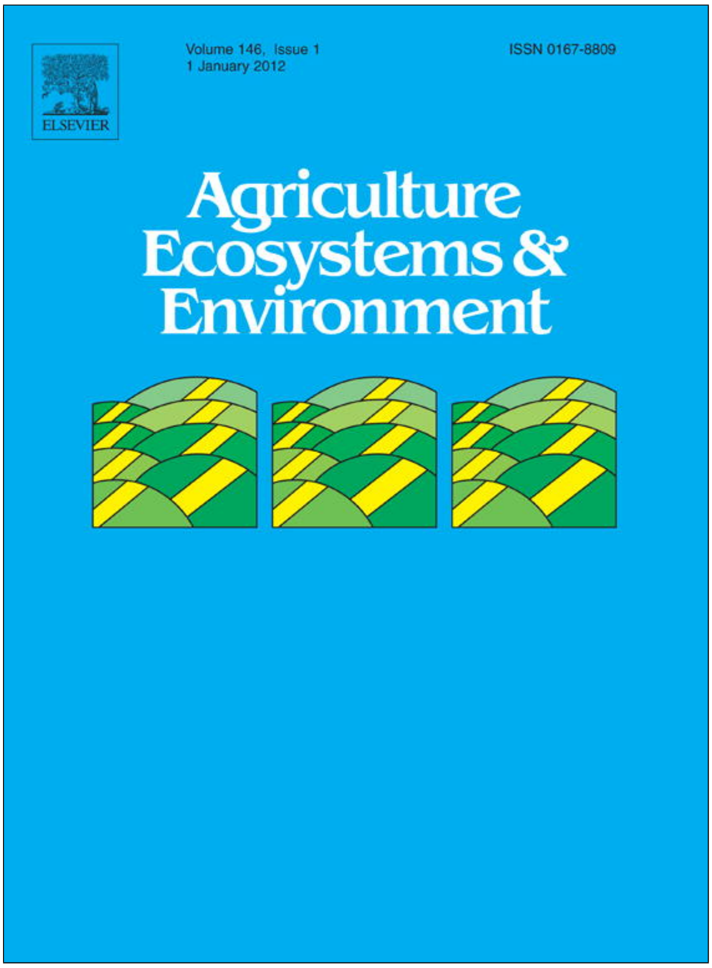

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Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic Plains of India

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ABSTRACT

Increasing scarcity of resources (labour, water, and energy) and cost of production, along with climate variability, are major challenges for the sustainability of rice–wheat system in the northwesten Indo-Gangetic Plains (IGP). We hypothesized that adopting the principles of conservation agriculture together with best crop management practices would improve system productivity and overall efficiency, resulting in a higher profitability. To test this hypothesis, we evaluated the performance of four cropping system scenarios (treatments), which were designed to be adapted to current and future drivers of agricultural changes. The treatments including farmers practices varied in tillage and crop establishment methods, residue management, crop sequence, and crop management. Zero-tillage direct-seeded rice (ZT-DSR) with residue retention and best management practices provided equivalent or higher yield and 30–50% lower irrigation water use than those of farmer-managed puddled transplanted rice (CT-TPR). Overall, net economic returns increased up to 79% with a net reduction in production cost of up to US\$ 55 ha^{-1} in ZT-DSR than CT-TPR. Substituting rice with ZT maize was equally profitable but with 88–95% less irrigation water use. Avoiding puddling in rice and dry tillage in maize with residue retention increased yield (by 0.5–1.2 t ha^{-1}) and net economic returns of the succeeding wheat crop. Inclusion of mungbean in the rotation further increased system productivity and economic returns. In summary, our initial results of 2-year field study showed positive effects of CA-based improved management practices on yield and system efficiencies with greater benefits in the second year. There is a need of longer term monitoring to quantify cumulative effects of various interventions and to eventually make recommendations for wider dissemination.

1. Introduction

The Indo-Gangetic Plains (IGP) of South Asia are home to nearly one billion people, about 40% of whom live in extreme poverty (Balasubramanian et al., 2012). In the Indian IGP, rice–wheat (R–W) is the dominant cropping system, occupying about 10.3 mha and accounts for 23% and 40% of India's total rice and wheat area, respectively (Ladha et al., 2003). In this system, rice is grown during the rainy summer season (*kharif*) from June to October and wheat during the dry winter season (*rabi*) from November to March/April. The land generally remains fallow between the harvest of wheat and planting of rice.

Rice is predominantly grown by transplanting seedlings into puddled (conventional wet-tillage) soil (CT-TPR) and is continuously flooded for much of the growing season. The soil is puddled to achieve good crop establishment, weed control, and to reduce deep percolation losses (Sanchez, 1973; Sharma et al., 2003). However, this requires large amounts of labour, water, and energy, which are gradually becoming scarce and more expensive, thus reducing the profitability and system sustainability. The CT-TPR is also a major contributor to global methane (a potent greenhouse gas) emissions (Mosier et al., 1998). Moreover, puddling has adverse effects on

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the productivity of the succeeding wheat crop through its negative impacts on soil structure for wheat (see for review Gathala et al., 2011b; Kumar and Ladha, 2011; Sharma et al., 2003). A yield decline of 8–9% has been observed in wheat when grown after puddled rice compared with non-puddled rice (Gathala et al., 2011a; Kumar and Ladha, 2011).

Similarly, conventional land preparation for wheat production is also intensive, involving several passes of discs and/or tine harrows and plankings to create a friable seedbed. Intensive tillage leads to a long turnaround period, often delaying wheat planting, with a yield loss of 15–60 kg ha^{-1} day^{-1} if delayed beyond mid-November (Pathak et al., 2003).

Rice and wheat in northwestern India is mostly harvested by large combine harvesters (Gajri et al., 2002). Following harvest, rice residue is partly or fully burnt to avoid incorporation which requires additional tillage. This results in 2–3 weeks delay in crop sowing to avoid N deficiency due to N immobilisation (Thuy et al., 2008; Singh et al., 2004). On the other hand, the wheat residue is removed to use as animal feed and sometimes partly burnt (Gajri et al., 2002). Residue burning results in (a) losses of C (almost 100%) and nutrients (90% N, 60% S and 25% of each of P and K) (Dobermann and Fairhurst, 2002), and (b) emissions of greenhouse gasess (annual emissions of 110, 2306, 2, and 84 Gg of CH_4, CO, N_2O, and NO_x, respectively; Gupta et al., 2004).

In addition to the large inefficiencies, the conventional rice–wheat system is faced with widespread yield stagnation or decline which resulting in a serious threat to the sustainability of this important crop rotation (Ladha et al., 2003). Projections indicate that production of rice, wheat, and maize will have to increase by about 1.1%, 1.7%, and 2.9% per annum, respectively, over the next four decades to ensure food security in South Asia. To meet the increasing cereal demand, there is a need of crop intensification while increasing resource-use efficiency and reducing the environmental footprint, or ‘ecological intensification’ (Cassman, 1999; Ladha et al., 2009). Achieving this will require a holistic system approach, incorporating the principles of conservation agriculture (CA), and judicious crop rotation (Balasubramanian et al., 2012).

During the last few years, several component technologies of CA such as reduced or zero tillage (ZT), dry drill seeding of rice (DSR), and rice residue retention have been evaluated in cereal systems (Gathala et al., 2011a,b; Ladha et al., 2009; Kumar et al., 2013b). Zero-till wheat has been adopted on a significant area in the R–W system in the northwestern IGP (Harrington and Hobbs, 2009) with positive impacts on wheat yield, profitability, and resource-use efficiency (Erenstein and Laxmi, 2008; Ladha et al., 2009). Unlike wheat, rice continues to be almost entirely grown by the conventional practice of CT-TPR. Also, crop residues continue to be either burned or removed both in rice and wheat. To harness the full potential of CA, not only residue will have to be used as soil surface mulch but also rice will have to be brought under zero tillage. Surface residue retention provides multiple benefits, including soil moisture conservation, suppression of weeds, and improvement in soil organic matter and soil structure (Singh et al., 2011a; Kumar et al., 2013a; Verhulst et al., 2011; Singh et al., 2005). The development of the “Happy Seeder” has now made it possible to sow wheat successfully into heavy loads of loose and anchored rice residues (Sidhu et al., 2008). Recently, interest has been rapidly increasing in non-ponded direct seeded rice (dry-DSR), due to increasing labor scarcity, energy constraint, and rising input costs (Kumar et al., 2013a; Kumar and Ladha, 2011).

In the future, in addition to shifting to CA based improved practices, there is a need to explore other crops in the traditional cereal based rotation. For example, if labour and water continue to become scarcer, a maize–wheat cropping system could be a potential alternative to the rice–wheat rotation. Likewise, driven by the need to maximise land and water productivity, other changes such as superior management practices and inclusion of legumes in the cropping system will be needed.

Table 1
Initial soil characteristics (0–15-cm soil depth) of CSISA Research Platform site, CSSRI, Karnal, India.

Soil properties	Soil sampling depth Mean ± SE
Clay (%)	19.89 ± 0.50
Silt (%)	46.07 ± 0.76
Sand (%)	34.03 ± 0.77
Soil texture	Loam
pH (1:1 soil:water)	8.00 ± 0.02
EC (dS m^{-1}) (1:1 soil:water)	0.37 ± 0.02
Total carbon (%)	0.56 ± 0.01
Available P (mg kg^{-1})	5.74 ± 0.29
Exchangeable K (mg kg^{-1})	130 ± 1.73
TN (%)	0.06 ± 0.002
Particle density (g cm^{-3})	2.57 ± 0.01

Therefore, we designed and established large-scale production-level experimental research platforms to (1) assess the performance (short- to long-term) of different cereal-based cropping systems within key scenarios of agricultural change, using a wide range of indicators (e.g. yield; resource-use efficiency; crop, soil, and environmental health; economics; and energy), and (2) refine and parameterise simulation models for assessing key future cropping system scenarios and technology options. The platforms were established at four locations in India and Bangladesh as part of the comprehensive Cereal Systems Initiative for South Asia (CSISA) project. This paper presents the performance of four cereal cropping systems during the first two years at Karnal, northwestern India, in relation to yield, water use, water productivity, and economics.

2. Materials and methods

2.1. Experimental site

The study was conducted at the CSISA experimental research platform located at the Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India (29°70′N, 76°96′E). A production-scale long-term trial with cropping systems adapted to four different scenarios was established in 2009 with an expected time frame of at least 10 years. The climate of the area is semi-arid, with average annual rainfall of 700 mm (75–80% of which is received during June–September), daily minimum temperature of 0–4 °C in January, daily maximum temperature of 41–44 °C in June, and relative humidity of 50–90% throughout the year. Seasonal weather data including rainfall, evaporation rate, minimum and maximum temperature, and solar radiation during the first two years are presented in Fig. 1. The site was under a continuous R–W system for many years before the establishment of the experimental platform. The experimental site is a reclaimed alkali loam soil. The initial soil characteristics of the site are given in Table 1.

In May 2009, before the start of the experiment, the entire experimental area was leveled (zero gradient) using a laser-equipped drag scraper (Trimble^{TM}, USA) with an automatic hydraulic system powered by a 60-HP tractor. After levelling, the experimental area was divided into 12 permanent plots separated by earthen bunds about 1.0 m wide and 0.20 m high. Puddled transplanted rice (as a uniformity crop) was grown in all plots during July–October 2009 to check for and promote site uniformity. The crop was very even across the entire 2.4-ha site. The cropping system treatments commenced with the 2009–2010 wheat season after harvest of the uniformity rice crop.

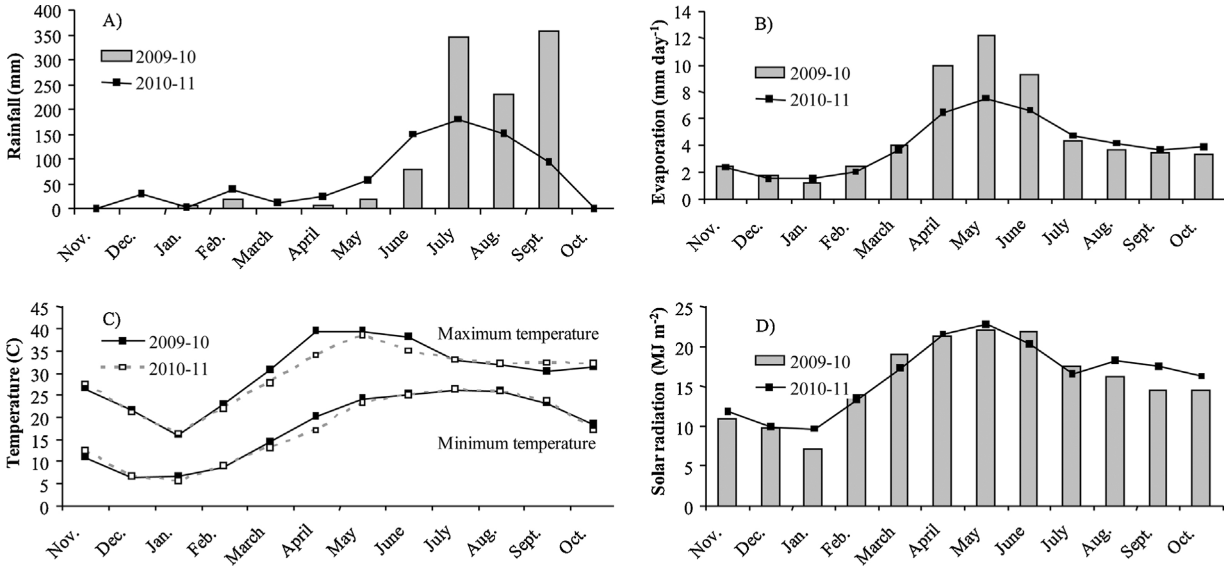

Fig. 1. Monthly rainfall (A), monthly mean daily pan evaporation (B), monthly average daily maximum and minimum temperature (C), and monthly mean daily solar radiation (D) during study years 2009–2010 and 2010–2011.

2.2. Experimental details and management

Four cropping system treatments (scenarios) varying in crop sequence, tillage, establishment method, residue management, and other management practices were evaluated during 2009–2010 and 2010–2011. Each scenario was replicated thrice in production-scale plots, each of 2000 m^2 size (20 m × 100 m), in a randomized complete block design. The scenarios were designed based on different drivers of agricultural change and were assigned to individual plots for the long term. A summary of the drivers of change and the scenarios designed to address them is provided in Table 2, while Table 3a and b provides details of crop management practices within each scenario.

2.2.1. Scenario 1 (business as usual)

This scenario is based on current farmer practices of crop rotation and management (Table 2). Forty farmers were surveyed from 10 to 12 surrounding villages in 2009–2010 and 2010–2011 prior to the rice and wheat seasons to make an inventory of their practices. Rice–wheat–fallow was the rotation in this scenario because this is the dominant cereal cropping system in the region. The rice was grown by transplanting rice seedlings in puddled soil,

Table 2
Drivers of agricultural change, crop rotation, tillage, crop establishment method, and residue management of the four scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Business-as-usual	Integrated crop and resource management	Conservation agriculture (CA)-based systems	Futuristic and diversified systems based on principles of CA
Drivers of change	None	The need to increase cereal production and farmers' income	The need to increase cereal production and income in the face of increasing scarcity of water, labour, and energy, and soil degradation	The need to diversify and increase cereal production and income in the face of increasing scarcity of labour and energy, and soil degradation, and even greater water scarcity and food demand
Approach	Current farmers' practice	By intensification and best management practices	By intensification, best management practices, including zero tillage and residue retention	By intensification, best management practices, including zero tillage and residue retention, and diversifying by replacing rice with maize
Crop rotation	Rice–wheat	Rice–wheat–mungbean	Rice–wheat–mungbean	Maize–wheat–mungbean
Tillage	Conventional till Rice-puddling Wheat-conventional till	Conventional/zero till Rice-puddling Wheat-zero till Mungbean-zero till	Zero till Rice-zero till Wheat-zero till Mungbean-zero till	Zero till Maize-zero till Wheat-zero till Mungbean-zero till
Crop establishment method	Rice-transplanting Wheat-broadcasting	Rice-transplanting Wheat-drill seeding Mungbean-drill/relay broadcasting	Rice-drill seeding Wheat-drill seeding Mungbean-drill/relay broadcasting	Maize-drill seeding Wheat-drill seeding Mungbean-drill/relay broadcasting
Residue management	All residue removed	Partial rice residue (anchored) retained; partial wheat residue (anchored); full mungbean residues incorporated during puddling for rice	Full (100%) rice and mungbean; partial (anchored) wheat residue retained on soil surface	Full (100%) maize and mungbean; partial (anchored) wheat residue retained on soil surface

Table 3

(a) Field operations and crop management details for wheat under different scenarios during 2009–2010 and 2010–2011. (b) Field operations and crop management details for rice/maize under different scenarios during 2010 and 2011.

(a) Activitiy/operation	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cultivar	PBW 343	DBW 17	DBW 17	DBW 17
Field preparation	Harrowing (2 passes) and cultivator (2 passes) followed by wooden planking	ZT	ZT	ZT
Crop establishment				
Date of sowing	19 Nov. 2009 and 14 Nov. 2010	18 Nov. 2009 and 13 Nov. 2010	17 Nov. 2009 and 31 Oct. 2010	17 Nov. 2009 and 31 Oct. 2010
Seed rate (kg ha^{-1})	125	100	100	100
Seed treatment	Similar in all scenarios, i.e., raxil 2 DS (tebuconazole) at 1 g kg^{-1} seed			
Sowing method	Manual broadcast, then seeds mixed in the soil using rotavator	Drill (line sowing)	Drill (line sowing)	Drill (line sowing)
Row spacing (cm)	Random	22	22	22
Nutrient management	Basal: 125 kg ha^{-1} DAP at sowing; Topdressing: urea was applied in two splits manually at 150 and 125 kg ha^{-1} at first and second irrigation coinciding with crown root initiation (CRI) and maximum tillering	Basal: 200 kg ha^{-1} NPK (12:32:16) was drilled at sowing; Topdressing: urea was applied in 2 splits manually at 150 and 125 kg ha^{-1} at first and second irrigation as in scenario 1	Same as in scenario 2	Same as in scenario 2
Weed management	Same in all scenarios. In first year, pre-mixed herbicide sulfosulfuron + metsulfuron 32 g ai ha^{-1} was applied at 35 DAS. In second year, tank mixture of clodinafop-ethyl + metsulfuron 60 + 4 g ai ha^{-1} was applied at 35 DAS			
Water management	Similar in all scenarios. Irrigation was applied at the critical growth stages, including CRI, tillering, jointing, flowering, milk, and grain filling			
Pest management	No pesticide was applied in first year and tebuconazole (Tilt) was applied to prevent yellow rust at 107 DAS	Tebuconazole was applied to prevent yellow rust in both years. To protect from insects, one application of quinalphos was made in year 1 and of monocrotophos in year 2	Same as in scenario 2	Same as in scenario 2

(b) Activity/operation	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cultivar	Pusa-44	Arize-6444	Arize-6129	NK-6240
Field preparation	Harrowing (×2), cultivators (×2), followed by wooden planking. Puddling done using harrow (×2), followed by planking	Mungbean was killed by paraquat and then puddling was done using a harrow (×3), followed by planking	ZT (paraquat was used to kill mungbean and existing weeds)	ZT (paraquat was used to kill mungbean and existing weeds)
Crop establishment				
Date of sowing/transplanting	6 July 2010 and 2011	28 June 2010 and 2011	18 June 2010 and 10 June 2011	6 July 2010 and 7 June 2011
Seed rate (kg ha^{-1})	15	12	28	22
Seed treatment	Raxil 60 FS (tebuconazole) + Guicho 600 FS (imidacloprid) at 1 + 2 ml kg^{-1}	Same as in scenario 1	Same as in scenario 1	Guicho 600 FS (imidacloprid) at 5 ml kg^{-1}
Method	Transplanting	Transplanting	Drill (line sowing)	Drill (line sowing)
Spacing (cm)	Random	20 × 15	22 cm	60 × 20
Seedling age (days)	35	25	Not available	Not available
Nutrient management	Basal at the time of transplanting: 125 kg DAP ha^{-1} and 25 kg zinc sulphate ha^{-1} Topdressing: 330 kg urea ha^{-1} was applied in three equal splits at early establishment (7–10 DAT), active tillering (21–25 DAT), and panicle initiation stage (45–50 DAT)	Basal at the time of transplanting: 125 kg DAP ha^{-1}, 100 kg MOP ha^{-1}, and 25 kg zinc sulphate ha^{-1} Topdressing: 280 kg urea ha^{-1} was applied in three equal splits at early establishment (7–10 DAT), active tillering (21–25 DAT), and panicle initiation stage (45–50 DAT)	Basal: 200 kg NPK (12:32:16) was drilled at sowing + 50 kg MOP ha^{-1}. 25 kg zinc sulphate ha^{-1} applied at 7–10 DAS. Urea topdressing: 300 kg urea ha^{-1} was applied in three splits at 50 kg ha^{-1} at early establishment (15 DAS) and at 125 kg ha^{-1} each at active tillering (25 DAS) and panicle initiation (45–55 DAS)	Basal: 200 kg NPK drilled at sowing + 65 kg MOP. Urea topdressing: 325 kg urea ha^{-1} applied in three splits at 125 kg ha^{-1} each at 20 and 45 DAS and at 75 kg ha^{-1} at tasseling/silking stage
Water management	Continuous flooding of 5-cm depth for 1 month, followed by irrigation applied at hair-line crack (Gathala et al., 2011a)	Continuous flooding of 5-cm depth for first 15–20 days after transplanting 'fb' irrigation at −40 to −50 kPa matric potential at 15-cm depth till 1 wk before flowering 'fb' irrigation at −15 to −20 kPa	Kept soil wet for first 20 days 'fb' irrigation at −20 to −30 kPa matric potential	Applied 2–3 irrigations on need basis
Weed management	Butachlor at 1000 g ai ha^{-1} at 1 DAT + 1 hand weeding to remove escaped weeds	Same as in scenario 1	Oxadirgyl 90 g ai ha^{-1} or pendimethalin at 1000 g ai ha^{-1} as PRE at 2–3 DAS 'fb' azimsulfuron at 35 g ai ha^{-1} or fenoxaprop with safener + ethoxysulfuron 90 + 18 g ai ha^{-1} as POST at 20–25 DAS. One hand weeding was done to remove escaped weeds	Atrazine was applied either as PRE at 625 g ai ha^{-1} at 1 DAS in first year or as POST application at 11 DAS in year 2. 1 hand weeding to remove escaped weeds

whereas wheat was sown by broadcasting seeds manually in conventionally tilled fields. About 30- to 35-day-old seedlings of a popular rice variety (Pusa 44) were randomly (1–2 seedlings hill^{-1}) transplanted manually. In the region, farmers generally burn rice residues *in situ* before wheat sowing. However, in our study, the rice residues were removed at ground level instead of burning to avoid risks of accidental burning of residue-retained treatments. Similarly, the aboveground wheat residues were completely removed prior to land preparation for rice, as much of the wheat straw is used for fodder.

2.2.2. Scenario 2 (best integrated crop and resource management)

This scenario was designed to increase productivity and income through intensification (more crops per year) and best management practices. Instead of the R–W in scenario 1, rice–wheat–mungbean was the rotation in this scenario (Table 2). Drill sown wheat was established in non-tilled soil with partial rice residue retention (anchored rice stubbles about 30 cm high); mungbean, in the first year, was sown by a ZT drill after the wheat harvest with partial wheat residue retention (anchored wheat stubble about 15 cm high), but, in the second year, mungbean was relay-sown by manual broadcasting about 2 weeks before the wheat harvest; the mungbean was followed by puddled transplanted rice, with the mungbean (and remaining rice and wheat) residue fully incorporated into the soil during puddling. About (1–2 seedlings hill^{-1}) 20–25-day-old seedlings of a hybrid rice variety were transplanted in lines with 20-cm row spacing and 15-cm plant spacing. Recommended management practices were used for all crops.

2.2.3. Scenario 3 (conservation agriculture rice-based system)

This scenario was designed to deal with the increasing scarcity and/or cost of water, labour, and energy; rising input costs; and soil and environmental degradation, while increasing productivity and income (Table 2). In this scenario, the crop sequence was as for scenario 2 (rice–wheat–mungbean) but all crops were grown under ZT. Wheat was drilled into full rice residue; mungbean was drill-seeded during the first year and relay-sown by broadcasting in the second year as in scenario 2; rice was dry drill seeded into the mungbean residues (and remnant rice and wheat straw) after killing them with paraquat (a non-selective herbicide).

2.2.4. Scenario 4 (near futuristic and diversified cropping systems based on the principles of CA)

This scenario was designed to evaluate a near futuristic and diversified cereal-based cropping system as an alternative to a rice-based system to deal with the same issues as scenario 3, but with even greater water scarcity and food demand (Table 2). In this scenario, maize replaced rice, in a maize–wheat–mungbean rotation. All crops were grown under ZT, with partial or full residue retention. Mungbean was drill-seeded after the wheat harvest (first year) or relayed with wheat (in the second year) as in scenarios 2 and 3. In terms of residue management, in the first year, wheat was drilled-seeded in full rice residues (following harvest of the uniformity rice crop), whereas, in the second year, wheat was drilled-seeded with full maize residue retention. Residue management of wheat and mungbean was similar to that in scenario 3.

Crop management including land preparation, variety, seed rate, sowing time, seed treatment, fertilizer management, water management, and pest management for rice, wheat, and maize under each scenario is provided in Table 3a and b. Wheat was broadcast manually in conventionally tilled soil in scenario 1, whereas, in all other scenarios, the wheat was sown using a Turbo Happy Seeder, a zero-till seed-cum-fertilizer drill that can place both seeds and fertilizer in the soil in the presence of heavy loose and anchored crop residues (Sidhu et al., 2007, 2008). Rice was manually transplanted in scenarios 1 and 2, and drill-seeded in scenario 3 using the Turbo Happy Seeder. The Happy Seeder rotors (for straw chopping) were operated only when sowing the wheat in full rice or maize residues (scenarios 3 and 4), and when sowing the rice in mungbean residues (scenario 3). Maize in scenario 4 was planted with a zero-till multi-crop planter fitted with an inclined plate seed-metering system.

For mungbean, a 65-day-duration cultivar (SML-668) was used to fit in the short period between wheat harvest and rice planting. In the first year, mungbean was drill-seeded at 25 kg ha^{-1} on 24 April 2010, after wheat harvest, using the Turbo Happy Seeder, whereas, in the second year, it was manually broadcast at 30 kg seed ha^{-1} at the time of the last wheat irrigation (about 15 days before wheat harvesting) on 28 March 2011. When mungbean was drill-seeded after the wheat harvest in the first year, there was not enough time for the crop to mature in scenarios 3 and 4 as the succeeding DSR and maize needed to be sown about 15–20 days earlier than the date of rice transplanting in scenario 2. The use of relay sowing in year 2 allowed enough time for the mungbean to mature in all scenarios as it advanced the time of mungbean sowing. The mungbean did not receive any fertilizer or pesticide. At harvest, the mungbean was killed with paraquat (500 g ai ha^{-1}), a non-selective herbicide, and the mungbean pods were manually picked and threshed.

2.3. Residue management and estimation of crop residue recycling in the soil

After wheat harvest, all the loose residues were removed and only the anchored wheat stubbles were retained in all scenarios except scenario 1, in which all wheat (and rice) residues were removed from the plots. In the case of rice, all loose rice residues were removed and only the anchored stubbles were retained in scenario 2, but, in scenario 3, all the rice residues were retained on the soil surface. In scenario 4, the maize cobs were collected manually and all the stover was left standing in the field. Following the sowing of wheat into the maize residues using the Turbo Happy Seeder, all the residues were lying on the soil surface. The amount of crop residue either retained on the soil surface or incorporated in the soil (scenario 2) was determined by sampling five rows to a length of 1 m from four locations in each plot and was expressed as oven dry weight of residue per hectare.

2.4. Soil sampling and analysis

Before imposing the experimental treatments (after the harvest of the uniformity rice crop), baseline soil samples were collected from 0–15- to 15–30-cm soil depths using an auger of 5-cm diameter. For soil sampling, each plot was divided into four using a 10 m × 50-m grid. Within each grid cell, soil was collected from nine locations and composited depth-wise. The soil samples were air-dried in the shade, ground to pass through a 2-mm sieve, stored in plastic jars, and sent to the laboratory for physico-chemical analysis. The soil samples were analysed for pH, electrical conductivity (EC), total carbon (TOC SSM Analyzer Shimadzu), total N (TOC TN Analyzer Shimadzu), Olsen P (0.5 M $NaHCO_3$ extractable), and 1N neutral NH_4OAc extractable K (by emission spectrophotometry). Particle size distribution was determined using the hydrometer method (Bouyoucos, 1962). The textural class was determined by the United States Department of Agriculture (USDA) system.

2.5. Crop harvest and yield and yield parameter estimation

At crop maturity, the wheat was harvested either by combine or with a reaper and binder machine (BCS India Pvt. Ltd., Ludhiana) at about 15 cm above ground level in all scenarios except scenario 1, in which the wheat was harvested from ground level. The grains were threshed using a plot thresher. Similarly, rice was harvested by cutting at a height of 30 cm (scenario 2) or at the soil surface (scenario 1) and threshed either manually or using a combine. In scenario 3, the rice was harvested at ground level (because the crop was lodged at maturity) and threshed manually. The maize cobs were harvested manually and threshed using a maize sheller. Grain and straw yields of both rice and wheat were estimated by manually harvesting a total area of 100 m^2 from each plot from four locations of 25 m^2 each. Grain and straw yields of maize were determined by harvesting a total area of 120 m^2 from each plot from four locations of 30 m^2 each. Grain moisture was determined at the time of yield estimation using a grain moisture meter. The grain yield of rice, wheat, and maize is reported at 14%, 12%, and 14% grain moisture, respectively. Mungbean yields were estimated by hand harvesting the entire plot.

For comparing the productivity of different crops and total system productivity of the different scenarios, the yield of non-rice crops was converted into rice equivalent yield ($\mathrm{t\,ha^{-1}}$) using the following equation with maize as the example:

$$\text{Rice equivalent maize yield}\,(\mathrm{t\ ha^{-1}}) = \left(\frac{\text{Maize yield}\,(\mathrm{t\ ha^{-1}}) \times \text{Minimum support price of maize}\,(\mathrm{INR\ t^{-1}})}{\text{Minimum support price of rice}\,(\mathrm{INR\ t^{-1}})}\right)$$

2.6. Water application, measurement, and water productivity computations

For precise water application, a 6-inch polyvinyl chloride (PVC) pipeline was installed in a 90-cm-deep trench adjacent to the plots with an outlet (plot inlet) at the center of one end of each plot. The PVC pipeline was connected to a tube well with a water meter fitted in the outlet pipe. To avoid any water loss within and between irrigations, a non-return valve (NRV) was installed in the pipeline at the tube well delivery outlet link to the pipeline supplying the experimental field. Each outlet (plot inlet) had a water-tight butterfly valve to ensure that only one plot was irrigated at a time. To measure the irrigation water at each irrigation, the water meter reading (kilolitre, kL) was recorded at the start and end of the irrigation of each plot. For all crops in all scenarios, irrigation water was added until the water depth reached 5 cm. The amount of irrigation water applied was calculated as water depth (mm) using the equations:

$$\text{Irrigation water}\,(\mathrm{kL\ ha^{-1}}) = \left[\frac{(\text{Final water meter reading in kL} - \text{Initial water meter reading in kL})}{\text{Plot area in m}^2}\right] * 10000 \qquad (1)$$

$$\text{Irrigation water}\,(\mathrm{mm}) = \frac{\text{irrigation water}(\mathrm{kL\ ha^{-1}})}{10} \qquad (2)$$

(Note: $1\ \mathrm{kL} = 1\ \mathrm{m^3}$; $1\ \mathrm{kL\,ha^{-1}} = 1\ \mathrm{m^3}/10000\ \mathrm{m^2} = 0.0001\ \mathrm{m} = 0.1\ \mathrm{mm}$).

The total amount of water applied (input water) was computed by summing irrigation water and rainfall. Rainfall was measured using a manual rain gauge installed at the site. Irrigation water ($\mathrm{WP_I}$) and input water productivity ($\mathrm{WP_{I+R}}$) were computed as follows:

$$\mathrm{WP_I}(\text{kg grain m}^{-3}\text{ of irrigation water}) = \frac{(\text{Grain yield}\,(\mathrm{kg\ ha^{-1}})/\text{irrigation}\,(\mathrm{mm}))}{10}$$

$$\mathrm{WP_{I+R}}(\text{kg grain m}^{-3}\text{ of irrigation} + \text{rain water}) = \frac{(\text{Grain yield}\,(\mathrm{kg\ ha^{-1}})/\text{irrigation} + \text{rainfall}\,(\mathrm{mm}))}{10}$$

During the rice/maize season (*kharif*), irrigation water was applied based on tensiometer readings in scenarios 2 and 3 (Table 3b). However, during the wheat season (*rabi*), water was applied based on wheat growth stages (Table 3a), but soil matric potential was monitored daily. To monitor soil matric potential, gauge-type soil tensiometers (IRROMETER, Riverside, California) were installed with the centres of the ceramic cups at 15-cm and 30-cm depths in all plots immediately after each crop was planted.

2.7. Economic analysis

The economic analysis was done considering all production costs (fixed as well as variable), excluding land rent (Table 4). The variable costs included human labour, tractor use, the cost of production inputs (tillage, planting, seed, fertilizer, pesticide, irrigation, harvesting, threshing), and transport to market. The fixed costs consisted of depreciation of machinery and interest on working capital. The cost of human labour used for tillage, seeding, irrigation, fertilizer and pesticide application, weeding, and harvesting of crops was based on $\text{person-days}\,\mathrm{ha^{-1}}$. The time (h) required to complete each field operation in each treatment was recorded and expressed as $\text{person-days}\,\mathrm{ha^{-1}}$, considering 8 h to be equivalent to 1 person-day (standard working hours as per labour law of the government of India). The cost of labour was calculated using the minimum wage rate as per the labour law of the Indian government (Minimum Wage act, 1948). Similarly, the time (h) required by a tractor-drawn machine/implement to complete a field operation such as tillage, seeding, and harvesting was recorded, and expressed as $\mathrm{h\,ha^{-1}}$. For irrigation costs, the charges fixed by the electricity board of Haryana government (INR 0.30 per kWh of electricity) were used plus the cost of labour used for irrigation application. Gross returns (GR) were calculated by multiplying the grain yield of each crop by the minimum support price offered by the government of India (Economic Survey of India, 2012), and straw value was calculated using current local market rates. Net returns (NR) were calculated as the difference between GR and total cost (TC) ($\mathrm{NR} = \mathrm{GR} - \mathrm{TC}$). The system net returns (SNR) were calculated by adding the net returns of crops for the crops harvested within an individual calendar year. The benefit:cost ratio (B:C ratio) was calculated by dividing gross income by TC ($\text{B:C ratio} = \mathrm{GR}/\mathrm{TC}$). All the economic data were converted into US\$ using an exchange rate of 1 US\$ = 45 Indian rupees (INR).

2.8. 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). Data were either not transformed or transformed using log, square root, or inverse functions as needed to meet the assumptions of normality and equal variance of population distributions. Scenario mean values were separated by Fisher's protected least significant difference test at $P < 0.05$. The scenario-by-year interaction was significant; therefore, all the data are presented separately for each year.

Table 4
Minimum support price and rates used for calculating costs of key inputs in economic analysis during different seasons.

Particulars	Wheat 2009–2010	Wheat 2010–2011	Rice/maize 2010	Rice/maize 2011
Minimum support price of cereal (INR kg^{-1} grain)	11.0	11.2	10.1 (rice); 9.0 (maize)	10.8 (rice); 9.8 (maize)
Market price of wheat straw (INR kg^{-1})	3.0	3.0	–	–
Diesel cost (INR l^{-1})	36.5	36.5	36.5	40.0
Labor wage (INR person-day^{-1})	148.0	168.0	168.0	196.0
Urea (INR kg^{-1})	5.0	5.0	5.0	5.0
DAP (INR kg^{-1})	11.8	11.8	11.8	12.0
NPK (12:32:16) (INR kg^{-1})	11.2	11.2	11.2	11.2
MOP (INR kg^{-1})	5.0	5.0	5.0	5.0
Zinc sulphate (INR kg^{-1})	–	–	22.0	25.5
Electricity charge (INR kWh^{-1})	0.3	0.3	0.3	0.3
Seed (INR kg^{-1})	35.0	35.0	50 (variety); 200 (rice and maize hybrid)	50 (variety); 223 (rice hybrid); 240 (maize hybrid)

3. Results

3.1. Weather

The 2009–2010 wheat season (November to mid-April) was generally dry, with total rainfall of 29 mm, whereas the 2010–2011 season received relatively more rainfall of 78 mm (Fig. 1A). Monthly mean daily pan evaporation (Epan) was similar during most of the growing season of wheat in both years except during the latter stage (February–April), when Epan was lower in 2011 than in 2010 (Fig. 1B). Similarly, monthly mean daily maximum and minimum temperature were similar for most of the growing season in both years, except during the grain-filling period in February and March (Fig. 1C). In March, the average daily maximum and minimum temperatures were higher by 3.1 and 1.5 °C, respectively, in 2009–2010 than in 2010–2011 (Fig. 1C). Monthly mean daily solar radiation during the wheat season was variable; in some months it was similar in both years and in other months either higher in 2009–2010 (March) or in 2010–2011 (January) (Fig. 1D). The cooler grain-filling period in 2010–2011 suggests that the weather was more favourable for wheat than in 2009–2010.

During the rice/maize season (June to mid-October), the amount of rainfall was much higher in 2010 than in 2011 in all months except June (Fig. 1A). Total rainfall during the rice/maize season was 753–1000 mm in 2010 and 406–516 mm in 2011. Consistent with this, mean daily Epan and solar radiation were lower in 2010 than in 2011 in all months except June (Fig. 1 B and D). The monthly average daily minimum temperature was similar in both years (Fig. 1C). The monthly mean daily maximum temperature was also similar for the majority of the period except in September (the grain-filling period), during which the mean daily maximum temperature was 30.5 °C in 2010 and 32.2 °C in 2011 (Fig. 1C). The higher rainfall and cooler grain-filling period in 2010 were more favourable for rice, especially non-flooded rice, than in 2011, while the higher solar radiation from July to September was more favourable for maize in 2011.

During the mungbean season (April–June), the total amount of rainfall was higher in the second year (2011) (43–138 mm versus 147–233 mm), which resulted in lower evaporation and mean daily maximum and minimum temperature than in 2010 (Fig. 1A–C). Consistent with this, solar radiation was higher in 2010 than in 2011 during the mungbean crop (Fig. 1D).

3.2. Crop residue retention

There were large differences in the amounts of above-ground crop residues recycled in the four scenarios (Table 5). In scenario 1, all the above-ground residues were removed at ground level after the crop harvest apart from anchored stubbles of 4–5 cm, which were incorporated in the soil. On the other hand, totals of 21.7, 32.6, and 35.8 t ha^{-1} of crop residues were retained in scenarios 2, 3, and 4, respectively, in the first two years. In scenario 2, 4.1–4.2 t ha^{-1} of anchored rice stubbles and 2.6–3.5 t ha^{-1} of anchored wheat stubbles were retained on the soil surface at the time of wheat and mungbean sowing, respectively, while 2.6–4.7 t ha^{-1} of mungbean residues were incorporated into the soil during puddling for rice. In scenario 3, full rice (9.4–10.2 t ha^{-1}) and mungbean residues (2.2–4.4 t ha^{-1}) and anchored wheat stubbles (2.8–3.6 t ha^{-1}) were retained on the soil surface. In scenario 4, full rice residue (10.0 t ha^{-1}) during year 1 and maize stover (13.7 t ha^{-1}) during year 2 were retained on the soil surface, in addition to 2.6–3.5 t ha^{-1} of anchored wheat stubbles and 2.1–3.9 t ha^{-1} of full mungbean residues.

3.3. Crop and system yields

3.3.1. Wheat

Wheat yield differed significantly between scenarios (Table 6). In both years, wheat in scenarios 2, 3, and 4 yielded significantly more than in scenario 1. In year 1, yields of wheat were similar in scenarios 2, 3, and 4, but 0.5 t ha^{-1} higher than in scenario 1. As for year 1, wheat yield in scenario 2 was 0.4 t ha^{-1} higher than in scenario 1 in year 2, but wheat yield increased further in scenarios 3 and 4 and yielded 1.0–1.2 t ha^{-1} more than in scenario 1 and 0.6–0.8 t ha^{-1} more than in scenario 2. Wheat yields in scenarios 1 and 2 were similar each year, whereas in scenarios 3 and 4 yields were 0.4 and 0.7 t ha^{-1} higher, respectively, in year 2 compared with year 1.

3.3.2. Mungbean

In year 1, when mungbean was sown after the wheat harvest, grain yield was 0.7 t ha^{-1} in scenario 2, whereas, in scenarios 3 and 4, no grain yield of mungbean was obtained as the crop was killed before maturity to allow timely establishment of DSR and maize (Table 6). In year 2, when mungbean was relay-sown prior to the wheat harvest, yields of 0.3–0.5 t ha^{-1} were obtained in all three scenarios (2–4) but yield was 0.2 t ha^{-1} higher in scenario 2 than in scenarios 3 and 4 due to sufficient time for an extra second picking prior to the establishment of transplanted rice.

3.3.3. Rice/maize (rice equivalent)

In year 1, rice yields in scenarios 1, 2, and 3 were similar and significantly higher (by an average of 30%) than the rice equivalent yield of the maize in scenario 4 (Table 6). In year 2, rice yields in scenarios 2 and 3 and rice equivalent maize yield in scenario 4 were similar and significantly higher (by 1.23–1.45 t ha^{-1} or an average of 20%) than rice yield in scenario 1. Rice yields in scenarios 1, 2, and 3 were 2.0, 1.5, and 0.5 t ha^{-1} lower, respectively, in year 2 than in year 1. Maize yield was 0.9 t ha^{-1} higher in year 2 than in year 1.

3.3.4. System

Annual total rice equivalent yield of the four cropping systems ranged from 11.2 to 16.8 t ha^{-1} across scenarios and years (Table 6). In year 1, the rice equivalent system yield was significantly higher in scenario 2 (16.8 t ha^{-1}) than in all other scenarios, which had similar system yields. In contrast, in year 2, rice equivalent system yield of scenarios 2, 3, and 4 was similar and 3.3–3.4 t ha^{-1} higher than the system yield of scenario 1.

3.4. Water application and water productivity

The seasonal rainfall during the wheat, mungbean/fallow, and rice/maize season in all the scenarios is given in Table 7. During wheat, the amount of rainfall was higher in year 2 than in year 1 (78 versus 27 mm) but it was similar in all four scenarios. During the *kharif* rice season, scenario 3 with DSR received higher rainfall than scenario 1 because DSR was seeded earlier (18 June in 2010 and 10 June in 2011) in the main field than the transplanted rice in scenario 1 (6 July in 2010 and 2011). Scenario 2 also received higher rainfall than scenario 1 because younger rice seedlings (by 8–10 days) were transplanted earlier than in scenario 1 (28 June versus 6 July). Scenario 4 with maize received 753 and 516 mm of rainfall during years 1 and 2, respectively. During the summer fallow/mungbean season, rainfall was higher in year 2 than in year 1. In year 1, scenarios 2–4 had similar rainfall (43 mm), lower than in scenario 1 (138 mm) because of the shorter fallow period in these scenarios as rice or maize was planted earlier than in scenario 1. In year 2, the highest rainfall also occurred in scenario 1 but scenarios 3 and 4 received relatively lower rainfall (147 mm) than scenario 2 (173 mm) because of the earlier harvest in scenarios 3 and 4.

3.4.1. Water application

In wheat in year 1, total irrigation amount for wheat was similar in all scenarios, ranging from 403 to 440 mm (Table 8). In year 2, the irrigation amount was lowest in scenario 2 and highest in scenarios 3 and 4. Total water (irrigation + rainfall) input in wheat followed the same trend as irrigation water in both years.

In rice/maize, irrigation water application was highest in scenario 1 and was lowest in scenario 4 each year (Table 8). In both years, irrigation water application in transplanted rice was 30% lower in scenario 2, in which water was managed by alternate wetting and drying (AWD) compared with scenario 1 in which the plots were continuously flooded for much of the growing season. Similarly, irrigation water saving was 31% in year 1 and 52% in year 2, when rice was grown with zero-till direct-seeding with AWD in scenario 3 compared with scenario 1. Irrigation water application for maize was 94–95% lower than for rice in scenario 1, and about 90%

Table 5
The amount of crop residues retained on the surface after grain harvest in each scenario.

Scenario	2009–2010			2010–2011			Total
	Rice ($t\,ha^{-1}$)	Wheat ($t\,ha^{-1}$)	Mungbean ($t\,ha^{-1}$)	Rice/maize ($t\,ha^{-1}$)	Wheat ($t\,ha^{-1}$)	Mungbean ($t\,ha^{-1}$)	
1	Remove[a]	Remove	Fallow	Remove	Remove	Fallow	–
2	4.2	3.5	2.6	4.1	2.6	4.7	21.7
3	9.4	3.6	2.2	10.2	2.8	4.4	32.6
4	10.0	3.5	2.1	13.7	2.6	3.9	35.8

[a] Crop was harvested at ground level and all the aboveground residue was removed; however, some stubbles of 4–5-cm height remained after harvest and were incorporated.

Table 6
Grain yield of wheat, mungbean, and rice/maize, and system productivity (rice equivalent) of each scenario during 2009–2010 and 2010–2011.

Scenario	Wheat ($t\,ha^{-1}$)	Mungbean ($t\,ha^{-1}$)	Rice equivalent ($t\,ha^{-1}$)	System (rice equivalent) ($t\,ha^{-1}$)
2009–2010				
1	4.99b[a]	–	8.00a	13.4bc
2	5.48a	0.66a	8.71a	16.8a
3	5.53a	0.00b	7.97a	14.0bc
4	5.50a	0.00b	6.26b	12.2c (7.11)[b]
2010–2011				
1	4.94c	–	6.00b	11.2b
2	5.37b	0.53a	7.25a	14.5a
3	5.94a	0.32b	7.45a	14.6a
4	6.18a	0.30b	7.23a	14.6a (8.00)[b]

[a] Means within a column followed by the same letter are not different at 0.05% level using Fischer protected LSD test.
[b] Value in parentheses is original yield of maize crop.

Table 7
Rainfall during each crop in each scenario in 2009–2010 and 2010–2011.[a]

Scenario	Wheat (mm)	Mungbean/fallow (mm)	Rice/maize (mm)
2009–2010			
1	27	138	753
2	27	43	951
3	27	43	1000
4	27	43	753
2010–2011			
1	78	233	406
2	78	173	484
3	78	147	510
4	78	147	516

[a] Wheat includes the period between wheat sowing and wheat harvest; mungbean/fallow includes the period between the time of wheat harvest and the establishment of rice or maize in the main field; rice/maize includes the period between establishment of rice or maize in the main field and rice or maize harvest. There was no rain between rice/maize harvest and wheat sowing in either year.

lower than for rice in scenarios 2 and 3 each year. Total water input of the scenarios followed the same trend as irrigation water, with input reductions of 15%, 13%, and 67% during year 1, and 22%, 41%, and 77% during year 2 in scenarios 2, 3, and 4, respectively, vis-à-vis scenario 1.

In mungbean, irrigation water application was similar in scenarios 2–4 in both years (Table 8). However, irrigation water application in year 2 was only one-third of that in year 1 due to higher rainfall. The total water input (irrigation + rainfall) was similar in scenarios 2–4 in year 1 but, in year 2, it was 7–11% higher in scenario 2 than in scenarios 3 and 4 because of more rainfall during the crop in scenario 2 in year 2 (Tables 7 and 8).

On an annual system basis, irrigation water application each year varied significantly between scenarios and followed the trend of irrigation water during

Table 8
Irrigation water applied and total water input (irrigation + rainfall) during each crop in each scenario.

Scenario	Irrigation water				Total water input (irrigation + rainfall)			
	Wheat (mm)	Mungbean/ fallow (mm)	Rice/maize (mm)	System (mm)	Wheat (mm)	Mungbean/ fallow (mm)	Rice/maize (mm)	System[b] (mm)
2009–2010								
1	416a[a]	0b	1943a	2359a	443a	138b	2696a	3277a
2	440a	234a	1352b	2026b	467a	277a	2303b	3057b
3	410a	244a	1341b	1995b	437a	287a	2341b	3065b
4	403a	244a	126c	773c	430a	287a	879c	1596c
2010–2011								
1	434b	0b	2417a	2850a	512b	233ab	2823a	3568a
2	396c	71a	1707b	2174b	475c	244a	2191b	2909b
3	478a	81a	1145c	1704c	556a	229bc	1655c	2439c
4	483a	71a	132d	686d	561a	219c	648d	1428d

[a] Means within a column followed by the same letter are not different at 0.05% level using Fischer protected LSD test.
[b] Includes rainfall over the total 12-month period.

rice/maize (Table 8). Irrigation water application and total water input (irrigation + rainfall) were lower in scenario 4 than in all other scenarios by 61–67% and 48–51%, respectively, in the first year, and by 60–77% and 41–60% in the second year. Total water input in the scenarios decreased as follows: scenario 1 > scenario 2 = scenario 3 > scenario 4 in year 1 and scenario 1 > scenario 2 > scenario 3 > scenario 4 in year 2.

3.4.2. Water productivity

In both years, irrigation water productivity (WP_I) and total input water productivity (WP_{I+R}) of each crop differed significantly across the scenarios (Table 9). In both years, the WP_I and WP_{I+R} of wheat in scenario 1 were significantly lower than in scenarios 3 and 4, and also significantly lower than in scenario 2 in the second year.

The WP_I of maize (5–5.6 kg m^{-3} based on rice equivalent yield) was 8–22 times higher than that of rice in all scenarios, and 3.5–5 times that of wheat (Table 9). The WP_I of rice in scenario 1 was significantly lower than in scenarios 2 and 3, and, in the second year, the WP_I of rice in scenario 3 was significantly higher than in scenario 2. A similar trend was observed for WP_{I+R}; however, the differences were much smaller, with the WP_{I+R} of maize (rice equivalent) roughly 2 to 5 times that of rice.

The WP_I and WP_{I+R} of mungbean were significantly higher in scenario 2 than in scenarios 3 and 4 (Table 9). In the second year, the irrigation water productivity of rice equivalent mungbean yield of scenario 2 was 1.81–1.95 times higher than that of scenarios 3 and 4. Similarly, WP_{I+R} was 1.57 times higher in scenario 2 than in other scenarios. In scenario 2, the WP_I of rice equivalent mungbean was higher in year 2 than in year 1 despite the lower yield in year 2, mainly because of lower irrigation input in year 2 than in year 1. However, the WP_{I+R} of rice equivalent mungbean in scenario 2 was similar in both years.

The WP_I at the system level in both years was highest in scenario 4 and lowest in scenario 1 (Table 9). The WP_I of scenario 2 was significantly higher than that of scenario 3 in year 1, but the reverse occurred in year 2. The trends in system WP_{I+R} were similar to those in WP_I.

3.5. Economic analysis

The tillage and crop establishment cost, total cost, net return, and benefit:cost ratio (B:C ratio) for all crops differed significantly across scenarios, and also differed significantly at the total system level (Table 10). This was mainly due to differences in tillage and crop establishment costs of wheat and rice/maize across the scenarios.

3.5.1. Wheat

In both years, tillage and crop establishment cost as well as total cultivation cost were highest in scenario 1, followed by scenarios 3 and 4, and were lowest in scenario 2 (Table 10). The tillage and crop establishment cost was US$76 to 94 ha^{-1} lower in scenarios 2–4 than in scenario 1. Similarly, the reduction in total cost in both years in scenarios 2–4 ranged from US$ 90 to 122 ha^{-1} vis-à-vis scenario 1. Wheat was profitable in all systems; however, the net return was 16–19% higher in scenarios 2–4 than in scenario 1 in year 1, and was 14% higher in scenario 2 and 28–33% higher in scenarios 3–4 than in scenario 1 in year 2. The B:C ratio followed a trend similar to that of net return. The B:C ratio of scenarios 2–4 was similar but higher than that of scenario 1 in year 1; however, in year 2, the B:C ratio was highest in scenarios 3 and 4, intermediate in scenario 2, and lowest in scenario 1.

3.5.2. Rice/maize

Tillage and crop establishment cost of rice or maize was significantly different in all scenarios, following the trend scenario 1 > scenario 2 > scenario 3 > scenario 4 each year (Table 10). Compared to scenario 1, the saving in tillage and crop establishment cost in scenarios 3 and 4 was US$ 146–154 ha^{-1} and in scenario 2 it was US$ 14–20 ha^{-1}. In both years, the total production rice or maize cost was highest in scenario 2 and lowest in scenario 4 and followed the trend scenario 2 > scenario 1 > scenario 3 > scenario 4.

The net return of rice or maize in scenarios 1–3 was similar but significantly higher than the net return in scenario 4 in the first year (Table 10). However, in year 2, the net return of rice or maize in scenario 4 (US$ 1264 ha^{-1}) was significantly higher than that in all other scenarios. In comparison to scenario 1, net income was 39%, 54%, and 85% higher in scenarios 2, 3, and 4, respectively, in the second year. In year 1, the B:C ratio of rice or maize in all scenarios was similar (Table 10). In contrast, in year 2, the B:C ratio was highest in scenario 4 and lowest in scenario 1.

3.5.3. Mungbean

Tillage and crop establishment cost of mungbean did not differ with scenarios but it was US$ 10 ha^{-1} higher in year 1 than in year 2 because of the use of the seed drill in year 1 and broadcasting in year 2 (Table 10). The total production cost of mungbean was much lower than that of the other crops in the system, and highest in scenario 2 mainly because of the higher labour cost involved in extra picking of mungbean, whereas scenarios 3 and 4 did not differ in production cost. In the first year, the total cost in scenario 2 was US$ 224 higher than in scenarios 3 and 4, whereas, in the second year, it was US$ 67–87 ha^{-1} higher.

In year 1, grain yield was obtained only in scenario 2, which resulted in a net return of US$ 192 ha^{-1}. In year 2, mungbean was profitable in all scenarios, and the net return in scenario 2 was US$ 92–96 ha^{-1} higher than in scenarios 3–4. The B:C ratio of mungbean in scenario 2 was in the range of 1.68–1.70 in both years. In year 2, the B:C ratio was highest in scenario 2 and lowest in scenario 3.

3.5.4. System

Total tillage and crop establishment cost of the scenarios followed the same trend in both years: scenario 1 > scenario 2 > scenario 3 = scenario 4 (Table 10). Tillage and crop establishment cost was US$ 100–111 (see T10) ha^{-1} less in scenario 2 and US$ 222–239 (see T10) ha^{-1} less in scenarios 3 and 4 compared with scenario 1 each year. The total cost was highest in scenario 2 in both years. The total cost of scenarios 3 and 4 was 6 and 13% lower, respectively, than in scenario 1 in year 1, but, in year 2, the total cost of scenario 3 was significantly higher (by 4–6%) than that of scenarios 1 and 4. The system net return of scenario 2 was higher (17–32%) than in all other scenarios in year 1. In contrast, in year 2, the system net return of scenario 4 was the highest (57% higher than in scenario 1), followed by scenarios 2 and 3 (33–41% higher than in scenario 1). The B:C ratio in year 1 was similar in all scenarios. In year 2, the B:C ratio was highest in scenario 4 and lowest in scenario 1.

4. Discussion

4.1. Crop and system yield

The results of this 2-year study clearly show significant benefits of the 'improved' management interventions, including components of CA, on crop and cropping system yield, water productivity, and profitability. The responses tended to be greater in wheat than in rice, and with the replacement of rice by maize in the second year. Compared to the farmers' practice (scenario 1), average wheat yield in scenarios 2–4 increased by 10% in year 1 and by 18% in year 2 (Table 6). The response of wheat yield to the scenarios in year 2, but not year 1, suggests beneficial residual effects from the new systems, more so in scenarios 3 and 4. The positive responses could be due to a range of improved management practices acting alone or in combination. Avoiding puddling for rice in scenarios 3 and 4 together with full surface residue retention resulted in improved soil physical properties including infiltration rate and aggregate stability aggregate size distribution in comparison with scenario 1 after the second rice crop (data not shown). However, whether or the degree to which this contributed to the increased wheat yield is not known. The fact that the yield increase was higher in scenarios 3 and 4 than scenario 2, and that it only occurred in the second year, suggests the development of residual benefits over time from the change in tillage and residue management practices. An adverse effect of puddling for rice on the following wheat crop has been reported by many researchers (see the review of Kumar and Ladha, 2011) and has been attributed to poor rooting due to poor soil physical properties such as compaction and poor soil aggregation (Gathala et al., 2011b; Kumari et al., 2011).

Rice yields were high in year 1 and lower in year 2 than in year 1, more so in scenario 1. The lower yields in year 2 were likely due in part to seasonal effects (lower rainfall) and in part to relatively more infestations of plant hoppers and false smut in year 2. The higher mean daily maximum temperature during grain filling and relatively greater water deficit stress in year 2 than in year 1, as evidenced from soil matric potential data (data not shown), resulted in a shorter grain-filling period in year 2 and fewer grains per panicle (e.g. 182 versus 147 in scenario 1). Although rice yield did not differ among the four scenarios (except for higher rice equivalent yield of maize) in year 1, it was 21–24% higher in scenarios 2–4 than in scenario 1 in year 2, possibly reflecting a cumulative residual effect of improved crop and resource management practices. As for wheat, it is not possible to estimate the individual contribution of the various interventions, which include different varieties, amounts of fertilizer, level of residue retention, and inclusion of mungbean in the rotation. Our preliminary results suggest that rice under direct seeded conditions (scenario 3) can be as productive as puddled transplanted rice (scenarios 1 and 2), consistent with the findings of Yadav et al. (2011a). These results

Table 9
Irrigation (WP_I) and input (WP_{I+R}) water productivity (kg grain m^{-3} water) of crops and cropping systems.

Scenario	WP_I				WP_{I+R}			
	Wheat (mm)	Mungbean[b] (mm)	Rice/maize (mm)	System (rice eqv.) (mm)	Wheat (mm)	Mungbean (mm)	Rice/maize (mm)	System (rice eqv.) (mm)
2009–2010								
1	1.2b[a]	–	0.41c	0.57d	1.13b	–	0.30c	0.41d
2	1.3ab	0.27 (0.86)a	0.64b	0.83b	1.19ab	0.23 (0.73)a	0.38b	0.55b
3	1.4a	0.00b	0.60b	0.70c	1.27a	0b	0.34b	0.46c
4	1.4a	0.00b	4.96a[c] 5.64a[d]	1.58a	1.28a	0b	0.71a[c] 0.81a[d]	0.77a
2010–2011								
1	1.1c	–	0.25d	0.39d	0.96b	–	0.21d	0.31d
2	1.4a	0.76 (2.48)a	0.43c	0.60c	1.13a	0.22 (0.71)a	0.33c	0.50c
3	1.2b	0.39 (1.27)b	0.66b	0.81b	1.07a	0.14 (0.45)b	0.45b	0.60b
4	1.3ab	0.42 (1.37)b	5.62a 6.22a[c]	2.11a	1.10a	0.14 (0.45)b	1.12a 1.24a[c]	1.02a

[a] Means within a column followed by the same letter are not different at 0.05% level using Fischer protected LSD test.
[b] Value in parentheses is based on rice equivalent mungbean yield.
[c] Water productivity of maize based on rice equivalent maize yield.
[d] Water productivity of maize based on actual maize yield.

are in contrast to the lower yields of DSR found in some studies in the region (Kumar and Ladha, 2011; Ladha et al., 2009; Jat et al., 2009; Saharawat et al., 2010). The major reasons cited for lower yield under DSR in these studies included (1) higher weed infestation, (2) lack of suitable varieties, and (3) possibly sub-optimal irrigation scheduling. In our study, all these factors were taken care of by using effective integrated weed management, a suitable rice hybrid, and tensiometer-based irrigation scheduling (Kumar and Ladha, 2011; Kamboj et al., 2012). Maize yield in scenario 4 was lower in year 1 than in year 2 (7.1 t ha^{-1} compared with 8.0 t ha^{-1}), probably because of lower solar radiation and more waterlogging in year 1, which had higher rainfall than average. The residual

Table 10
Economic analysis of different scenarios (2009–2010 and 2010–2011).

Scenario	Tillage and CE cost (US$ ha^{-1})	Total cost (US$ ha^{-1})	Gross return (US$ ha^{-1})	Net return (US$ ha^{-1})	Benefit:cost ratio
Wheat (2009–2010)					
1	102a[a]	629a	1732a	1103b	2.75b
2	9c	507c	1825a	1318a	3.60a
3	18b	529b	1811a	1283a	3.42a
4	17b	527b	1817a	1290a	3.44a
Wheat (2010–2011)					
1	96a	640a	1756b	1115c	2.75c
2	10c	528c	1803b	1275b	3.42b
3	20b	550b	1973a	1422a	3.59ab
4	18b	546b	2032a	1486a	3.72a
Rice/maize (2010)					
1	162a	770b	1797a	1027a	2.34a
2	145b	790a	1954a	1164a	2.47a
3	15c	735c	1790a	1054a	2.43a
4	8d	634d	1422b	788b	2.24a
Rice/maize (2011)					
1	163a	764b	1448c	684c	1.90c
2	149b	785a	1736b	951b	2.22b
3	17c	736c	1786ab	1050b	2.43b
4	9d	681d	1946a	1264a	2.86a
Mungbean (2010)					
1	–	–	–	–	–
2	12a	280a	472a	192a	1.68a
3	12a	56b	0b	−56c	0.00b
4	12a	56b	0b	−56c	0.00b
Mungbean (2011)					
1	–	–	–	–	–
2	2a	242a	412a	170a	1.70a
3	2a	175b	248b	74b	1.42c
4	2a	155b	233b	78b	1.51b
System (2009–2010)					
1	264a	1399b	3528b	2130b	2.52a
2	166b	1577a	4251a	2674a	2.70a
3	45c	1320c	3601b	2281b	2.73a
4	37c	1218d	3239c	2022b	2.66a
System (2010–2011)					
1	259a	1404c	3204b	1800c	2.28d
2	161b	1555a	3951a	2396b	2.54c
3	39c	1461b	4007a	2546b	2.74b
4	29c	1383c	4211a	2829a	3.04a

[a] Means within a column followed by the same letter are not different at 0.05% level using Fischer protected LSD test.

effect of ZT and crop residue retention by the time the second maize crop was planted (6th crop) may have also been a factor.

The mungbean grain yield in scenario 2 in year 2 was lower than in year 1 (Table 6), despite higher biomass production (nearly double that in year 1) (Table 5). The higher biomass was mainly due to longer crop duration (by 26 days) due to earlier sowing and possibly due to higher rainfall. This all resulted in delayed maturity and picking before the crop was fully mature.

The system rice equivalent yield had a variable response to scenario across the 2 years. In year 1, scenario 2 had higher system productivity than the other scenarios, due to higher rice yield, and the additional yield of mungbean. But, in year 2, all three scenarios (scenarios 2–4) with improved management gave a similar system productivity increase of about 30% over the 11.2 t ha^{-1} with the farmers' practice (scenario 1).

4.2. Water application and water productivity

Like the crop productivity improvements in scenarios 2–4, water application and water productivity responded to improved management. Since the trends of irrigation and total water input and their productivities were similar, we discuss irrigation total water input and productivity in greater detail. Likewise, since the water application in wheat was only about 25% of that of rice, and since the trends are largely governed by rice, we focus our discussion more on rice. Total irrigation water application to rice in scenarios 1 and 2 in year 1 was 400–500 mm lower than in year 2, largely due to much higher total rainfall and to a smaller degree to lower evaporative demand in year 1 (Fig. 1A and B). In contrast, total irrigation application to rice in scenario 3 was lower in year 2 than in year 1, which could be due to the cumulative effects of permanent ZT with residue mulch in reducing evaporation losses, and also because of the lower irrigation requirement during early crop establishment in year 2 associated with more rainfall and lower evaporative demand in June (Fig. 1A and B). The irrigation application to maize was small and similar each year as a result of well-distributed rainfall each year (Fig. 1A). Rice WP_I in scenarios 1 and 2 was considerably higher in year 1 than in year 2 due to the lower irrigation input and higher yield, whereas WP_I of rice in scenario 3 was lower in year 1 than in year 2 as the higher yield in year 1 did not fully compensate for the higher irrigation amount (Tables 6, 8 and 9).

Both irrigation water application and productivity in rice were significantly different among scenarios in the two years (Tables 8 and 9). Scenario 1 of the farmers' practice with puddling followed by transplanting and continuous flooding had 591–1272 mm more irrigation water input than scenarios 2 (best managed puddled transplanted rice with AWD water management) and 3 (zero-till direct seeding with AWD). These results suggest that about 30% irrigation water can be saved in puddled transplanted rice by adopting safe AWD (Tables 8 and 3b), consistent with the findings of many other studies (Gathala et al., 2011a; Humphreys et al., 2010; Yadav et al., 2011a). In scenario 3, substituting puddling with ZT and mulching did not reduce irrigation input in comparison with TPR with AWD in year 1, a high rainfall rice season with significant rain after sowing of DSR and before transplanting of TPR. However, ZT-DSR with mulching had 33% lower irrigation input than TPR with AWD in year 2, a much lower rainfall rice season, without reducing yield. Based on meta-analysis of data from 44 studies from different countries, Kumar and Ladha (2011) reported an average of 21–25% irrigation water saving with DSR compared with TPR. In Punjab, Yadav et al. (2011b) found a 30% irrigation savings with DSR compared with TPR with the same AWD water management. In our study, the lower irrigation input with DSR (scenario 3) compared with TPR with AWD (scenario 2) in year 2 could be because of a combination of factors. These include using a shorter duration variety (by 7 days in the main field) in scenario 3 (Table 11), conservation of soil moisture by the mulch, and the fact that the TPR was continuously flooded for the first 2 weeks after transplanting. The trend of irrigation application was reflected in irrigation water productivity, which was significantly higher in scenarios 2 and 3 than in scenario 1 each year. In scenario 4, in which rice was replaced by maize, the irrigation water application was substantially lower and its rice equivalent productivity manyfold higher than in all other scenarios with either transplanted or DSR, primarily due to large differences in the ability of rice and maize to withstand soil drying. Hence, there was a need for frequent irrigation of rice, resulting in higher percolation and seepage losses. The water, yield, and economic results of the first two years suggest that, where water is scarce, maize can be an attractive alternative to rice.

Table 11
Duration (days) of rice crop in the field (main field duration) and from seed to seed (total crop duration).

Scenario	Main field duration	Total crop duration
2009–2010		
1	103	138
2	115	138
3	118	118
4	94	94
2010–2011		
1	105	135
2	115	135
3	111	111
4	99	99

In wheat, in year 1, irrigation water application in all four scenarios did not differ but WP_I was higher in scenarios 3 and 4 than in scenario 1. In year 2, WP_I was higher in scenarios 3 and 4 despite higher irrigation water application (Tables 8 and 9). These effects were due to higher yield. In year 2, the higher irrigation water application in scenarios 3 and 4 than in scenarios 1 and 2 was because of about 2-weeks' earlier planting in scenarios 3 and 4 (30 October versus 15 November) when the temperature is higher. In both years, total water input to wheat (430–560 mm) was high, given the high residual water content of the soil profile shortly after the monsoon rice crop, and the model simulations of Timsina et al. (2008), which indicate that ET of well-irrigated wheat sown in early November in northwest India is less than 400 mm. We postulate that irrigation water input to wheat would have been less in scenarios 2–4 with ZT and rice residue retention if irrigation had been based on soil matric potential (SMP) instead of applications at critical crop growth stages without taking soil water status into account. Singh et al. (2011a) found that, when wheat was irrigated based on SMP, mulch (8 t ha^{-1}) conserved soil water and delayed the need for irrigation, and resulted in a saving of 75 mm of irrigation water (one irrigation) compared with no mulch. The results of model simulations (Singh et al., 2011b) suggested that, with mulch, one-irrigation would be saved in about 50% of the years. These initial results suggest the need for more research to develop irrigation water scheduling based on SMP for ZT wheat with mulch conditions to reduce the irrigation water requirement.

In mungbean, the much lower irrigation water application in year 2 than in year 1 was mainly due to the higher rainfall in year 2.

4.3. Economics

The short term positive effects of reduced/zero tillage and improved management practices observed on yield were translated into more favourable economics. Tillage (dry or wet) and crop establishment (direct seeding or transplanting) account for a major part of total crop production costs (Erenstein and Laxmi, 2008). By adopting ZT for all crops in scenarios 3 and 4 and ZT in wheat in scenario 2, tillage and crop establishment costs decreased by 79–95% compared to conventional tillage and crop establishment costs in scenario 1 (Table 10). The significant savings in tillage and crop establishment costs with ZT in scenarios 2–4 in wheat (US$ 76–94 ha^{-1}) compared with scenario 1 was reflected in savings in total cultivation costs of US$ 90–122 ha^{-1} (Table 10). However, in rice/maize, a significant savings in tillage and crop establishment costs with ZT drill-seeding in scenario 3 compared with puddled transplanted rice in scenario 1 (US$ 145 ha^{-1}) was not reflected in total savings (US$ 28–35 ha^{-1}), which was lower than that (US$ 116 ha^{-1}) reported by Gathala et al. (2011a). This was mainly because of the higher cost of the hybrid rice seeds used in scenario 3 in our study than the inbred varieties used in transplanted rice. Additionally, in our study, the fertilizer costs were higher in scenario 3 than in scenario 1 because potash was applied in scenario 3 but not in scenario 1. The differences in cost of cultivation in mungbean in scenarios 2 and 3 in two years were mainly because of differences in labour cost for harvesting (picking mungbean pods, a labour-intensive operation). In the first year, there was no grain yield; hence, there was no pod picking cost involved, resulting in much lower total cost.

At the system level, the highest cost of cultivation was for scenario 2 (US$ 1555–1577). Despite the lower total cost of rice and wheat in scenario 3 than in scenario 1, the system-level cost was higher in scenario 3 than in scenario 1 in the second year mainly because of the inclusion of mungbean in the rotation, which was manually harvested/picked in the second year only. As a result, scenario 2 yielded the highest net returns (US$ 2674) in 2009–2010 and scenario 4 the highest (US$ 2829) in 2010–2011, which were 26% and 57% higher than in scenario 1 of the farmers' practice, respectively. The trend in net returns of the scenarios was also reflected in the benefit:cost ratio. During 2009–2010, scenarios 1, 3, and 4 had the same net returns (US$ 2022–2281), whereas, during 2010–2011, scenario 1 had the lowest net returns (US$ 1800). The substantially higher returns in scenarios 2–4 in year 2 clearly reflect the cumulative effects of improved management practices, especially the reduction in labour and tillage, and higher yields.

5. Conclusions

This study evaluated a set of CA-based improved management practices, and new diversified crop rotations to address the fast emerging constraints such as rising scarcities of labour and water and rising cultivation costs in a rice–wheat rotation of northwestern India. Our 2-year results demonstrate that various crop and management interventions can increase the system-level land productivity with large efficiencies of resource usages (labour, water, energy) and economic returns. We established that rice can successfully be grown without puddling and transplanting causing positive effects on subsequent wheat. In areas, where water availability is becoming a serious constraint, maize is a feasible and economically viable option. There is a large potential of increasing cropping intensity an inclusion of mungmean in currently practiced double cereal based rotation, which will not only increase the economic returns but also nutritional value. Although our results are from an initial 2 year study, we expect further improvements in overall system performance through positive changes in soil and water resource base. Undoubtedly, not only such a study should be continued on a longer-term basis but should be replicated in other agro-ecologies to address food, nutrition, economic and environmental problems.

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