	NA	NA	0.43	0.49	0.49
Certified rice seed (US\$ kg ⁻¹)	0.58	0.63	0.57	NA	NA	0.58	0.58	0.58
Seed potato (US\$ kg ⁻¹)	0.67	0.64	0.58	NA	NA	NA	NA	NA
Maize seed (US\$ kg ⁻¹)	NA	NA	NA	2.92	NA	NA	NA	NA
Mungbean seed (US\$ kg ⁻¹)	NA	NA	NA	NA	1.14	NA	NA	NA
Nitrogen (US\$ kg ⁻¹)	0.38	0.36	0.55	0.38	NA	0.38	0.36	0.60
Phosphorus (US\$ kg ⁻¹)	1.61	1.54	1.58	NA	NA	1.59	1.53	1.81
Potassium (US\$ kg ⁻¹)	0.79	0.76	0.38	NA	NA	0.78	0.75	0.42
Sulphur (US\$ kg ⁻¹)	0.81	0.78	0.84	NA	NA	0.81	0.77	0.93
Zinc (US \$ kg ⁻¹)	6.69	6.41	5.27	NA	NA	6.64	6.37	6.17
Boron (US\$ kg ⁻¹)	13.14	12.59	9.49	NA	NA	NA	NA	NA
Bavistine (US\$ kg ⁻¹)	39.71	38.04	34.43	NA	NA	39.4	37.8	37.78
Pendimethalin (US\$ l ⁻¹)	13.28	12.73	11.52	NA	NA	13.2	12.6	12.64
Furadan 5G (US\$ kg ⁻¹)	1.94	1.86	NA	NA	NA	1.93	1.85	1.85
Cidan 4G (US\$ kg ⁻¹)	1.53	NA	NA	NA	NA	1.52	NA	NA
Kumulus (US\$ kg ⁻¹)	5.40	5.17	2.35	NA	NA	NA	NA	NA
Suntap (US\$ kg ⁻¹)	NA	20.14	17.09	NA	NA	NA		20.00
Dursban (US\$ l ⁻¹)	NA	NA	10.13	NA	NA	NA	NA	NA
Virtako (US\$ l ⁻¹)	NA	NA	NA	NA	NA	NA	NA	180.56
Diesel (US\$ l ⁻¹)	0.64	0.62	0.77	NA	NA	0.64	0.64	0.85
Octane (gasoline) (US\$ l ⁻¹)	NA	NA	NA	NA	NA	1.12	1.10	1.25
Electric power (US\$ kW ⁻¹)	0.04	0.04	0.03	0.04	NA	NA	0.04	0.04
Power tiller rent (US\$ pass ⁻¹ ha ⁻¹)	10.22	9.79	12.00	NA	NA	10.1	9.72	12.50

Wage (US\$ person d ⁻¹)	2.92	3.50	3.29	2.92	3.29	3.26	3.47	4.17
Outputs								
Rice (unhusked) (US\$ kg ⁻¹)	0.26	0.26	0.22	NA	NA	0.24	0.24	0.24
Potato (US\$ kg ⁻¹)	0.18	0.15	0.15	NA	NA	NA	NA	NA
Maize (US\$ kg ⁻¹)	NA	NA	NA	0.15	NA	NA	NA	NA
Mungbean (US\$ kg ⁻¹)	NA	NA	NA	NA	0.63	NA	NA	NA

[¶]Exchange rate (US\$ = BDT): Taka 68.50 in Boro 2009-10 and Aus 2010, Taka 69.00 in Aman 2010, Taka 71.50 in Boro 2010-11, Taka 72.00 in Aman 2011, Taka 79.00 in Boro 2011-12, and Taka 72.00 in Aman 2012.

NA, not applicable.

Table 6

Total rainfall and mean daily solar radiation during growth period of each crop in different scenarios.

Scenario	Rainfall (mm)			Solar radiation (MJ m ⁻²)		
	2009-10	2010-11	2011-12	2009-10	2010-11	2011-12
Boro rice/potato [†]						
1	49	291	233	15.78	14.72	15.07
2	50	281	234	15.78	14.09	15.12
3	50	291	234	15.79	14.27	15.03
4	0	50	12	10.89	11.54	10.77
Maize/mungbean [‡]						
1	NA [§]	NA	NA	NA	NA	NA
2	NA	NA	NA	NA	NA	NA
3	NA	NA	NA	NA	NA	NA
4	281	517	199	15.83	14.86	15.45
Aman rice						
1	788	1006	490	13.34	13.65	13.45
2	788	1006	599	13.62	13.86	13.62
3	788	1006	630	13.56	13.71	13.74
4	788	1006	474	13.63	14.00	13.81

[†]In scenario 4, the value is for potato.

[‡]In 2009-10 and 2010-11, the values are for maize and in 2011-12 the values are for mungbean.

[§]NA, not applicable.

Table 7

Grain yields of Boro rice and Aman rice and rice equivalent yields (REY) of potato, maize, and mungbean, and cropping system in different scenarios.

Scenario	Boro rice or REY of potato [†] (Mg ha ⁻¹)	REY of maize or mungbean [€] (Mg ha ⁻¹)	Aman rice (Mg ha ⁻¹)	REY of cropping system (Mg ha ⁻¹)
2009-10				
1	5.1 c [‡]	NA	4.3 b	9.4 c
2	6.6 b	NA	5.1 a	11.7 b
3	6.5 b	NA	5.0 ab	11.5 b
4	9.9 a (17.3) [§]	5.2 ^μ (9.2) [£]	4.8 ab	20.0 a
2010-11				
1	4.9 c	NA	3.5 c	8.4 b
2	6.0 b	NA	5.2 a	11.2 a
3	5.8 b	NA	5.1 a	11.0 a
4	7.1 a (17.7) [§]	0.0 [*]	4.5 b	11.6 a
2011-12				
1	4.9 c	NA	3.6 b	8.5 c
2	5.6 b	NA	5.3 a	10.9 b
3	5.6 b	NA	4.9 a	10.5 b
4	8.4 a (14.8) [§]	2.1 ^f (0.7) [¥]	4.8 a	15.4 a

[†]In scenario 4, the value is the REY of potato.

[‡]Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[€]NA, not applicable.

[§]Value in parentheses is actual yield of potato.

^μREY of maize.

[£]Value in parentheses is actual yield of maize.

^fREY of mungbean.

[¥]Value in parentheses is actual yield of mungbean.

^{*}No yield from maize as maize failed to grow due to waterlogging at 80–85 days after planting as a result of heavy rainfall.

Table 8

Irrigation water and total water (irrigation + rainfall) inputs during growing period of crops and cropping system in different scenarios.

Scenario	Irrigation water (mm)				Total water (mm)			
	Boro rice or potato [†]	Maize or mungbean	Aman rice	Cropping system	Boro rice or potato [†]	Maize or mungbean [€]	Aman rice	Cropping system
2009-10								
1	1247 a [‡]	NA [€]	0	1247 a	1296 a	NA	788	2084 a
2	951 a	NA	0	951 a	1001 b	NA	788	1789 ab
3	1060 a	NA	0	1060 a	1110 ab	NA	788	1898 a
4	202 b	155 [§]	0	357 b	202 c	436 [§]	788	1426 c
2010-11								
1	819 a	NA	56 b	875 a	1110 a	NA	1062 a	2172 a
2	599 b	NA	61 ab	660 b	880 b	NA	1067 a	1946 b
3	593 b	NA	111 a	704 b	884 b	NA	1117 b	2001 b
4	130 c	0.0 [§]	50 b	180 c	180 c	517 [§]	1056 a	1186 c
2011-12								
1	727 a	NA	0 b	727 a	960 a	NA	490 b	1450 b
2	578 b	NA	70 a	648 b	812 b	NA	669 a	1481 b
3	599 b	NA	67 a	666 b	833 b	NA	697 a	1530 a
4	120 c	0 [£]	0 b	120 c	132 c	199 [£]	474 b	805 c

[†]In scenario 4, the value is for potato.

[‡]Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[€]NA, not applicable.

[§]Value for maize.

[£]Value for mungbean.

Table 9

Irrigation water productivity (WP_I) and total water (irrigation + rainfall) productivity (WP_{I+R}) based on rice equivalent yield (REY) of crop and cropping system in different scenarios.

Scenario	WP_I (kg grain m^{-3} of water)				WP_{I+R} (kg grain m^{-3} of water)			
	Boro rice or potato [†]	Maize or mungbean	Aman rice	Cropping system	Boro rice or potato [†]	Maize or mungbean	Aman rice	Cropping system
2009-10								
1	0.4 b [‡]	NA [€]	NA	0.8 b	0.4 b	NA	0.5 c	0.5 c
2	0.7 b	NA	NA	1.2 b	0.7 b	NA	0.7 a	0.7 b
3	0.6 b	NA	NA	1.1 b	0.6 b	NA	0.6 abc	0.6 b
4	4.9 a (8.7) [§]	3.4 ^μ (5.9) [£]	NA	5.6 a	4.9 a (8.7) [§]	1.2 ^μ (5.9) [£]	0.6 abc	1.4 a
2010-11								
1	0.6 c	NA	6.3 bc	1.0 c	0.4 b	NA	0.3 c	0.4 c
2	1.0 b	NA	8.8 ab	1.7 b	0.7 b	NA	0.5 a	0.6 b
3	1.0 b	NA	5.0 c	1.6 b	0.7 b	NA	0.5 a	0.5 b
4	5.5 a (13.6) [§]	0.0	9.1 a	6.5 a	3.9 a (9.7) [§]	NA	0.4 b	1.0 a
2011-12								
1	0.7 b	NA		1.2 b	0.5 b	NA	0.7 b	0.6 c
2	1.0 b	NA	8.8 a	1.7 b	0.7 b	NA	0.8 b	0.7 b
3	0.9 b	NA	7.5 a	1.6 b	0.7 b	NA	0.7 b	0.7 b
4	7.1 a (14.2) [§]	NA		12.9 a	6.4 a (12.8) [§]	1.1 ^f (0.4) [¥]	1.0 a	1.9 a

[†]In scenario 4, the value is based on REY of potato.

[‡]Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[€]NA, not applicable.

[§]Value in parentheses is based on actual yield of potato.

^μValue is based on REY of maize.

[£]Value in parentheses is based on actual yield of maize.

^fValue is based on REY of mungbean.

[¥]Value in parentheses is based on actual yield of mungbean.

Table 10

Total variable cost (US\$ ha⁻¹) for crop and cropping system in different scenarios.

Scenario	Boro rice or potato [†]	Maize or mungbean	Aman rice	Cropping system
2009-10				
1	1134 b [‡]	NA [€]	782 c	1916 b
2	1078 b	NA	886 a	1964 b
3	1095 b	NA	801 bc	1896 b
4	2397 a	808 [§]	855 ab	4059 a
2010-11				
1	1064 b	NA	719 b	1782 bc
2	1037 b	NA	863 a	1900 b
3	1001 b	NA	735 b	1735 c
4	2400 a	0 (341)£	740 b	3140 a
2011-12				
1	928 b	NA	680 c	1608 c
2	924 b	NA	976 a	1900 b
3	908 b	NA	748 b	1656 c
4	2030 a	283 ^μ	755 b	3068 a

[†]In scenario 4, the value is for potato.

[‡]Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[€]NA, not applicable.

[§]Value is for maize.

^μValue is for mungbean.

£ Total variable cost (seed fertilizers and crop establishment) of maize, which not included in analysis

Table 11

Gross return, net return, and benefit:cost ratio (BCR) for crop and cropping system in different scenarios.

Scenario	Gross return (US\$ ha ⁻¹)	Net return (US\$ ha ⁻¹)	BCR
	Boro rice/potato [†]		
1	1225 c [‡]	183 b	1.2 b
2	1500 b	487 a	1.5 a
3	1478 b	477 a	1.5 a
4	2667 a [§]	392 a [§]	1.2 b [§]
	Maize or mungbean ^μ		
4	1340 [£]	532 [£]	1.7 [£]
4	0.0 [*]	0.0 [*]	0.0 [*]
		(-341) ^f	
4	468 [¥]	185 [¥]	1.7 [¥]
	Aman rice [†]		
1	882 c	156 c	1.2 c
2	1223 a	315 b	1.4 b
3	1184 ab	423 a	1.6 a
4	1107 b	323 b	1.4 b
	Cropping system		
2009-10			
1	2312 c	396 b	1.2 b
2	2929 b	966 ab	1.5 a
3	2892 b	996 ab	1.5 a
4	5545 a	1486 a	1.4 a
2010-11			
1	2128 c	346 b	1.2 b
2	2833 b	933 a	1.5 a
3	2781 b	1046 a	1.6 a
4	3817 a	677 ab	1.2 b
		(336) [¶]	
2011-12			
1	1882 c	274 c	1.2 c
2	2407 b	507 b	1.3 b
3	2314 b	658 ab	1.4 a
4	3766 a	699 a	1.2 c

[†]Values are the means of 3 years.

[‡]Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[§]Value is for potato.

^μValue is for one year.

[£]Value is for maize in first year.

* Value is for maize in second year.

‡ Value is for mungbean in third year.

^f Value for maize is negative as crop failed to grow

[¶] Cropping system net return when negative net return of maize considered in calculation

Table 12

Energy input, specific energy, and energy use efficiency of crops and cropping systems in different scenarios.

Scenario [¶]	Energy input (MJ ha ⁻¹)				Specific energy (MJ kg ⁻¹)			
	Boro rice or potato [†]	Maize or mungbean	Aman rice	Cropping system	Boro rice or potato	Maize or mungbean	Aman rice	Cropping system
2009-10								
1	35834 a [‡]	NA [€]	10541 d	46374 b	7.1 a	NA	2.5 b	5.0 a
2	33325 a	NA	17086 b	50411 ab	5.1 b	NA	3.3 a	4.3 b
3	32337 a	NA	18459 a	50796 ab	5.0 b	NA	3.7 a	4.4 ab
4	33327 a	8471 [§]	11852 c	53650 a	1.9 c	0.9 [§]	2.5 b	1.7 c
2010-11								
1	29782 b	NA	12896 c	42679 c	6.1 a	NA	3.7 b	5.1 a
2	28779 b	NA	17606 b	46385 b	4.8 b	NA	3.4 bc	4.2 b
3	25534 c	NA	24010 a	49544 a	4.4 b	NA	4.7 a	4.5 b
4	31398 a	0 [§]	13514 c	44912 b	1.8 c	0 [§]	3.0 c	2.0 c
2011-12								
1	26791 b	NA	10056 c	36847 c	5.4 a	NA	2.8 a	4.3 a
2	25224 c	NA	16441 a	41338 b	4.5 b	NA	3.0 a	3.8 b
3	24679 c	NA	16376 a	41055 b	4.4 b	NA	3.3 a	3.9 b
4	28502 a	1238 ^μ	15185 b	44925 a	1.9 c	1.7 ^μ	3.2 a	2.2 c

[¶] Refer to Table 2 and Table 3 for description of scenarios.

[†] Under Boro rice/potato, the values in scenario 4 are for potato.

[‡] Means within a column for each year followed by the same letter are not different at 0.05% level using Tukey's Studentized Range test.

[€] NA, not applicable.

[§] Value is for maize.

^μ Value is for mungbean.

Fig. 1

Monthly total rainfall and monthly average maximum and minimum temperatures during three cropping years, 2009-10, 2010-11, and 2011-12.