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RESEARCH ARTICLE

Achieving the win–win: targeted agronomy can increase both productivity and sustainability of the rice–wheat system

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Abstract

Maximizing productivity of the rice–wheat (RW) system is a major challenge for achieving food security in the Eastern Gangetic Plains (EGP) of South Asia. Ideally, productivity should increase along with increasing farm profits while sustaining or enhancing the natural resource base. However, research focused on increasing the productivity and profitability of the RW system while considering long-term system sustainability is lacking from the EGP. Here, we show that using the process-based cropping system model Agricultural Production Systems sIMulator (APSIM) (earlier robustly validated in these environments), maximization of target variables (e.g. production, farm profit, water productivity) can be achieved by modifying the agronomic management currently recommended for RW farmers in the region. Our analysis demonstrates conservation agriculture-based intensification, through the addition of mungbean with modified irrigation and increased nitrogen fertilization, increases not only the system production (34%), farm profit (39%), and water productivity (54%), but also the soil organic carbon (31%) and total soil nitrogen (52%) in the 0–15 cm soil layer. In contrast, conventional tillage-based intensification increases system productivity but not sustainability. We found the ideal agronomic management varied across different environments for maximizing target variables. Our analysis illustrates the power of validated modeling tools like APSIM and has broader application for farmers globally whose production and sustainability are constrained by inefficient agronomic practices.

Keywords APSIM · Crop modeling · Water productivity · Resource use efficiency · Smallholder farming · Sustainable intensification

Abbreviations

APSIM	Agricultural Production Systems sIMulator
AWD	Alternate wetting and drying
CA	Conservation agriculture
CS	Cropping systems
CT	Conventional tillage
EGP	Eastern Gangetic Plains
Ep:Es	Transpiration-to-soil evaporation ratio
ESW	Extractable soil water
ET	Evapotranspiration (Ep + Es)
GM	Gross margin
NUE	Nitrogen use efficiency
PTR	Puddled transplanted rice
REY	Rice equivalent yield
RFP	Recommended farmers' practice
RW	Rice–wheat
RWM	Rice–wheat–mungbean
SOC	Soil organic carbon
STN	Soil total nitrogen
WI	Wheat irrigation strategy
WP	Water productivity
WP_I	Irrigation water productivity
WP_{I+R}	Irrigation and rainwater productivity
ZT	Zero-tillage
ZT UPTR	Zero-till unpuddled transplanted rice

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1 Introduction

The Eastern Gangetic Plains (EGP) of South Asia contains the world's highest concentration of rural poor populations (Ericksen et al. 2011). The rice–wheat (RW) system plays a major food security role in this region (Fig. 1). While increasing crop production is essential to meeting future food demands for hundreds of millions of people, the challenge is to do this while utilizing natural resources sustainably. Traditional agronomic practices such as intensive tillage (conventional tillage (CT)), sub-optimal irrigation and fertilizer management, coupled with low research investment, limit crop productivity growth (Pittelkow et al. 2015). The sustainability of the traditional RW system in this region is also threatened by inefficient use of resources (Bhatt et al. 2016; Ladha et al. 2009). Breakthroughs in crop production that suit the smallholder-dominated farming system are urgently needed for sustaining system productivity and profitability. Conservation agriculture (CA) through its three linked principles- minimum soil disturbance, maximum soil cover, and crop rotation could offer a potential solution to the production sustainability problem (Hobbs 2007; Jat et al. 2020).

Although CA interventions have major system benefits (Gathala et al. 2020; Kumar et al. 2018; Ladha et al. 2016; Chaki et al. 2021; Chaki et al. 2019), these may vary across a range of geographies (Hobbs 2007; Giller et al. 2009). Therefore, CA technological interventions considering local environments and resource availability could sustain productivity through more efficient use of natural resources (e.g. soil, water, energy) while reducing environmental impacts (Gathala et al. 2020). Productivity could be further increased through targeted fertilizer and irrigation management.

Here, we used a locally and robustly calibrated/validated process-based model Agricultural Production Systems sIMulator (APSIM) (Holzworth et al. (2014)) to investigate the long-term impact of several cropping systems intensification options for maximizing system variables (such as system production, water productivity, and farm profit) while examining the impact on sustainability performance (soil organic carbon (C) and soil total nitrogen (N)). We conducted a Monte Carlo analysis by incrementally modifying N fertilizer rates and irrigation strategies and comparing all combinations across several RW cropping system intensification options which included the addition of mungbean and introduction of CA elements. There are three major variables a farmer could consider while optimizing system productivity: system production, gross margin, and water productivity. Though any of these variables could be the primary focus, they should complement sustainable crop production indicators such as soil organic C stocks, soil total N, and more productive use of water. We analyzed the APSIM output for each treatment combination across two significantly different cropping environments (soil type, water table dynamics,

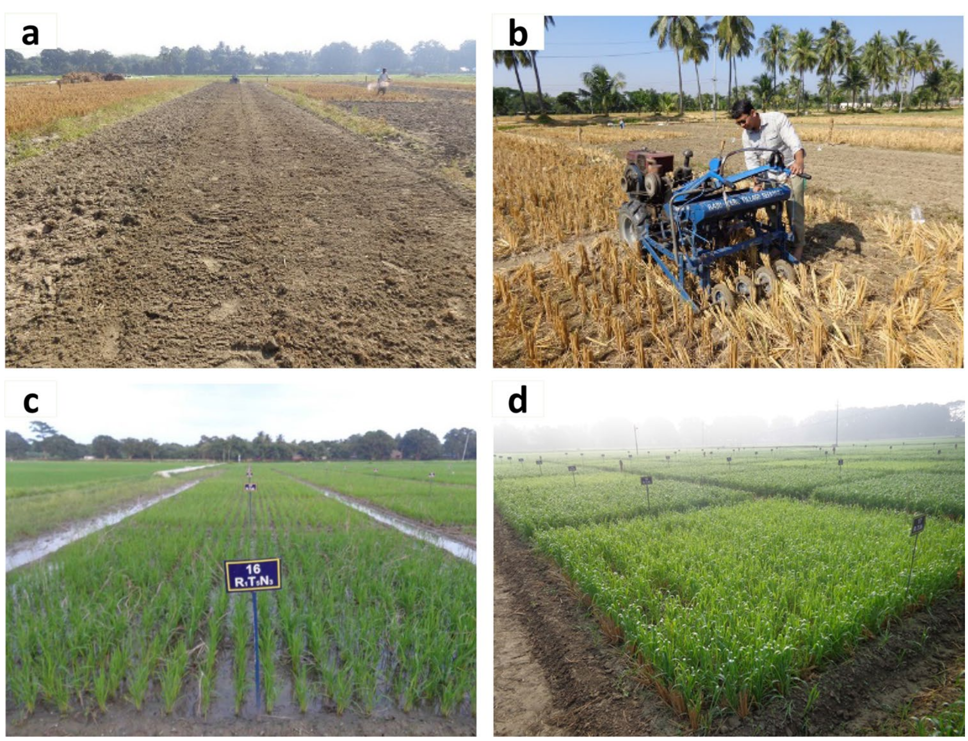

Fig. 1 Rice–wheat system (RW) in the Eastern Gangetic Plains (EGP): **a** conventional till (CT) land preparation for wheat; **b** two-wheel tractor operated zero-till (ZT) wheat seeding machine; **c** zero-till unpuddled transplanted rice (ZT UPTR) in early growth stage; and **d** ZT wheat in early growth stage.

and agro-climate) in the EGP and explored how a farmer can optimize RW system performance based on access to resources and their own aspirations.

2 Methods

We used the APSIM model (v7.5) to explore the impact of cropping system intensification options, wheat irrigation strategy, and fertilizer rate on the productivity of the RW system in two diverse environments (varied in soil type, water table dynamics, and agro-climate) of the EGP (Supplementary Fig. 1). One of the study sites (Rajshahi) represents fine-textured soil with a shallow perched water table, and the other site (Dinajpur) represents coarse-textured soil with a deep water table (Supplementary Table 1 and Supplementary Fig. 2). The model was robustly calibrated and validated in the RW system under a diverse range of tillage (conventional till (CT) vs zero-till (ZT)), crop establishment options (puddled transplanted rice vs unpuddled transplanted rice), residue allocation (about 25 cm standing rice and wheat stubbles, and full mungbean residues were retained in the CA, and all the crop residues were removed from the CT system), N rates (zero, half, and full recommended doses applied to rice and wheat only), and deficit irrigation practices (five irrigation treatments were considered for wheat only) at two diverse sites (Chaki et al. 2022).

2.1 Cropping system scenarios examined

Three cropping system intensification scenarios (CS) were compared under a range of N fertilizer and deficit irrigation practices. We have conducted a Monte Carlo analysis through the combination of these factors which led to a total matrix scenario number of 162 for each site. The crop varieties used for the scenario analysis were robustly calibrated and validated at the study sites and included rice (var. BRRI dhan52), wheat (var. BARI Gom-26 for Rajshahi and BARI Gom-32 for Dinajpur), and mungbean (var. BARI Mung-6) (Chaki et al. 2022). A 37-year APSIM simulation was commenced with the first rice crop in 1982 and finished with a mungbean crop in 2019 using the historical climate data collected from the Bangladesh Meteorological Department (Rajshahi and Dinajpur station) (Supplementary Fig. 3):

(A) Cropping system scenarios:

CS1 Puddled transplanted rice (PTR) – conventional till (CT) wheat

CS2 PTR rice – CT wheat – CT mungbean

CS3 Zero-till unpuddled transplanted rice (ZT UPTR) – zero-till (ZT) wheat – ZT mungbean (full CA-based option)

(B) N rate scenarios:

N fertilizer multiplier (F) – applied to current recommended fertilizer N application rates in rice and wheat crops. No N fertilizer applied to mungbean.

F1 = 0x, F2 = 0.25x, F3 = 0.5x, F4 = 0.75x, F5 = 1.0x (current recommended N rate, for rice 90 kg N ha^{-1}, for wheat 120 kg N ha^{-1}), F6 = 1.25x, F7 = 1.5x, F8 = 1.75x, and F9 = 2.0x

(C) Wheat irrigation strategy (WI):

WI triggered when extractable soil water (ESW) within the root zone falls below the specified value and then apply 60 mm water per irrigation event

WI1 = 140 mm (0–1 irrigation), WI2 = 160 mm (1–2 irrigations), WI3 = 180 mm (2–3 irrigations), WI4 = 200 mm (3–4 irrigations, current recommended practice), WI5 = 220 mm (4–5 irrigations), and WI6 = 240 mm (most wet conditions, most irrigations, 5–6 irrigations)

We did not consider rice irrigation strategies in our analysis as farmers in the region predominantly grow rice (wet season rice) as a rainfed crop which is also supported by surface water sources through field-to-field water movement along natural land slope gradients (Islam et al. 2019). The groundwater irrigation application is mainly as supplementary irrigation if there is a dry period or during transplanting through to early establishment period to ensure timely transplanting and establishment of rice. We captured this information while specifying the rice irrigation management in APSIM manager logic. The dry season winter crop production following monsoon rice is highly dependent on irrigation supply either from shallow or deep underground water pumping sources. Considering irrigation is a decisive factor in dry season winter crop production, strategic water management is necessary for maximizing water productivity and farm profit.

2.2 Crop establishment and management specified in APSIM

2.2.1 Rice

The sprouted rice seeds were sown in a nursery on 20 June each year. The land for the PTR was prepared following the heavy monsoon rainfall anticipated in July in the region (Supplementary Fig. 3a and b) or if necessary, after applying 1–2 irrigations (100 mm per irrigation, applied if pond depth was below 20 mm) to facilitate wet tillage and transplantation of rice seedlings. The land for the ZT UPTR treatment was saturated by rainfall, or by applying 1–2 irrigations (75 mm per irrigation) if rainfall was not sufficient, to soften the soil sufficiently for transplanting without tillage. Following field preparation, transplanting established a crop pattern of two seedlings (20 days old) per hill with hill spacing of 200 mm × 150 mm (33 hills m^{-2}). Three equal splits of N (according to treatment N specification) were applied at 15 days after transplanting (15 DAT) (early establishment), 35 DAT (active tillering), and 55 DAT (panicle initiation) as topdressing. The crops were supported through supplementary irrigation (75 mm of irrigation water was applied whenever the pond disappeared) during the first 2 weeks after transplanting for ease of crop establishment. Thereafter, the crop was irrigated within 2 days after the disappearance of the pond (alternate wetting and drying (AWD)) during dry spells as necessary, and the irrigation was terminated 2 weeks before harvest. Rice crop residues were removed from the PTR (CS1 and CS2), and 35% of the rice stubbles (approximately 25 cm standing stubbles) was left in the UPTR (CS3).

2.2.2 Wheat

Wheat was routinely sown 1 week after rice harvest if the date was after 15 November; otherwise, wheat sowing was delayed for a few more days (after rice harvest) to sow wheat within the optimum wheat sowing window for the EGP (Jahan et al. 2018). Pre-sowing irrigation of 60 mm was applied if the soil water content of the 0–15 cm soil layer was below the drained upper limit. Wheat seeds were sown into a friable seedbed for the CT system (CS1 and CS2) and into a no-till field using a ZT drill seeder, maintaining a sowing depth of 25 mm and row spacing of 200 mm to achieve a plant population of 250 m^{-2}. Two-thirds of the N (according to N treatment specification) was applied as basal, and the remaining N was top-dressed at 21 days after sowing (crown root initiation stage (CRI), Z 1.3–1.4). The first irrigation was applied in all scenarios to ensure the effectiveness of top-dressed N fertilizer applications, only if the cumulative rainfall within the previous 3 days of scheduled N topdressing was less than 25 mm. Thereafter, 60 mm irrigation was applied to the crop when ESW within the root zone fell below a set value as specified for the treatment. The crop was harvested at maturity. Wheat residues were removed from the CT (CS1 and CS2), and 30% of wheat stubbles (approximately 25 cm standing stubbles) were left in the CA (CS3).

2.2.3 Mungbean

Mungbean was sown 1 week after wheat harvest following a similar method to that used for wheat. Pre-sowing irrigation of 60 mm was applied if the soil water content of the 0–15 cm soil layer was below the drained upper limit. Thereafter, the mungbean crop was grown as a rainfed crop. The mungbean pods were harvested when mature. All the mungbean residue (100%) was retained in the CA system (CS3), while all residue was removed from the CT system (CS2).

2.3 APSIM output variables compared

2.3.1 Rice equivalent yield (REY)

Annual system productivity was calculated by summing up the simulated grain yield of component crops in each cropping cycle. The system productivity of different cropping system scenarios was compared by calculating the REY, using Eq. 1:

$$REY = \frac{Yield\ of\ non-rice\ crop\ \left(kg\ ha^{-1}\right) \times Price\ of\ non-rice\ crop\ \left(\text{USD}\ kg^{-1}\right)}{Price\ of\ rice\ \left(\text{USD}\ kg^{-1}\right)} \tag{1}$$

2.3.2 Gross margin (GM)

For the calculation of GM, we used input and output values from published data for the study sites (Chaki 2021). Production cost was calculated considering the amount and prices of all inputs used in simulating crop production. Gross return was computed from the amount and prices of simulated grain and straw, while the gross margin was calculated by deducting the production cost from the gross return.

2.3.3 Irrigated water productivity (WPi)

Irrigated water productivity was calculated for each cropping system scenario on an annual basis, using Eq. 2:

$$System\ WPi = \frac{Gross\ margin\ \left(USD\ ha^{-1}\right)}{System\ irrigation\ \text{input}\ (mm)} \tag{2}$$

2.3.4 Soil organic C (SOC) and soil total N (STN)

The SOC and STN were simulated daily to compare the changes in SOC during the 37 years of cropping and the changes in STN after 37 years of cropping. The starting

Table 1 The maximum achievable system rice equivalent yield (REY), gross margin (GM), irrigation water productivity (WPi), and transpiration-to-evaporation ratio (Ep:Es) under each cropping system at Rajshahi and Dinajpur (average 1982–2019). Average number of irrigations for wheat is in parentheses.

Cropping system		Wheat irrigation strategy	Rice irrigation (No.)	N fertilizer multiplier	REY (t ha^{-1})	GM (USD ha^{-1})	WPi (USD ha^{-1} mm^{-1})	Ep:Es
Rajshahi								
Current RFP		3–4 irrigs (3)	3	1.00x	11.9	1730	4.24	1.47
CS1	Maximum REY	I6 (1)	3	2.00x	12.3	1780	6.46	1.59
	Maximum GM	I6 (1)	3	2.00x	12.3	1780	6.46	1.59
	Maximum WPi	I6 (1)	3	2.00x	12.3	1780	6.46	1.59
CS2	Maximum REY	I6 (1)	3	2.00x	16.0	2270	8.05	2.09
	Maximum GM	I6 (1)	3	2.00x	16.0	2270	8.05	2.09
	Maximum WPi	I6 (1)	3	1.00x	15.6	2240	8.12	2.06
CS3	Maximum REY	I6 (1)	3	1.75x	16.2	2440	9.29	2.23
	Maximum GM	I6 (1)	3	1.25x	16.0	2450	9.29	2.23
	Maximum WPi	I6 (1)	3	1.00x	15.9	2440	9.29	2.23
Dinajpur								
Current RFP		3–4 irrigs (4)	8	1.00x	11.3	1500	1.93	1.43
CS1	Maximum REY	I1 (5)	8	1.75x	12.0	1580	1.76	1.52
	Maximum GM	I1 (5)	8	1.75x	12.0	1580	1.76	1.52
	Maximum WPi	I1 (5)	8	1.25x	11.7	1560	1.80	1.46
CS2	Maximum REY	I1 (5)	8	1.75x	14.9	1850	1.97	1.81
	Maximum GM	I1 (5)	8	1.50x	14.8	1860	1.98	1.80
	Maximum WPi	I1 (5)	8	1.25x	14.7	1850	2.01	1.76
CS3	Maximum REY	I1 (6)	11	1.50x	15.3	2040	1.68	1.95
	Maximum GM	I1 (6)	11	1.25x	15.2	2050	1.69	1.94
	Maximum WPi	I6 (3)	11	1.50x	14.5	1890	1.81	1.83

values for both parameters in different soil depths are presented in Supplementary Table 1.

2.3.5 Components of water balance

Components of water balance such as runoff, drainage, infiltration, crop transpiration (Ep), soil evaporation (Es), and evapotranspiration (ET) were simulated by APSIM and compared amongst the cropping system scenarios examined.

3 Results

3.1 System REY

At the Rajshahi site (fine-textured soil with a shallow water table), an average REY of 11.9 t ha^{-1} was achieved under the current recommended farmers' practice (RFP) (Table 1). The N fertilizer rate for the RFP was 90 kg ha^{-1} for rice and 120 kg ha^{-1} for wheat, and on average, three irrigations were applied to both rice (AWD 2 days) and wheat (applied at the critical growth stages (CRI (Z 1.3–1.4), booting (Z 4.0–4.9), and dough development (Z 8.0)). The maximum average REY achieved under the CT-RW system (CS1) was 12.3 t ha^{-1}. This was possible when increasing the N fertilizer rate by a factor of 2.00 (i.e. 180 kg ha^{-1} for rice and 240 kg ha^{-1} for wheat), practicing the same irrigation for rice (AWD 2 days, average three irrigations), but, reducing irrigation for wheat (irrigated when ESW fell below 140 mm, average two irrigations reduction). The maximum achievable average system yield with the CT-based intensification in the RW system (CS2) was 16.0 t ha^{-1}, while the maximum achievable yield with the CA-based intensification (CS3) was 16.2 t ha^{-1} compared to the RFP (11.9 t ha^{-1}). The irrigation strategy for maximum rice yield was similar to that of RFP, while the wheat required reduced irrigation (irrigated when ESW fell below 140 mm, average two irrigations reduction) than what farmers currently apply. Maximum yield was achieved by increasing N fertilizer rate by a factor of 2.00 in CS2 and by a factor of 1.75 in CS3. The maximum possible system REY increased under the modified operating strategy in the following order: CS3 > CS2 > CS1.

At the Dinajpur site (coarse-textured soil with a deep water table), an average REY of 11.3 t ha^{-1} was achieved under the current RFP (Table 1). The N fertilizer and irrigation management strategy for rice and wheat in the RFP were similar to that of the Rajshahi site. The rice crop was irrigated on average eight times per season, while the wheat crop was irrigated on average four times per season (including pre-sowing irrigation, if applied) in the RFP. The maximum average REY achieved under the CT-RW system (CS1) was 12.0 t ha^{-1} and under the CT-RWM system (CS2) was 14.9 t ha^{-1}. Both of these REY's were achieved by applying a higher N rate (increased by a factor of 1.75 to both rice and wheat) and one extra irrigation to wheat (irrigated when ESW fell below 240 mm, average five irrigations) compared to the current RFP. The rice irrigation application was similar to that of the RFP in both the CS1 and CS2 (average eight irrigations). The average system yield was maximized to 15.3 t ha^{-1} under increased N rate and modified irrigation management strategy for both rice and wheat in the CA-RWM system (CS3). The applied N fertilizer rate was increased by a factor of 1.50 (i.e. 135 kg ha^{-1} for rice and 180 kg ha^{-1} for wheat), three extra irrigations to rice (AWD 2 days, average eleven irrigations), and two extra irrigations to wheat (irrigated when ESW fell below 240 mm, average six irrigations). The maximum possible system REY increased under the modified operating strategy in the following order: CS3 > CS2 > CS1.

3.2 System GM

At the Rajshahi site, the N fertilizer and irrigation management strategy which maximized system REY was similar to that which maximized system GM in all the cropping system scenarios tested, except in the CA-RWM system (CS3). The CA-RWM system required less N fertilizer (approximately 14% less) to maximize GM compared to the N fertilizer required for maximizing system REY (Table 1).

At the Dinajpur site, the CT-RW system (CS1) required the same amount of N fertilizer, while the CT-RWM system (CS2) and CA-RWM system (CS3) required less N fertilizer (approximately 14% less in CS2 and 17% less in CS3) to maximize GM compared to the N fertilizer required for maximizing system REY (Table 1). The irrigation requirement for both rice and wheat which maximized GM was similar to that required to maximize system REY.

3.3 System WPi

At the Rajshahi site, the irrigation management strategy which maximized WPi (average one irrigation to wheat and three irrigations to rice per season) was similar to that which maximized the system REY and GM in all the cropping system scenarios considered (Table 1). However, the maximum WPi was achieved with the recommended N rate for both rice and wheat (i.e. 90 kg ha^{-1} for rice and 120 kg ha^{-1} for wheat), except in the CT-RW system where the N rate was similar (i.e. 180 kg ha^{-1} for rice and 240 kg ha^{-1} for wheat) to that which maximized the system REY and GM.

At the Dinajpur site, the irrigation management strategy which maximized WPi (average five irrigations to wheat and eight irrigations to rice per season) was similar to that which maximised the system REY and GM in CT-based systems (CS1 and CS2) (Table 1). The maximum WPi in the CA-RWM system (CS3) was achieved with reduced irrigation application to wheat (irrigated when ESW fell below 140 mm, average two irrigations reduction) compared to that which maximized the system REY and GM. The maximum WPi was achieved with a reduced N rate for both rice and wheat in CT-based systems (CS1 and CS2). However, in the CA-RWM system (CS3), the maximum WPi was achieved with a slightly higher N rate (average 20% increase) than that required to maximize the system GM.

3.4 System response across the management space

The outputs of the simulation study considering wheat irrigation and N management across the cropping system intensification options have been illustrated as contour plots focusing on key system variables such as system REY (Fig. 2), GM (Fig. 3), and WPi (Fig. 4). There were trade-offs between the system REY, GM, and WPi. The contour lines closer together indicate more rapid changes of system variables, and contour lines further apart with flatter regions indicate plateauing or a small change of system variables per unit of change in management. From these contour plots, a farmer can decide which agronomic modification(s) (i.e. wheat irrigation and N rate) he/she will make to achieve his/her target variable(s). This process will help smallholder farmers to make their own judgement for maximising outcomes by adopting appropriate strategic management options (tillage, irrigation, and N fertilizer, etc.) under different cropping systems and environments with additional benefits of improving soil health and sustainability while reducing environmental risk. Table 2 provides an example of optimization when keeping system REY as the key target; further, it can be targeted for simultaneous optimization of multiple variables, depending on the farmer's priorities and incentives (REY, GM, soil health, sustainability, etc.). The details of crop yield and components of water balance associated with this optimization are provided in Supplementary Table 2.

At the Rajshahi site, the contour lines changed only with the N rates, which indicates that the system variables did not respond to the wheat irrigation strategy (Figs. 2, 3, and 4). The contour lines are closer at the lower N rates, which indicates more rapid changes of the system output variables with increasing N rates (from 0 to 0.75× recommended rates), and

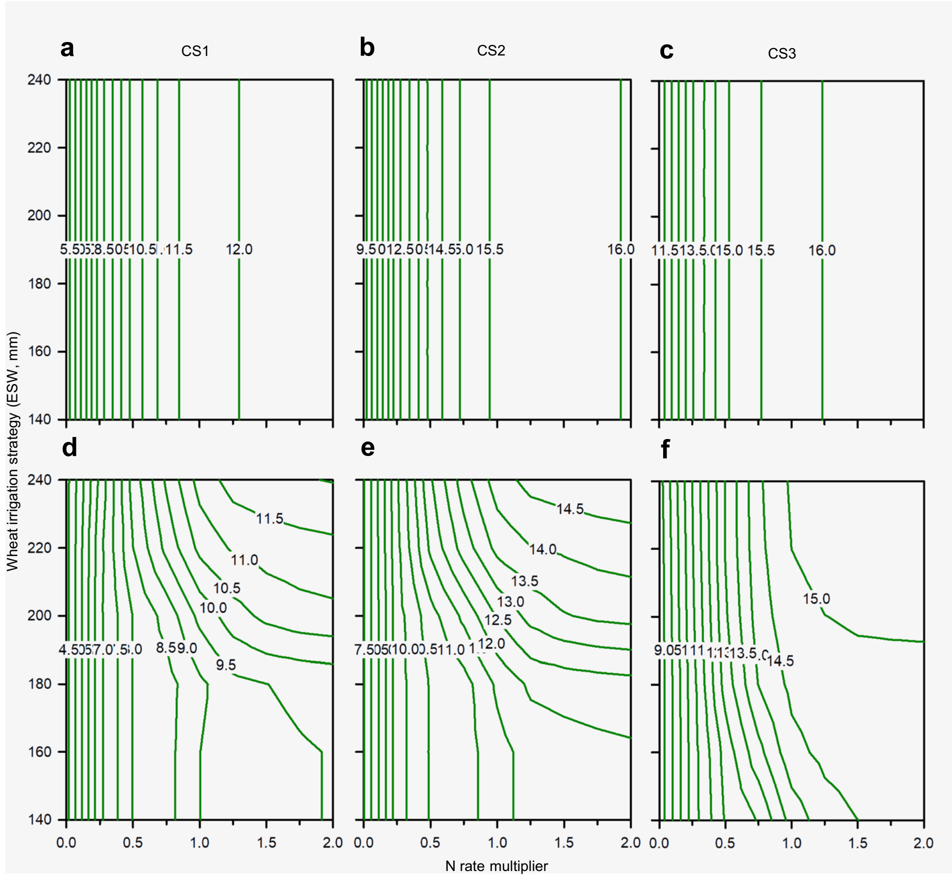

Fig. 2 Effect of wheat irrigation strategy and N rate on system rice equivalent yield (REY, t ha^{-1}). REY compared under each cropping system (CS1 = PTR rice – CT wheat, CS2 = PTR rice – CT wheat – CT mungbean, and CS3 = ZT UPTR rice – ZT wheat – ZT mungbean) at **a**–**c** Rajshahi and **d**–**f** Dinajpur. ESW is the trigger level for re-irrigation in wheat. The contour lines closer together indicate more rapid changes of system variables, and contour lines further apart with flatter regions indicate plateauing or a small change of system variables per unit of change in management.

after that, a flatter region indicates a small change with further increases in N rates. If a farmer wants to optimize resource allocation (irrigation and N fertilizer) by keeping system REY as the key target, then the modified operating strategy (wheat irrigation, N rate, and adopting CA-RWM) provides 16.0 t ha^{-1} system REY, which is 4.10 t ha^{-1} higher than what farmers currently achieve (RFP) but 0.20 t ha^{-1} lower than the maximum possible amongst the investigated scenario combinations (Tables 1 and 2). The modified operating strategy includes adopting the CA-RWM (CS3), a reduction in wheat irrigation (irrigate when ESW falls below 140 mm, average two irrigations reduction), and an increase in N rate by a factor of 1.25 compared to the current RFP. The associated GM for these settings (2450 USD ha^{-1}) is 41% higher than the RFP and similar to the maximum possible GM amongst the investigated combination scenarios. The WPi (9.29 USD ha^{-1} mm^{-1}) is 119% higher than that of the RFP (4.24 USD ha^{-1} mm^{-1}) and similar to the best possible WPi (Tables 1 and 2). The Ep:Es ratio is 52% higher (2.23) than that of current RFP (1.47) under these settings, which indicates more productive use of water. The average crop yields are 6180 kg ha^{-1} for rice, 4650 kg ha^{-1} for wheat, and 1110 kg ha^{-1} for mungbean, with standard deviations of 380 kg ha^{-1}, 366 kg ha^{-1}, and 88 kg ha^{-1} respectively (Supplementary Table 2).

At the Dinajpur site, the contour lines changed for both wheat irrigation strategy and N rates, which indicates that the system variables responded to both management factors (Figs. 2, 3, and 4). Similar to the Rajshahi site, the optimized system REY of 15.2 t ha^{-1} is achieved in the CA-RWM (CS3) by increasing the N rate by a factor of 1.25; however, it requires two extra irrigations to wheat and three extra irrigations to rice compared to RFP (Table 2). The achievable system REY under these settings is 3.90 t ha^{-1} higher than what farmers currently achieve (RFP) but 0.10 t ha^{-1} lower than the maximum possible amongst the investigated scenario combinations (Tables 1 and 2). The GM of 2040 USD ha^{-1} is 37% higher than that of the RFP and similar to the maximum possible GM (2050 USD ha^{-1}) amongst the investigated combinations. The WPi of 1.71 USD ha^{-1} mm^{-1} is 11% less than that of the RFP and 15% less than the best possible WPi. The Ep:Es ratio is higher (1.94) than that of current RFP (1.43), which indicates more productive use of water. The associated average crop yields are 5820 kg ha^{-1} for rice, 4960 kg ha^{-1} for wheat, and 858 kg ha^{-1} for mungbean, with standard deviations of 326 kg ha^{-1}, 386 kg ha^{-1}, and 210 kg ha^{-1}, respectively (Supplementary Table 2).

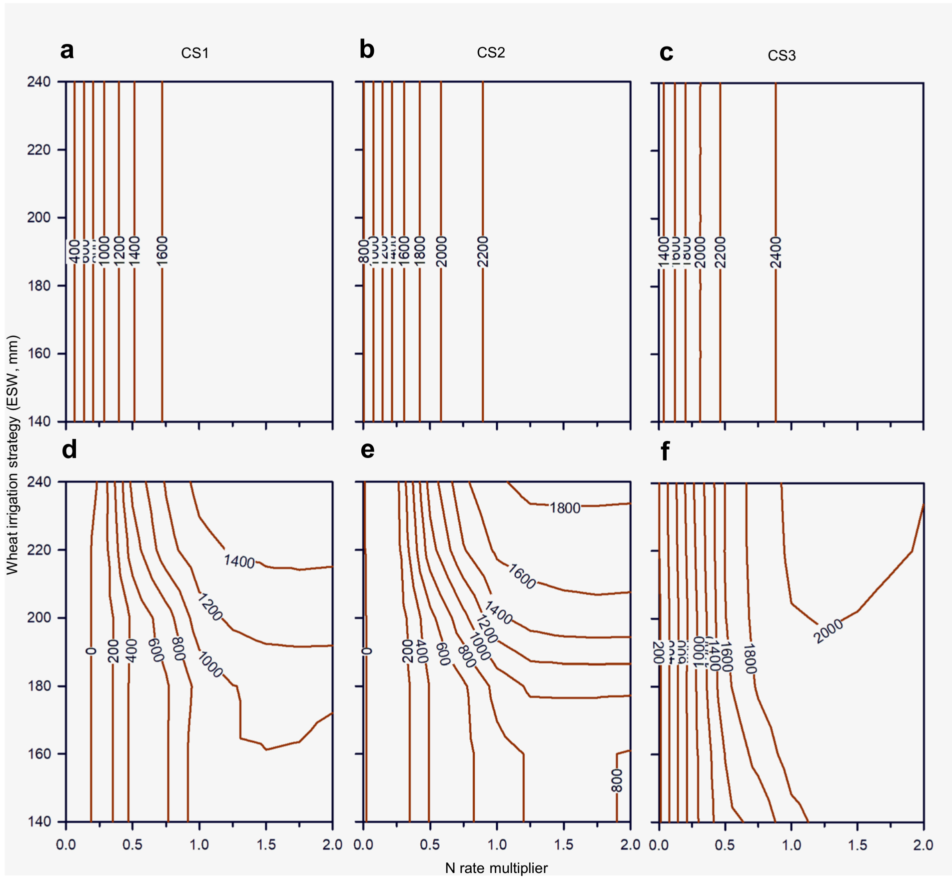

Fig. 3 Effect of wheat irrigation strategy and N rate on system gross margin (GM, USD ha^{-1}). GM compared under each cropping system (CS1 = PTR rice – CT wheat, CS2 = PTR rice – CT wheat – CT mungbean, and CS3 = ZT UPTR rice – ZT wheat – ZT mungbean) at **a**–**c** Rajshahi and **d**–**f** Dinajpur. ESW is the trigger level for re-irrigation in wheat. The contour lines closer together indicate more rapid changes of system variables, and contour lines further apart with flatter regions indicate plateauing or a small change of system variables per unit of change in management.

3.5 Changes in SOC

At the Rajshahi site, the optimized management strategy resulted in increased SOC (0–15 cm soil depth) over time in the CA-RWM (CS3) compared with that of the initial value (Fig. 5a). The SOC increased steadily from 12.2 g kg^{-1} and reached 15.7 g kg^{-1} after 37 years of cropping. The SOC in all the CT-based systems (CS1, CS2, and RFP) decreased over time.

At the Dinajpur site, the SOC under optimised management in the CA-RWM (CS3) also increased steadily from 7.3 g kg^{-1} and reached 13.8 g kg^{-1} after 37 years of cropping (Fig. 5b). In contrast to the SOC of CT-based system at the Rajshahi site, the SOC increased slowly under CT-based systems at the Dinajpur site.

3.6 Changes in STN

At the Rajshahi site, the optimized management strategy resulted in a 46% increase of STN (0–15 cm soil depth) in the CA-RWM (CS3) after 37 years of cropping compared with that of the initial year (Fig. 5c). The STN in all the CT-based systems (CS1, CS2, and RFP) remained relatively constant.

At the Dinajpur site, the STN under optimized management in the CA-RWM (CS3) increased by 59% after 37 years of cropping compared with that of the initial year (Fig. 5d). The STN in all other systems remained almost unchanged.

3.7 Components of water balance

The optimized management strategy in all the cropping system intensification options (CS1 to CS3) increased the average Ep and reduced Es (Supplementary Table 2). The ET was higher in the intensified systems (CS2 and CS3) compared to the double-crop systems (RFP and CS1) due to the inclusion of one extra crop (mungbean) in the system. Although the ET was higher in CS2 and CS3, the Ep:Es was higher in these intensified systems, which indicates more efficient use of water.

4 Discussion

4.1 Optimizing system productivity

Our analysis suggests that the productivity of the RW system can be increased by modifying the agronomic management

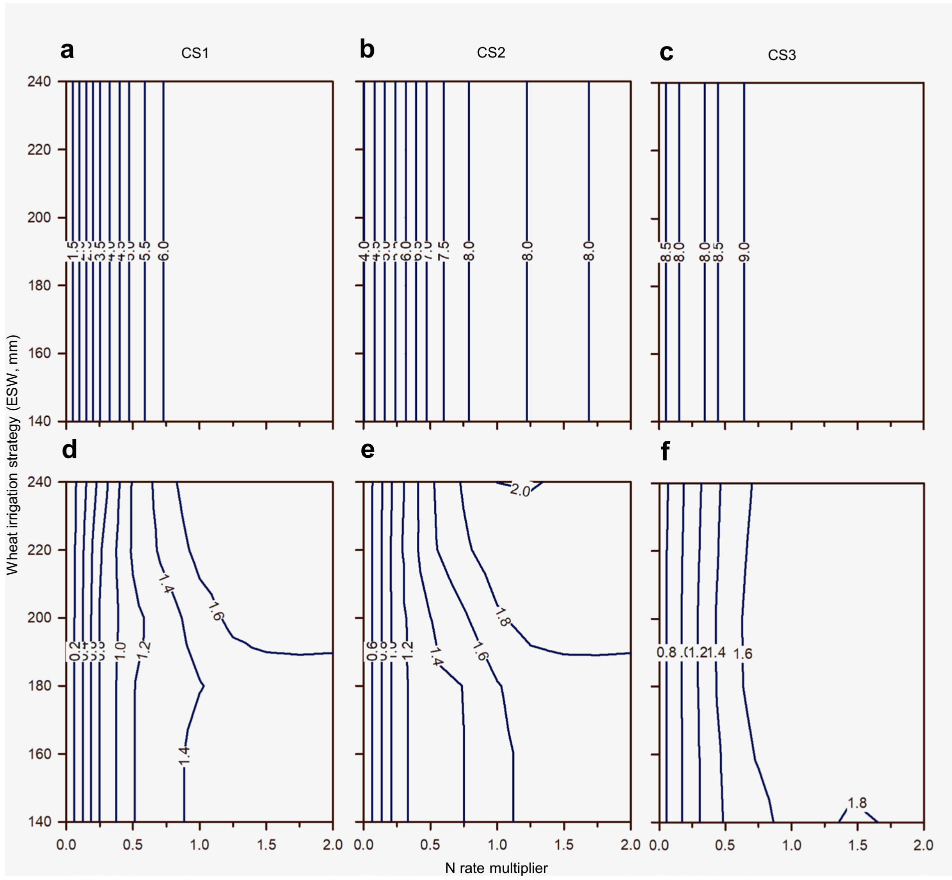

Fig. 4 Effect of wheat irrigation strategy and N rate on irrigation water productivity (WPi, USD ha^{-1} mm^{-1}). WPi compared under each cropping system (CS1 = PTR rice – CT wheat, CS2 = PTR rice – CT wheat – CT mungbean, and CS3 = UPTR rice – ZT wheat – ZT Mungbean) at **a**–**c** Rajshahi and **d**–**f** Dinajpur. ESW is the trigger level for re-irrigation in wheat. The contour lines closer together indicate more rapid changes of system variables, and contour lines further apart with flatter regions indicate plateauing or a small change of system variables per unit of change in management.

Table 2 An example of optimization keeping system rice equivalent yield (REY) as the key target in each cropping system at Rajshahi and Dinajpur (average 1982–2019). Average number of irrigations for wheat is in parentheses.

Cropping system	Wheat irrigation strategy	Rice irrigation (No.)	N fertilizer multiplier	REY (t ha^{-1})	GM (USD ha^{-1})	WPi (USD ha^{-1} mm^{-1})	Ep:Es
Rajshahi							
Current RFP	3–4 irrigs (3)	3	1.00x	11.9	1730	4.24	1.47
CS1	I6 (1)	3	1.25x	12.0	1760	6.38	1.57
CS2	I6 (1)	3	1.00x	15.6	2240	8.12	2.06
CS3	I6 (1)	3	1.25x	16.0	2450	9.29	2.23
Dinajpur							
Current RFP	3–4 irrigs (4)	8	1.00x	11.3	1500	1.93	1.43
CS1	I1 (5)	8	1.25x	11.7	1560	1.80	1.46
CS2	I1 (5)	8	1.25x	14.7	1850	2.01	1.76
CS3	I2 (5)	11	1.25x	15.2	2040	1.71	1.94

currently recommended for farmers in the region. The cropping system, soil type, water table depth, and environment are the main factors influencing crop production that need to be considered when varying management strategies. The modifications that can increase productivity include irrigation management in wheat, increased N fertilization in rice and wheat, and intensification of the system through the inclusion of a summer legume (mungbean). The increased productivity achieved through the inclusion of a summer legume in the RW system has also been reported in other studies (Islam et al. 2019; Laik et al. 2014). The system productivity is increased further when the modification includes CA-based management together with irrigation and N management. The crops responded differently to the modified management across the sites, confirming that agronomic management interventions should be made following consideration of the local soil types, water table dynamics, and agro-climates (Jat et al. 2020).

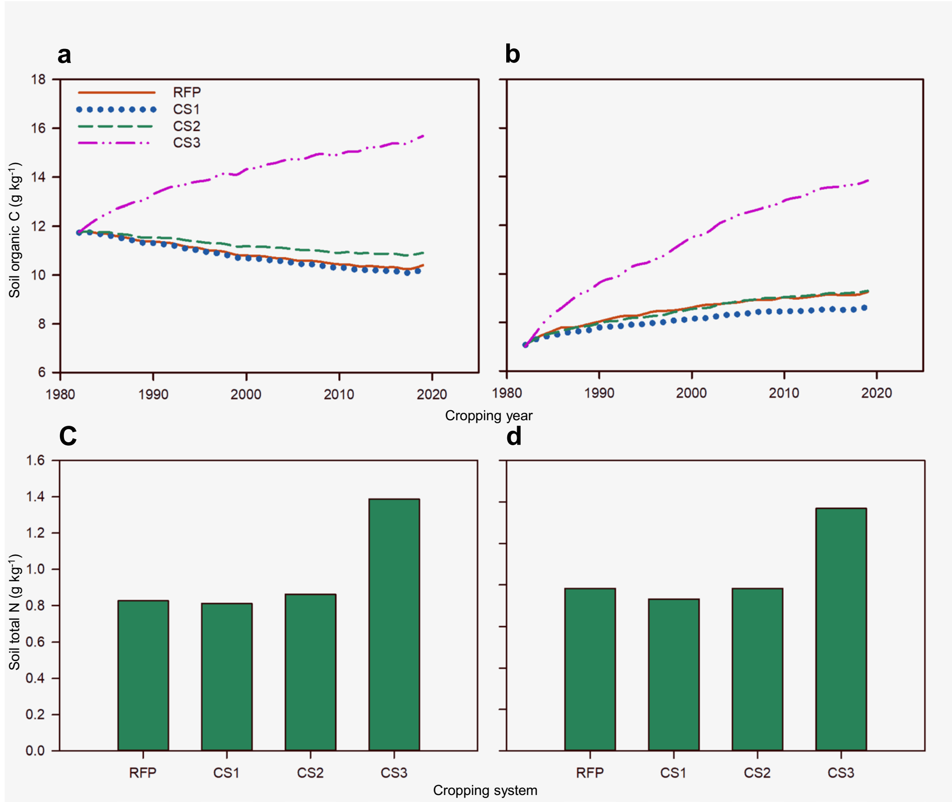

Fig. 5 Changes in soil organic C and soil total N. Changes in **a**, **b** soil organic C during 37 years (1982–2019) of cropping and **c**, **d** soil total N after 37 years (1982–2019) of cropping at 0–15 cm soil layer under current and optimise resource (irrigation and N) management in the cropping systems (RFP = recommended farmers practice, CS_1 = PTR rice – CT wheat, CS_2 = PTR rice – CT wheat – CT mungbean, and CS_3 = ZT UPTR rice – ZT wheat – ZT mungbean) at **a**, **c** Rajshahi and **b**, **d** Dinajpur.

There are always trade-offs between the system yield, GM, WPi, and components of water balance. Therefore, the optimization of agronomic management depends on which system variable(s) is (are) to be increased and by how much, as the target variable(s) and farmer's aspirations may differ between individual farmers and according to regional characteristics and perspectives. If land availability is the most limiting factor, the target should be to maximize the system production per unit area (i.e. maximize yields) (Balwinder-Singh et al. 2015). In a land limited environment, the target may also be to increase the system GM by optimizing agronomic management (Gaydon et al. 2021). If, however, water is the most limiting factor and land is abundant, the target will be to maximize the system WPi which would allow cropping and irrigating over a wider area, consequently increasing profit from the whole farm (Gaydon et al. 2012). From a regional perspective in a water-limited environment, the target may also be to reduce ET which means maximizing the system water productivity with respect to ET (Sudhir-Yadav et al. 2011).

Smallholder RW farmers dominate food production in the EGP region. Therefore, achieving food security from limited land is a major concern for policymakers and people of the region. Thus, policymakers may want farmers to maximize system production to feed people of the region. Maximizing system production is also important for the farmers who largely depend on their limited land for their own family food security. In general, the optimization should focus on system productivity while maintaining sustainability with higher resiliency under changing climate scenarios in the EGP region. At the Rajshahi site (fine-textured soil with a shallow water table), the strategy includes adopting CA practices (CA-RWM) together with 25% higher N fertilizer application in both rice and wheat than current RFP, AWD irrigations to rice (allowing the soil to dry for 2 days between irrigations, three irrigations per season same as RFP), and deficit irrigation to wheat (apply irrigation when ESW within root zone falls below 140 mm, two irrigations less than current RFP). At the Dinajpur site (coarse-textured soil with a deep water table), optimization suggests a very similar approach (adopting CA plus 25% higher N fertilizer) to that of Rajshahi, however, with extra irrigations to rice (allowing the soil to dry for 2 days between irrigations, three extra irrigations than current RFP) and wheat (apply irrigation when ESW within root zone falls below 140 mm, one extra irrigation than current RFP). Our analysis also suggests that the CT-RWM system with similar N and wheat irrigation strategy followed in the optimized CA-RWM achieves good system yield (3% less than optimized CA-RWM), however, saves irrigation in rice (three irrigations less than the optimized CA-RWM).

Rabi season (dry season) crops (e.g. wheat, maize, potato, oilseeds, and *boro* rice) rely on irrigation from groundwater.

Rabi season water shortage in the drier region of the EGP (e.g. Barind Tract of Bangladesh, parts of Bihar, and West Bengal states of India) limits *Rabi* crops planting in wider areas. For example, groundwater depletion in the Barind Tract of Bangladesh has been reported in the literature (Dey et al. 2013; Shahid and Hazarika 2009). Irrigation in the Barind Tract is mainly operated through the government-subsidised and installed deep tube well (pump). An assigned pump operator runs the irrigation service for the farmers under the area coverage of the pump. Each pump has a limited capacity to irrigate a certain area in each dry season, and thus, all the farms may not get irrigation water in a certain dry season. In the last couple of decades, the extraction of irrigation water through shallow pumps has been limited because of highly seasonal fluctuations in the water table which makes water extraction more difficult and expensive from shallow aquifers (Krupnik et al. 2017). In this water-limited environment, a strategy that maximizes WPi would result in less yield per unit area but permit a much larger area of production and thus deliver more yield and profit for the whole region.

It should be noted that the economic cost–price structures considered in this paper implicitly contain economic subsidies which operate in the region. It would be a worthwhile future undertaking to evaluate the impact of removing (or changing) subsides by re-running this simulation exercise with different cost–price structures and examining the result on both optimal agronomic management practices and also profitability and input use efficiency.

4.2 System sustainability

Our analysis clearly shows that the productivity improvement of the RW system is possible by changing the current agronomic management practiced by farmers. However, the improvement will become meaningful only if the achievement comes along with the sustainable utilization of resources. The optimized management strategy in the CA-RWM (CS3), focusing on the system yield, results in more productive use of water, and an increase in SOC, and STN in the topsoil (0–15 cm depth). The rate of increase in SOC was higher in Dinajpur than Rajshahi due to light soils and lower base SOC at Dinajpur. The improvement of SOC and STN under CA-RWM system could be attributed to the combination of a greater crop biomass (three crops rather than two) and retention of crop residues in the field, resulting in the gradual accumulation of soil organic matter (Jat et al. 2019). The greater accumulation of SOC and STN under CA-RWM system is likely to be associated with factors such as a reduction in soil disturbance, retention of crop residues on the soil surface, the additional legume crop biomass, and higher moisture retention; all of these factors capable of contributing to the formation and stabilisation of soil aggregates and protection of their associated organic carbon (Jat et al. 2019; Kumari et al. 2011).

The ET was higher under the intensified production system (CS2 and CS3) due to increasing the productivity by accommodating one extra crop (mungbean) and also to increased biomass and grain yield of most of the component crops of the higher input system. Reducing the system ET is an important parameter in saving water at a regional scale (Humphreys et al. 2010; Loeve et al. 2004). The Es is the unproductive loss of water from the system, and according to our findings, the Es was reduced and Ep increased (which increased the total system ET) under the optimized management compared to the current RFP.

5 Conclusions

Our investigation using the process-based cropping system model APSIM (earlier robustly validated in these environments) demonstrates that the long-term productivity of the RW system can be improved by modifying the current agronomic management practices. Intensification of the CT-based system (CT-RWM) increases productivity and farm profit but not sustainability due to decreasing SOC and STN in long-term simulations. The intensified CA system however provided both increased productivity and sustainability. We found that there are always trade-offs between system variables when optimizing the system performance, and optimized management settings varied across different environments. We believe that this process-based simulation study provides a guideline for modifying the agronomic management from both a production and sustainability perspective and that this approach could be followed for future cropping system studies in any region of the world.

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Authors' contributions Conceptualization, AKC and DSG; methodology, AKC, DSG, NWM, and RCD; investigation, AKC, NEAS, and AH; formal analysis, AKC; writing — original draft preparation, AKC; writing — review and editing, AKC, DSG, NWM, RCD, WDB, MKG, and AH; supervision, DSG, NWM, RCD, and WDB; funding acquisition, DSG, NWM, and MKG.

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Data availability The data that support the findings of this study are available from the principal author on reasonable request.

Code availability Available from the principal author on reasonable request.

Declarations

Ethics approval Not relevant for this research

Consent to participate Not relevant for this research

Consent for publication Not relevant for this research

Conflict of interest The authors declare no competing interests.

References

Balwinder-Singh, Humphreys E, Gaydon DS, Sudhir-Yadav (2015) Options for increasing the productivity of the rice-wheat system of north West India while reducing groundwater depletion. Part 2. Is conservation agriculture the answer? Field Crops Res 173:81–94. https://doi.org/10.1016/j.fcr.2014.11.019

Bhatt R, Kukal SS, Busari MA, Arora S, Yadav M (2016) Sustainability issues on rice–wheat cropping system. International Soil and Water Conservation Research 4(1):64–74. https://doi.org/10.1016/j.iswcr.2015.12.001

Chaki AK (2021) The value of conservation agriculture (CA) technologies in improving productivity and resource-use efficiency for farmers in the eastern Gangetic Plains (EGP) of Bangladesh. The University of Queensland, Brisbane, Queensland, Australia

Chaki AK, Gaydon DS, Dalal RC, Bellotti WD, Menzies NW (2019) Conservation agriculture practices lead to increased water and nitrogen use efficiency in the rice-wheat system of the Eastern Gangetic Plains (EGP), Rajshahi, Bangladesh. Paper presented at the 2019 ASA-CSSA-SSSA International Annual Meeting, San Antonio, Texas, USA, 10-13 November 2019

Chaki AK, Gaydon DS, Dalal RC, Bellotti WD, Gathala MK, Hossain A, Rahman MA, Menzies NW (2021) Conservation agriculture enhances the rice-wheat system of the eastern Gangetic Plains in some environments, but not in others. Field Crops Res 265:108109. https://doi.org/10.1016/j.fcr.2021.108109

Chaki AK, Gaydon DS, Dalal RC, Bellotti WD, Gathala MK, Hossain A, Menzies NW (2022) How we used APSIM to simulate conservation agriculture practices in the rice-wheat system of the eastern Gangetic Plains. Field Crops Res 275:108344. https://doi.org/10.1016/j.fcr.2021.108344

Dey NC, Bala SK, Islam AS, Rashid MA, Hossain M (2013) Sustainability of groundwater use for irrigation in Northwest Bangladesh. BRAC, Dhaka, Bangladesh

Ericksen P, Thornton P, Notenbaert A, Cramer L, Jones P, Herrero M (2011) Mapping hotspots of climate change and food insecurity in the global tropics | CGIAR climate. In: CCAFS report no. 5. CGIAR research program on climate change, agriculture and food security (CCAFS), Copenhagen, Denmark citeulike-article-id:10500044

Gathala MK, Laing AM, Tiwari TP, Timsina J, Islam MS, Chowdhury AK, Chattopadhyay C, Singh AK, Bhatt BP, Shrestha R, Barma NCD, Rana DS, Jackson TM, Gerard B (2020) Enabling smallholder farmers to sustainably improve their food, energy and water nexus while achieving environmental and economic benefits. Renew Sust Energ Rev 120:109645. https://doi.org/10.1016/j.rser.2019.109645

Gaydon DS, Meinke H, Rodriguez D (2012) The best farm-level irrigation strategy changes seasonally with fluctuating water availability. Agric Water Manag 103:33–42. https://doi.org/10.1016/j.agwat.2011.10.015

Gaydon DS, Khaliq T, M-u-D A, Cheema MJM, Gull U (2021) Tweaking Pakistani Punjab rice-wheat management to maximize productivity within nitrate leaching limits. Field Crops Res 260:107964. https://doi.org/10.1016/j.fcr.2020.107964

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res 114(1):23–34. https://doi.org/10.1016/j.fcr.2009.06.017

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145(2):127. https://doi.org/10.1017/S0021859607006892

Holzworth DP, Huth NI, Devoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z et al (2014) APSIM - evolution towards a new generation of agricultural systems simulation. Environ Model Softw 62:327–350. https://doi.org/10.1016/j.envsoft.2014.07.009

Humphreys E, Kukal SS, Christen EW, Hira GS, Balwinder-Singh S-Y, Sharma RK (2010) Halting the groundwater decline in north-West India-which crop technologies will be winners? Adv Agron 109:155–217. https://doi.org/10.1016/B978-0-12-385040-9.00005-0

Islam S, Gathala MK, Tiwari TP, Timsina J, Laing AM, Maharjan S, Chowdhury AK, Bhattacharya PM, Dhar T, Mitra B, Kumar S, Srivastwa PK, Dutta SK, Shrestha R, Manandhar S, Sherestha SR, Paneru P, Siddquie N-EA, Hossain A et al (2019) Conservation agriculture based sustainable intensification: increasing yields and water productivity for smallholders of the eastern Gangetic Plains. Field Crops Res 238:1–17. https://doi.org/10.1016/j.fcr.2019.04.005

Jahan MAHS, Sen R, Ishtiaque S, Choudhury AK, Akhter S, Ahmed F, Biswas JC, Manirruzaman M, Miah MM, Rahman MM, Kalra N (2018) Optimizing sowing window for wheat cultivation in Bangladesh using CERES-wheat crop simulation model. Agric Ecosyst Environ 258:23–29. https://doi.org/10.1016/j.agee.2018.02.008

Jat HS, Datta A, Choudhary M, Sharma PC, Yadav AK, Choudhary V, Gathala MK, Jat ML, McDonald A (2019) Climate smart agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of north-West India. CATENA 181:104059. https://doi.org/10.1016/j.catena.2019.05.005

Jat ML, Chakraborty D, Ladha JK, Rana DS, Gathala MK, McDonald A, Gerard B (2020) Conservation agriculture for sustainable intensification in South Asia. Nat Sustain 3(4):336–343. https://doi.org/10.1038/s41893-020-0500-2

Krupnik TJ, Schulthess U, Ahmed ZU, McDonald AJ (2017) Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential. Land Use Policy 60:206–222. https://doi.org/10.1016/j.landusepol.2016.10.001

Kumar V, Jat HS, Sharma PC, Balwinder-Singh GMK, Malik RK, Kamboj BR, Yadav AK, Ladha JK, Raman A, Sharma DK, McDonald A (2018) Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric Ecosyst Environ 252:132–147. https://doi.org/10.1016/j.agee.2017.10.006

Kumari M, Chakraborty D, Gathala MK, Pathak H, Dwivedi BS, Tomar RK, Garg RN, Singh R, Ladha JK (2011) Soil aggregation and associated organic carbon fractions as affected by tillage in a rice–wheat rotation in North India. Soil Biol Biochem 75(2):560–567. https://doi.org/10.2136/sssaj2010.0185

Ladha JK, Kumar V, Alam MM, Sharma S, Gathala M, Chandna P, Saharawat YS, Balasubramanian V (2009) Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In: Erenstein O, Hardy B (eds) Ladha JK, Yadvinder-Singh. Integrated crop and resource management in the rice-wheat system of South Asia. IRRI, Los Baños, Philippines, pp 69–108

Ladha JK, Rao AN, Raman AK, Padre AT, Dobermann A, Gathala M, Kumar V, Saharawat Y, Sharma S, Piepho HP, Alam MM, Liak R, Rajendran R, Reddy CK, Parsad R, Sharma PC, Singh SS, Saha A, Noor S (2016) Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. Glob Change Biol 22(3):1054–1074. https://doi.org/10.1111/gcb.13143

Laik R, Sharma S, Idris M, Singh AK, Singh SS, Bhatt BP, Saharawat Y, Humphreys E, Ladha JK (2014) Integration of conservation agriculture with best management practices for improving system performance of the rice-wheat rotation in the eastern indo-Gangetic Plains of India. Agric Ecosyst Environ 195:68–82. https://doi.org/10.1016/j.agee.2014.06.001

Loeve R, Dong B, Molden D, Li YH, Chen CD, Wang JZ (2004) Issues of scale in water productivity in the Zhanghe irrigation system: implications for irrigation in the basin context. Paddy Water Environ 2(4):227–236. https://doi.org/10.1007/s10333-004-0061-4

Pittelkow CM, Liang X, Linquist BA, van Groenigen KJ, Lee J, Lundy ME, van Gestel N, Six J, Venterea RT, van Kessel C (2015) Productivity limits and potentials of the principles of conservation agriculture. Nature 517(7534):365. https://doi.org/10.1038/nature13809

Shahid S, Hazarika MK (2009) Groundwater drought in the northwestern districts of Bangladesh. Water Resour Manag 24(10):1989–2006. https://doi.org/10.1007/s11269-009-9534-y

Sudhir-Yadav LT, Humphreys E, Gill G, Kukal SS (2011) Evaluation and application of ORYZA2000 for irrigation scheduling of puddled transplanted rice in north West India. Field Crops Res 122(2):104–117. https://doi.org/10.1016/j.fcr.2011.03.004

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