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Identifying optimum residue levels for stable crop and water productivity and carbon sequestration under a conservation agriculture based rice-wheat system

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ABSTRACT

To sustain food-production targets while reducing residue burning in the Indo-Gangetic Plains, adoption of conservation agriculture (CA) is desirable, amongst other potential adaptations. To identify the optimum residue levels for sustainable CA, the Agricultural Production Systems Simulator (APSIM) model was used to analyse 37 years (1984–2022) of diverse CA scenarios on productivity, sustainability and carbon footprints in the rice-wheat cropping system (RWCS). The study highlighted that APSIM has the capacity to capture the crop performance, phenology and CA scenario in RWCS. The scenario analysis indicated that maximum system productivity (SP) was recorded under higher residue (HR-9.33 t ha^{-1}) followed by higher-medium residue (HMR-8.97 t ha^{-1}) scenarios of CA, as compared to conventional tillage (CT-8.75 t ha^{-1}). Stable productivity was achieved under CA. Sustainable yield index and sustainable value index were significantly higher under HR (0.83 and 0.79, respectively) followed by HMR. The soil organic carbon concentration is predicted to increase ~30–95% in CA with a carbon sequestration rate of 0.1–0.37 t ha^{-1} yr^{-1}. The system water productivity was highest under HR (3.68 kg ha^{-1} mm^{-1}) which was ~10% higher than CT. Overall, the study revealed that the APSIM model is efficient in capturing CA effects in South Asian RWCS and that the adoption of CA results in greater and stable yields, higher water productivity, and more carbon capture over the long term, while reducing production costs.

1. Introduction

The rice-wheat cropping system (RWCS) acts as the mainstay of the world's food security system (Lalik et al., 2014; Banjara et al., 2021) and it is the foremost food-system of South Asia (Dhanda et al., 2022). In India, rice and wheat constitutes ~60% of total calorie intake (Gupta et al., 2003), contributing ~40% to country's total food basket (Gupta and Seth, 2007; Sharma et al., 2015). The importance of the RWCS in India increased considerably after the Green Revolution during the 1960 s, however, in the past 2–3 decades RWCS is becoming unsustainable because of injudicious use of natural resources (Chauhan et al., 2012). The predominant factors which resulted in the unsustainability of RWCS are: (i) Soil compaction beneath the plough layer (Bhatt et al., 2021); (ii) Emissions of greenhouse gases (Saini and Bhatt, 2020); (iii) Emergence of herbicide-resistant weeds and shift in weed flora (Chauhan et al., 2012; Bana et al., 2020); (iv) Decline in the level of water table (Bhatt et al., 2020); (v) Burning of crop residues and environmental pollution (Saini and Bhatt, 2020); (vi) Declining factor productivity (Ladha et al., 2003; Jat et al., 2011); (vii) Multi-nutrient deficiencies (Bana et al., 2013; Jat et al., 2014). However, the present population growth trends in South Asia indicate the need for a ~1.1% and ~1.7% increase per annum in rice and wheat production, respectively, over the next 30–40 years for ensured food supply in the region (Ray et al., 2013; Gathala et al., 2014). On the other hand, the natural

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resources in the region are 3–5 times more stressed due to population and economic pressures compared to the rest of the world and are more vulnerable to adversities of changing climate (Easterling et al., 2007).

Conservation Agriculture (CA) has been recommended by various researchers to make the RWCS more sustainable and environmental friendly (Chauhan et al., 2012; Nawaz et al., 2019; Bana et al., 2020; Dhanda et al., 2022; Chaki et al., 2022a). The CA is a crop production system that is based on three main principles (FAO, 2014; Pittelkow et al., 2015): (i) least disruption of soil with tillage implements, (ii) permanent soil coverage with crop residues or cover crops, (iii) diversification of existing cropping system. Various short and medium-term studies on CA have been reported to improve soil health (Norris and Congreves, 2018), soil-water conservation (Bhatt and Kukal, 2017), reduction in greenhouse gas emission and environmental pollution (Mangalassery et al., 2014), improved weed control (Bana et al., 2020), improvement in input use efficiency (Meena et al., 2016) and carbon sequestration under RWCS. However, most of these studies are either of shorter duration or considered just one or two CA practices. Studies on the long-term CA practices on crop and water productivity, economic sustainability, and carbon footprints under RWCS are lacking. Further, information on optimum residue levels for effective CA, and carbon sequestration rate under South Asian ecologies are not available. Therefore, it is required to understand the effect of practicing CA for the long-term on water productivity, sustainability, and carbon sequestration under RWCS. However, long-term field studies face a lot of constraints like limited money, labor, land availability, and delay in getting results (Choruma et al., 2019). Furthermore, field experiments present the findings from the research studies conducted at a particular time period and location, making the results site and season-specific (Patricia et al., 2013). Moreover, field experiments may not give sufficient data in space and time to make a decision regarding the most effective management practices (Jones et al., 2017a; Jones et al., 2017b). Seeing the shortcoming in the field experiments, there is a need to use alternative options to generate sufficient data for scientific advancements in CA science and decision and policy making.

Crop modelling is such a tool that can help in overcoming the constraints of long-term field experiments (Kephe et al., 2021). Crop modelling has been found to be effective in evaluating the influence of change in climatic conditions and crop management practices on productivity and environmental footprints (Xiong et al., 2014; Kadiyala et al., 2015). The crop models are rapid and cost-efficient alternatives for identifying the best practices for achieving sustainable and profitable crop yields (Yadav et al., 2012). However, crop simulation models cannot replace field research because field trials are a key part for the calibration and validation of crop models.

APSIM, the *Agricultural Production Systems Simulator* is such a modelling platform that uses data from field trials for the simulation of biophysical processes in cropping systems, particularly those relating to the production and ecological outcomes of management practices in the face of climate risks (Holzworth et al., 2014; Gaydon et al., 2017). APSIM focuses on the simulation of crop resource supply and soil resource dynamics in long-term changes in the soil conditions and sustainability associated with varying crop and management practices (Gaydon et al., 2017). It is a well-tested model in Indo-Gangetic Plains (IGP) (Balwinder-Singh et al., 2011; Mohanty et al., 2012; Subash et al., 2015; Balwinder-Singh et al., 2015; Gaydon et al., 2017; Kabir et al., 2017; Kabir et al., 2018a; Kabir et al., 2018b; Bana et al., 2022; Chaki et al., 2022b) under different cropping systems including RWCS. Gaydon et al. (2017) successfully simulated rice, wheat, maize, cotton, mustard, soybean, and canola yield with R^2 values of 0.83, 0.79, 0.85, 0.79, 0.55, 0.53, and 0.71, respectively across 12 Asian countries. Efficacious simulation of different crops across diverse management and environmental conditions indicates that APSIM is a reliable and robust simulation model which can be helpful to understand the long-term effect of different crop management strategies in a short time.

Therefore, considering the urgent need for understanding long-term CA effects and the model efficiency, the present study was planned to analyze modelled scenarios for diverse tillage and residue management options, by gaining insights into long-term system variability; and to simulate the likely impacts of the varying residue management options on intensive farming systems, including effects of different options on yield sustainability, water-productivity and carbon sequestration under RWCS.

2. Methodology

2.1. Model and scenario

The conventional-till (CT) puddled transplanted rice (PTR)–wheat system was compared with five crop residue management options of double zero-till (ZT) CA based rice–wheat rotations using APSIM model (version 7.9). Based on holding size and socio-economic conditions of IGP farmers, a rapid survey (n = 371) was carried out (Table S1) and following six residue management scenarios were identified and analyzed under long-term:

i) Direct seeded rice (DSR) – ZT wheat under no-residue (NR) retention: NR scenario;

ii) DSR – ZT wheat with 30% retention of rice residues: Low residue (LR) scenario;

iii) DSR with 30% wheat residue – ZT wheat with 30% retention of rice residues: Lower-medium residue retention (LMR) scenario;

iv) DSR with 30% retention of wheat residues – ZT wheat with 60% rice residue retention: Higher-medium residue retention (HMR) scenario;

v) DSR with 30% retention of wheat residues – ZT wheat with 100% rice residue retention: High residue retention (HR) scenario; and

vi) PTR – CT wheat with residue of both the crops removed: CT scenario.

2.2. Model parameterization

The APSIM model has been parameterized, calibrated and validated for the rice (cv. 'Pusa Sugandh-5′) and wheat (cv. 'HD-2967′) crops for north Indian conditions. The parameterization of the model was carried out using data from field experiments conducted by ICAR-Indian Agricultural Research Institute (IARI), New Delhi (Bana et al., 2020) (Fig. 1). A few phenotypic coefficients used for parameterization of rice and wheat are presented in Table 1. The simulations were performed using 37 years (1984–2022) of daily weather data (rainfall, temperature and sunshine hours) from the meteorological station at ICAR-IARI, New Delhi. However solar radiation, which is a necessary input for the model, was not available, hence, it was estimated from sunshine hours following the procedure of Bandyopadhyay et al. (2008). The IARI is located at 28°40′ N latitude; 77°12′ E longitude; 228.6 m altitude and characterized with semi–arid & sub–tropical climate, hot dry summers & severe cold winters. The mean annual rainfall is ~ 650 mm, of which nearly 80% is received during south–west monsoon (July to September) and the rest during October to May. The mean daily U.S. Weather Bureau Class 'A' open pan evaporation value reaches as high as 10.9 mm in the month of June and as low as 1.5 mm in January. The annual pan evaporation is about 850 mm.

To test the model accuracy, the root mean square error (RMSE) between simulated and observed data was calculated:

$RMSE = \sum_{i=1}^{n}(Si - Ai)^2/n]^{1/2}$.

Here Si and Ai are simulated and observed values respectively, and n is the number of observations.

The simulation experiments were carried out under on-farm environments in the national capital region of Delhi. The soil of the experimental site was sandy clay loam in the plough layer (0–150 mm) and further detail of the soil properties in different horizons is given in Table 2. As the crop residue retention for longer period enhances the

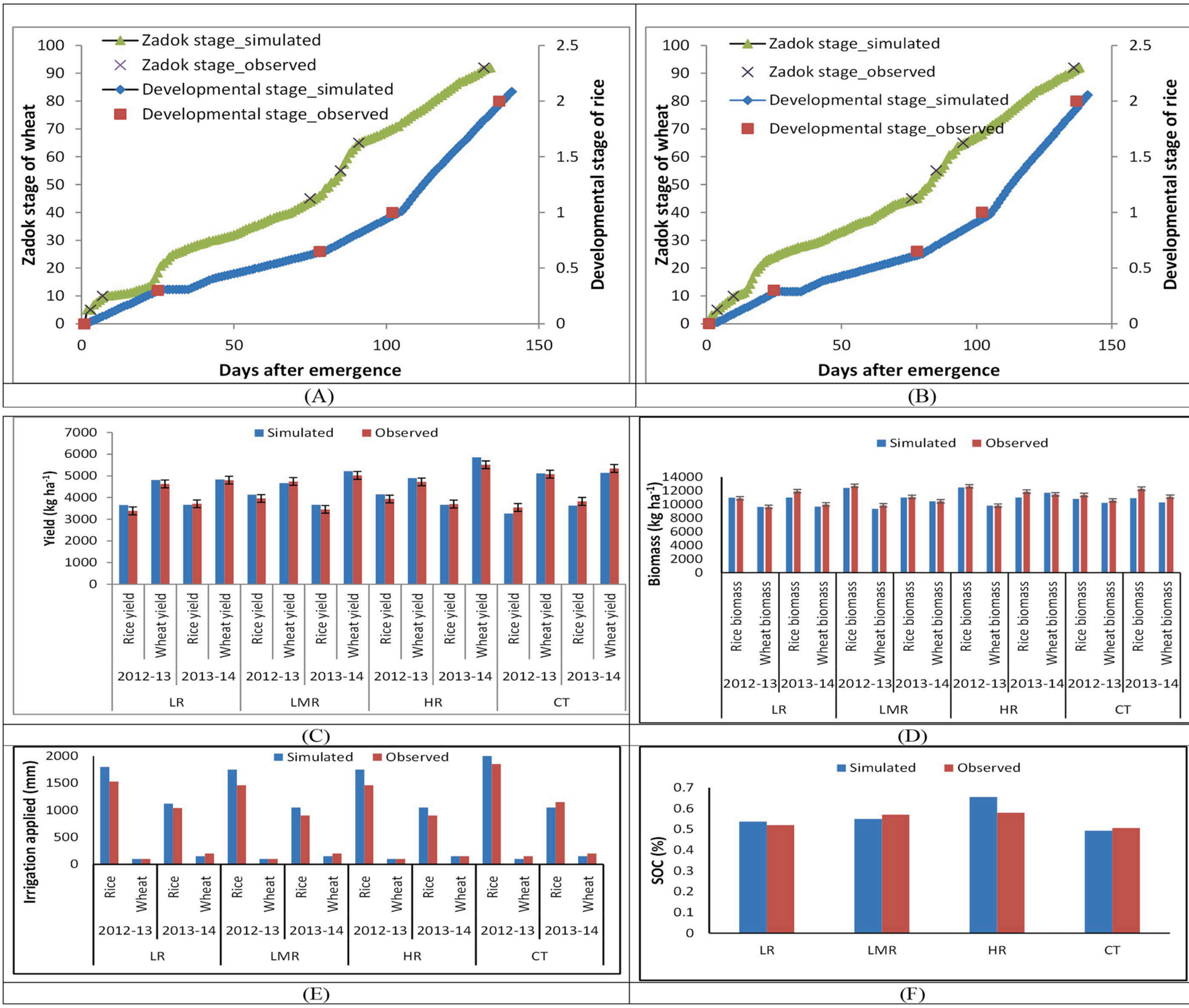

Fig. 1. Calibration and validation of APSIM Model. (A) calibration of phenology of rice and wheat; (B) validation of phenology of rice and wheat; (C) calibration and validation of APSIM model for yield of rice and wheat; (D) calibration and validation of APSIM model for biomass of rice and wheat; (E) calibration and validation of APSIM model for irrigation water use by rice and wheat crops; (F) calibration and validation of APSIM model for soil organic carbon (SOC) under RWCS under IGP conditions.

Table 1
Parameterization of crop cultivars used in model for rice and wheat simulation.

Parameters	Value	Unit (days)
(a) *'PS-5' cultivar of rice*		
Development rate in juvenile phase	0.00070	°C
Development rate in photoperiod-sensitive phase	0.00037	°C
Development rate in panicle development	0.00080	°C
Development rate in reproductive phase	0.00200	°C
(a) *'HD-2967' cultivar of wheat*		
Potential grain filling rate	0.009	
Grains per gram stem	28.0	
Potential grain growth rate	0.0010	
Max grain size	0.045	
tt_end_of_juvenile units	520	°C
tt_floral_initiation units	660	°C
tt_flowering units	252	°C
tt_start_grain_fill units	700	°C

Table 2
Soil properties of experimental field.

Depth (cm)	BD (g cc^{-1})	Air dry (mm mm^{-1})	LL 15 (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	WB-OC (%)	pH (1:2.5 Soil-water)
0–15	1.49	0.061	0.125	0.263	0.397	0.540	7.80
15–30	1.54	0.093	0.117	0.253	0.374	0.420	7.70
30–60	1.53	0.124	0.123	0.246	0.380	0.310	7.60
60–90	1.57	0.133	0.131	0.257	0.367	0.190	7.90
90–120	1.59	0.065	0.133	0.247	0.363	0.140	8.00
120–150	1.59	0.065	0.133	0.247	0.363	0.140	8.00

#BD= Bulk density; LL= Lower limit (soil moisture at −1500 kPa); DUL= - Drainage upper limit (soil moisture at −33 kPa); SAT=water content at saturation; WB_OC= Walkley-Black organic carbon

macro-porosity of the top-soil (Mulumba and Lal, 2008; Singh et al., 2016), therefore, to simulate the realistic conditions in the CA scenarios, the water holding capacity of the 0–150 mm soil layer was increased by 20% from that of soil in the conventional system (as suggested by

Balwinder-Singh et al., 2015). In the APSIM, this was done through increasing the volumetric water content at saturation (SAT). The tillage effects on soil roughness was simulated by altering the USDA curve number at 60 for ZT and 80 for CT as also observed by Balwinder-Singh et al. (2015). Afterwards, the curve numbers were reset to the default curve number when at least 40 mm of water was added to soil (by rain or irrigation) to simulate the smoothing of a newly tilled soil owing to raindrops and saturation influence. In the like manner, the saturated percolation-rate was fixed to 20 and 6 mm day^{-1} for the non-puddled and puddled soils, respectively, based on the observations of Humphreys et al. (2008) and Balwinder-Singh et al. (2015) on the alike soils. Due to adoption of CA, the soil microbial activity and rooting parameters were expected to be greater than CT in the upper soil layer (Das et al., 2014; Bamboriya et al., 2017; Bana et al., 2020). To capture CA effects in APSIM, based on the observations of Chaki et al. (2022b), root hospitality factor (KI), relative root advancement rate (xf) and Fbiom (fraction of soil microorganisms) were enhanced by 20% in CA relative to CT. Whereas, Finert (inert fraction of organic matter of soil) and bulk density were reduced by 20% and 5%, respectively under CA (Chaki et al., 2022b).

2.3. Crop management

Under CT scenario, the field was flooded a day prior to transplanting and one discing and two harrowings were carried out. Rice seedlings of 21 days age were transplanted at 20 × 10 cm spacing with 2 seedlings $hill^{-1}$ in PTR. In DSR too, seeding was done at 20 cm row spacing with 150 plants m^{-2}. Sowing of DSR and nursery of PTR was done between 15 and 20 June every year. The 37-year simulations were initiated with the soil profile full of water at the time of establishment of the first rice crop in 1984. During subsequent years, for DSR, an irrigation of 70 mm was applied on the day of seeding, if soil water content in the 0–15 cm soil layer was lesser than the lower limit (LL). Water management for PTR involved continuous ponding, whereas under the CA scenarios, the DSR was irrigated by alternate drying and wetting (AWD) approach. In APSIM, irrigation trigger in AWD was pond = 0 to simulate the irrigations. In each irrigation, 70 mm of water was applied both in PTR and DSR. Irrigation of rice in all systems ceased about one week before crop maturity, and the rice was harvested eight days after physiological maturity to allow time for grain moisture content to decline to < 20% as per standard recommendations.

The optimum wheat planting period in the IGP is late October-late November. In the model, wheat sowing was set at 15 November, regardless of rice harvest date. In the CT system, wheat was sown following rice straw removal and CT practices (one discing and two harrowings to a depth of 0–150 mm followed by one planking with wooden-plank). In the CA systems, the wheat crop was sown into the rice residues using the Happy Seeder (Sidhu et al., 2007), except NR scenario, where residues were removed. An irrigation of 50 mm was applied four days prior to sowing only when the water content of the 0–150 mm soil layer was below the drainage upper limit (DUL) to ensure good crop establishment. Wheat was sown at 22.5 cm row spacing with a plant density of 200 plants m^{-2} at 5 cm depth in all the systems. The wheat was irrigated whenever soil water deficit (SWD) increased to 50% in the 0–30 cm soil profile. The wheat crop was harvested one week after physiological maturity to allow time for the grain to dry in the field.

2.4. Measurement of different observations

2.4.1. System productivity (SP)

SP is a sum of rice grain yield and rice equivalent yield (REY) of wheat grain yield. The REY of wheat was calculated using Eq. (1):

$$\text{REY of wheat} = (Y_w \times P_w) / P_r \tag{1}$$

Where, Y_w is the grain yield of wheat, P_w is the price of wheat (US$ 261.7 t^{-1}), and P_r is the price of rice (US$ 254.5 t^{-1}).

2.4.2. Sustainable yield index (SYI), which was calculated by the following expression (Singh et al., 1990) (Eq. (2))

$$SYI = (Y_a - \sigma / Y_m) \tag{2}$$

Where, Y_a is the mean yield, σis the standard deviation of yield for that treatment across years, and Y_m is the maximum yield obtained under that treatment in any year.

2.4.3. Sustainable Value Index (SVI)

The SVI was calculated by Eq. (3).

$$SYI = (NR_a - \sigma / NR_m) \tag{3}$$

Where, NR_a is the mean net return (NR), 'σ' the standard deviation of NR for that treatment across the years, and NR_m is the maximum NR obtained under that treatment in any year.

Relatively lower values of σ suggest higher sustainability of the system (Efthimiadou et al., 2010), because σ measures variation in yield. If σ is high, SYI and SVI will be low and this indicates lesser sustainable management practice (Singh et al., 1990). SYI and SVI value close to 1.0 implies the nearness to an ideal situation that can sustain maximum crop yields over years, while deviation from 1.0 indicates the lower sustainability.

2.4.4. Carbon sequestration rate (CSR)

The CSR was calculated using Eq. (4).

$$CSR= C_f\text{-}C_i/ N \tag{4}$$

Where C_f is total soil carbon at the end of simulation, C_i is total carbon at initiation of experiment and N is no. of years of simulation.

2.4.5. System Water Productivity (SWP)

Based on the rainfall data of ICAR-IARI, effective rainfall was calculated using standard method given by FAO and then total amount of water applied was computed as the sum of water applied through irrigations and effective rainfall. Water productivity (kg grains ha^{-1} mm^{-1} of water) was computed using Eq. (5) as described by Das et al. (2014):

$$SWP = SP\ (\text{kg ha}^{-1}) / \text{water applied (mm)} \tag{5}$$

2.4.6. Economic analysis

Cost of cultivation under various treatments was estimated on the basis of prevailing market prices and approved rates for inputs by the ICAR-IARI, New Delhi. The input costs include common cost of cultivation e.g. costs of seed, pesticide, mineral fertilizers, and the hiring charges of human labour and machineries for land preparation, irrigation, nutrient applications, crop protection, harvesting, and threshing. Measurement also included the cost of residues (here US$ 23.3 and 62 t^{-1} for rice and wheat residues, respectively). Gross returns (GR) were calculated on the basis of minimum support price (MSP) offered by Government of India for rice (US$ 254.5 t^{-1}) and wheat (US$ 261.7 t^{-1}) at current (2021–22) prices. Net returns (NR) were calculated as the difference between gross income and total cultivation cost.

3. Results

3.1. APSIM model performance

Overall performance of APSIM in capturing the crop performance, phenology, residue retention and method of crop establishment in rice and wheat and RWCS in IGP, was very good (Figs. 1 and 2). The RMSE of

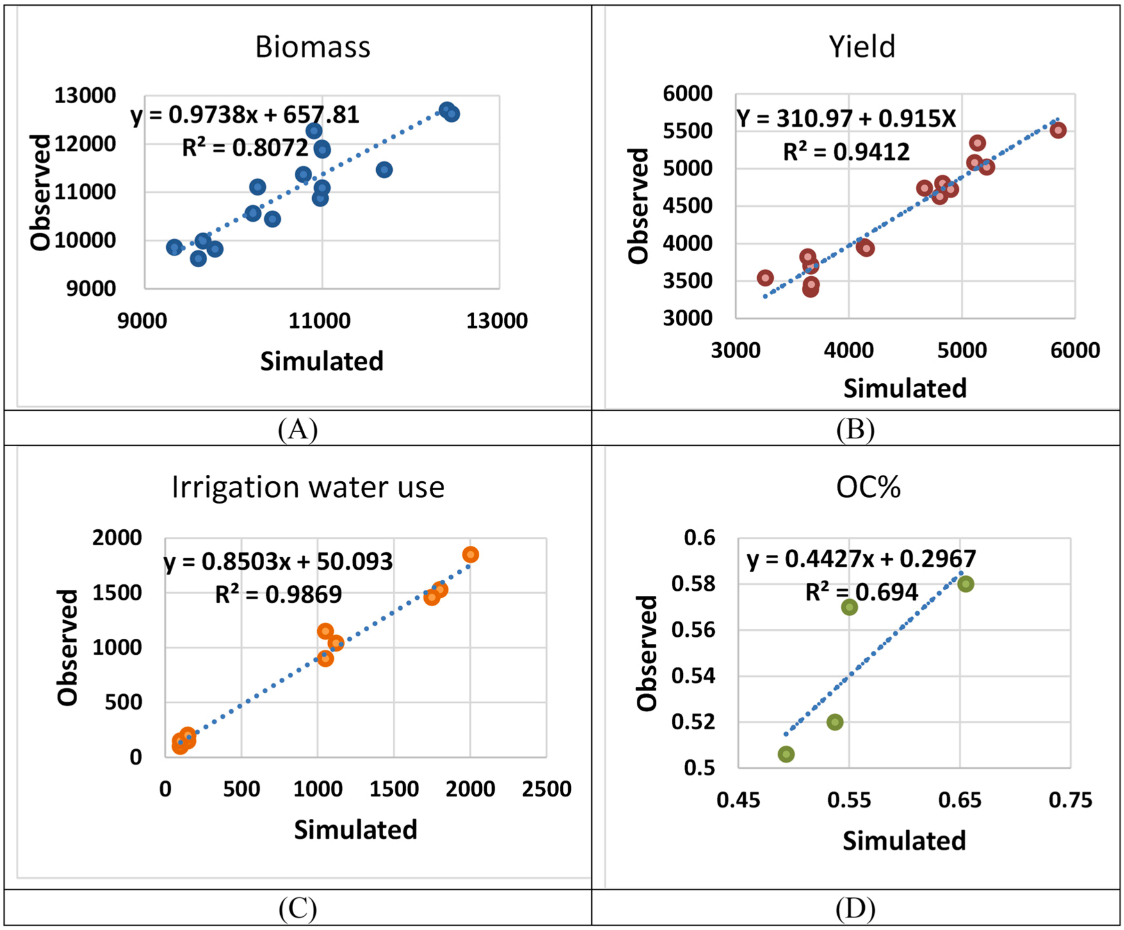

Fig. 2. Evaluation of APSIM model accuracy for (A) biomass; (B) yield; (C) irrigation water use and; (D) organic carbon (OC).

2.17–2.37 days in the phenology dataset (observed and simulated) of rice and wheat crops compares the model efficiently. Likewise, RMSE of rice yield (157–238 kg ha^{-1} across different scenarios) and wheat yield (27–269 kg ha^{-1} under diverse scenarios) also indicated acceptable model performance. The RMSE was of similar size to the standard deviation of the observed yields, indicating that the model was simulating

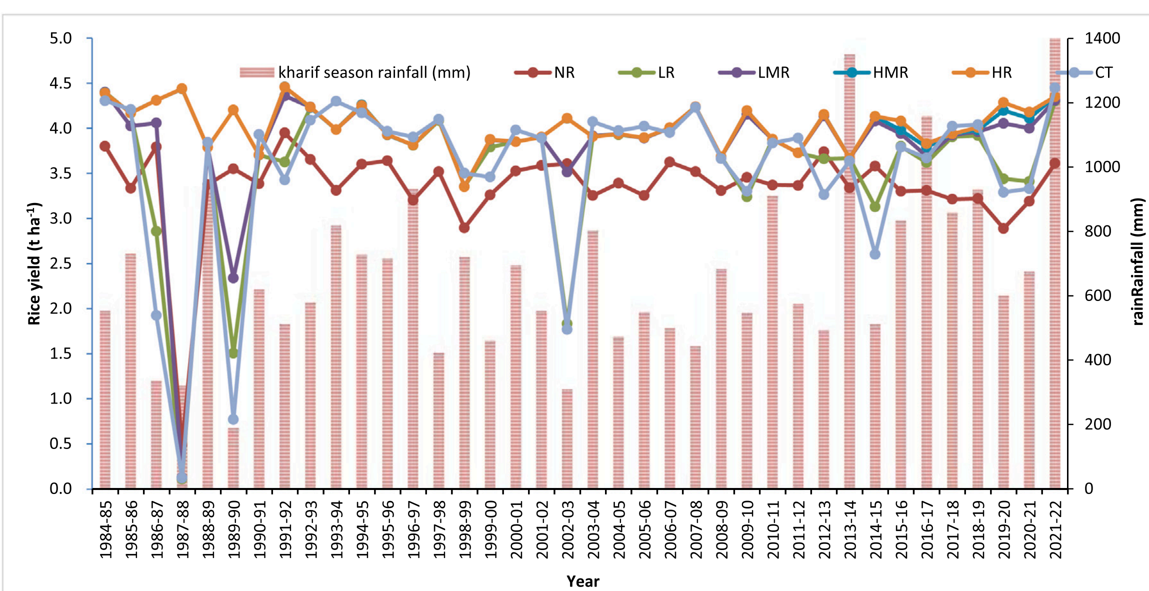

Fig. 3. Effects of long-term conservation agriculture portfolios and mean rainfall during experimental period on rice grain yield from 1984 to 85–2021–22 under rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

observed behaviour within the bounds of experimental error (Gaydon et al., 2017). It was further supported by the greater degree of correlation (r^2 =0.94) between simulated and observed yield data (Fig. 2). Furthermore, higher correlation (r^2 =0.81) and the acceptable RMSE of rice and wheat biomass dataset ranging from 217 to 1050 kg ha^{-1} and 169–637 kg ha^{-1}, respectively under different crop establishment and residue level scenarios also indicated that model is performing satisfactorily. Calibration and validation of irrigation water use for water productivity estimation also highlighted strong model prediction as the r^2 value of water use was 0.98 and RMSE remained 127.5–230.9 mm ha^{-1} of rice and 35.4–50.0 mm ha^{-1} of wheat under diverse scenario. In the similar manner, soil carbon increase as affected by different scenarios was also predicted acceptably by the model with r^2 = 0.69. Overall, there are convincing evidence that the APSIM model is simulating rice and wheat yields in addition to water use and soil organic carbon (SOC) well within the boundaries of experimental error across the crop establishment systems and residue management scenario in the RWCS.

3.2. Productivity and profitability

Rice is a rainy season crop and depending on the weather conditions over 37 years of experimentation site in Delhi, considerable variation in its yield was observed (Fig. 3). The highest (4.03 t ha^{-1}) simulated mean of scented rice yield was recorded with HR and HMR scenarios while the lowest (3.35 t ha^{-1}) mean yield was observed under NR, whereas under CT the mean simulated yield was 3.64 t ha^{-1} (Fig. 4). Though, there was no much variation between HMR and HR but a constant yield decline was observed with further reduction in residue levels. The mean yield gap ranged from 0 to 0.43 t ha^{-1} in the CA scenarios (HR, HMR, LMR and LR) but the yields were more stable under higher residue levels. There was wide rice yield variability in CT and NR scenarios, with a coefficient of variation (CV) of ~ 26% and 16%, respectively, whereas the respective CV figures were 22.9%, 18.5%, 6.1% and 6.0% under LR, LMR, HMR and HR.

During the initial 4 years of simulations, wheat yield decline was recorded due to residue application and the yield reduced linearly with the increased amount of residues (Fig. 5). But from 5th year (1988–89) onwards, higher yields were recorded under HR (5.18 t ha^{-1}) and CT (5.01 t ha^{-1}) followed by HMR (4.90 t ha^{-1}), LMR (4.63 t ha^{-1}), LR (4.59 t ha^{-1}) and lowest yield was observed under NR (4.38 t ha^{-1}) (Fig. 4). This indicated that after initial conversion years, the CA becomes more beneficial. Annual yield variability in wheat yield was less (CV ranges from 6.3% to 13.3%) as compared to rice (CV ranges from 6.0% to 26.0%) because of higher water requirement in rice and its strong dependence on weather parameters.

A system productivity (SP) analysis of RWCS indicates that maximum SP (9.33 t ha^{-1}) was recorded under HR followed by HMR (8.97 t ha^{-1}), CT (8.75 t ha^{-1}), LMR (8.62 t ha^{-1}), LR (8.36 t ha^{-1}) and NR (7.91 t ha^{-1}) (Fig. 6). The Fig. 7 on probability of exceedance illustrates that CT remained second best treatment after HR during good monsoon years, but when the weather conditions were adverse (worst 33% seasons), the SP under CT was less than HR, and HMR. During worst 10% years, LMR and LR were also resulted in higher SP than CT. Under NR, the SP remained invariably lowest during all the years.

Long-term profitability analysis illustrates that adoption of CA resulted in higher system net returns (SNR) of RWCS in terms of REY as compared to CT (Fig. 6). Average SNR were highest in the HR (US$ 2286 ha^{-1}) scenario closely followed HMR (US$ 2259 ha^{-1}), LMR (US$ 2173 ha^{-1}) and LR (US$ 2095 ha^{-1}). The lowest SNR are expected to be from NR (US$ 1999 ha^{-1}) scenario, whereas under CT, the farmers would earn annually US$ 2091 ha^{-1}.

3.3. Sustainability

The polynomial maxima indicated that the SYI and SVI of SP in RWCS were recorded highest under HR (0.83 and 0.79, respectively, (Fig. 8). Higher values of SYI under HR (0.83), HMR (0.83), LMR (0.81) and LR (0.81) than CT (0.79) shows that CA is a sustainable practice in long-run. In terms of economic farm sustainability (SVI) too, all the CA practices remained better than CT and a medium level of residue retention is enough to sustain the productivity and profitability of RWCS. Quantification of optimum residue level, based on the mean straw yield (Fig. S1), through polynomial equations shows that 7.6 t ha^{-1} yr^{-1} residue loads is most sustainable as the peaks of SYI and SVI on the polynomial graphs were recorded maximum at HMR and declines thereafter.

3.4. Carbon sequestration

The model predicted that soil organic carbon (SOC) concentration in the top (0–150 mm) soil profile increased linearly over time with increase in residue levels (Fig. 9). Under NR, a decline of 7.3% in SOC concentration from its initial level was observed after 37 years of RWCS. Similarly in CT, even after use of recommended fertilizer doses in both rice and wheat over the years, SOC concentration did not increase and remained almost static.

The highest SOC concentration (1.17%) was predicted under HR treatment, where the SOC increases by ~ 95% after 37 years of CA-based RWCS. Under LR, LMR and HMR also, long-term residue retention

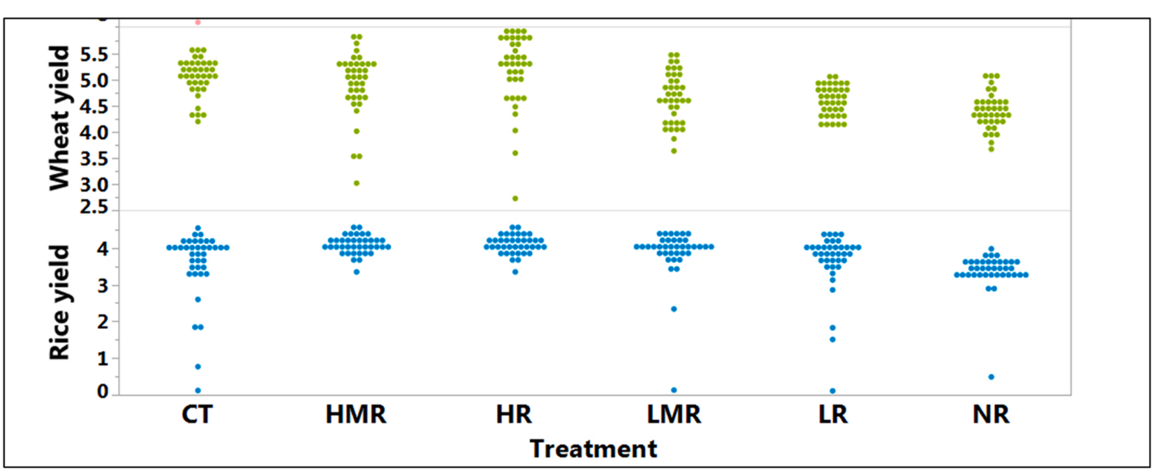

Fig. 4. Effects of long-term conservation agriculture portfolios on rice and wheat mean yield (mean of 37 years). NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

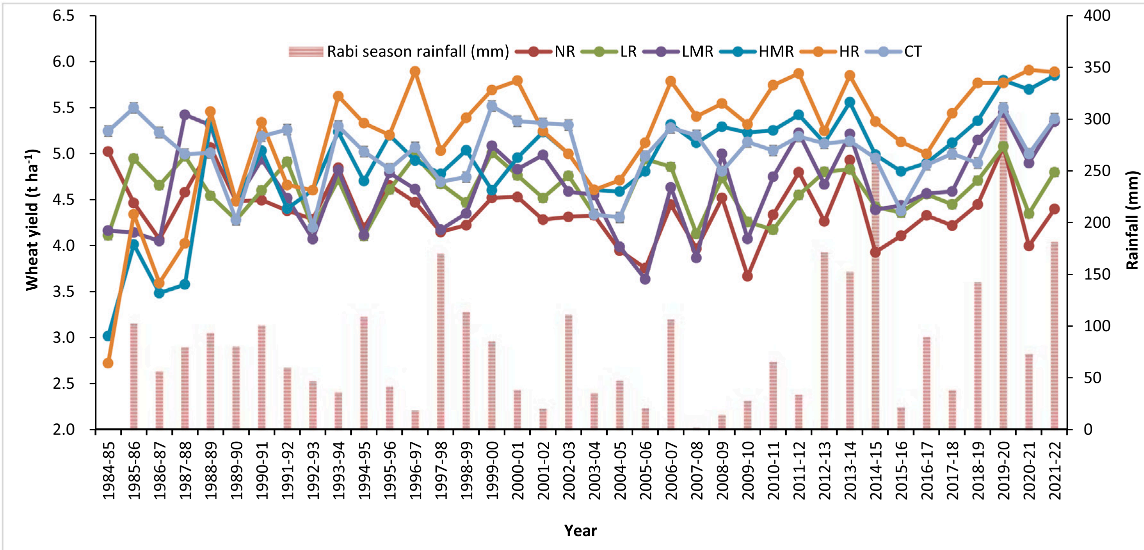

Fig. 5. Effects of long-term conservation agriculture portfolios and mean rainfall during experimental period on wheat grain yield from 1984 to 85–2021–22 under rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

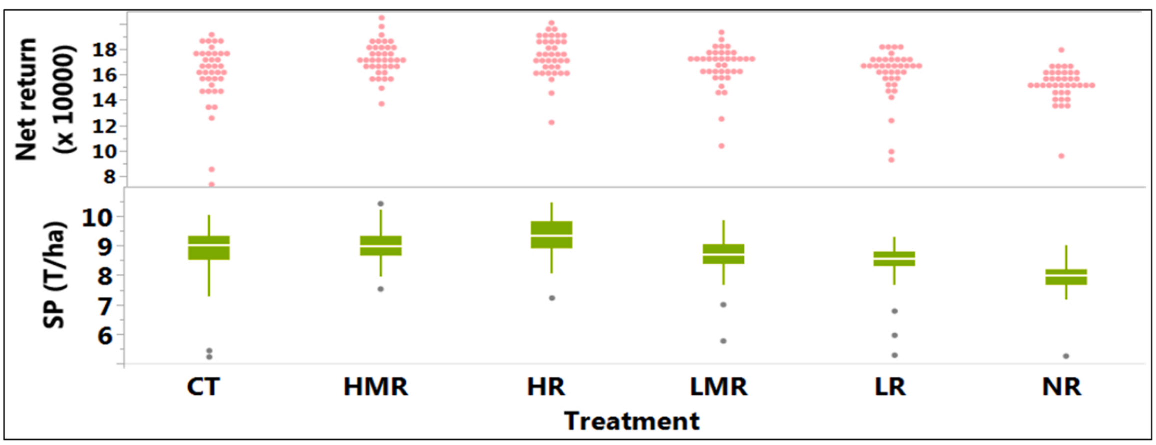

Fig. 6. Effects of long-term conservation agriculture portfolios on system productivity (SP) and net return of rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

increased SOC by ~ 30%, 34% and 63%, respectively, as compared to initial levels. As compared to CT, the SOC concentration increased by 0.18–0.61% under different residue management practices after 37-years of continuous rice-wheat rotation.

The simulation indicates that highest carbon sequestration rate (CSR) in 0–150 mm soil profile was recorded under HR (0.37 t ha^{-1} yr^{-1}) due to addition of higher amount of biomass and consequent enhancement in SOM. In NR simulations, a negative CSR (−0.02 t ha^{-1} yr^{-1}) was predicted (Fig. 10), whereas under CT scenario, the CSR was negligible (0.007 t ha^{-1} yr^{-1}). At lower residue levels also decomposition of crop biomass added SOM in the upper layer leading to build-up of SOC. The respective CSR under HMR, LMR and LR scenarios were 0.23, 0.13 and 0.10 t ha^{-1} yr^{-1}.

In the similar manner, the soil microbial activity also remained higher under CA systems and it is positively correlated with amount of residue recycled in the RWCS (Fig. 11). A long-term scenario analysis of microbial activity illustrated that biomass C and N increased significantly with addition of residues and remained at peak with HR and negative with NR. The HMR remained the second best treatment, whereas, LMR and LR were at par. No notable difference was observed between NR and CT over the years. After 37 years, the biomass C increases by ~23, 17, 13 and 4 kg ha^{-1} yr^{-1} due to HR, HMR, LMR and LR, respectively. Likewise, enrichment of 0.61–2.6 kg ha^{-1} yr^{-1} in the biomass N was predicted due to long-term adoption of CA practices in RWCS.

3.5. System water productivity

Crop residues retention on soil surface reduced the consumptive use of water in RWCS (data not presented) and enhanced the crop productivity, leading to increase in water productivity. Considering irrigation and rain water used for production of both the cereals on long-term, it was observed that HR scenario resulted in greatest water productivity of rice, wheat and system water productivity (SWP) followed by HMR (Fig. 12). The average SWP under HR and HMR (3.68 and 3.44 kg ha^{-1} mm^{-1}, respectively) remained ~10% more than CT. However, in the LMR, LR and NR scenarios (3.34, 3.19 and 3.04 kg ha^{-1} mm^{-1}, respectively), SWP was lower than CT.

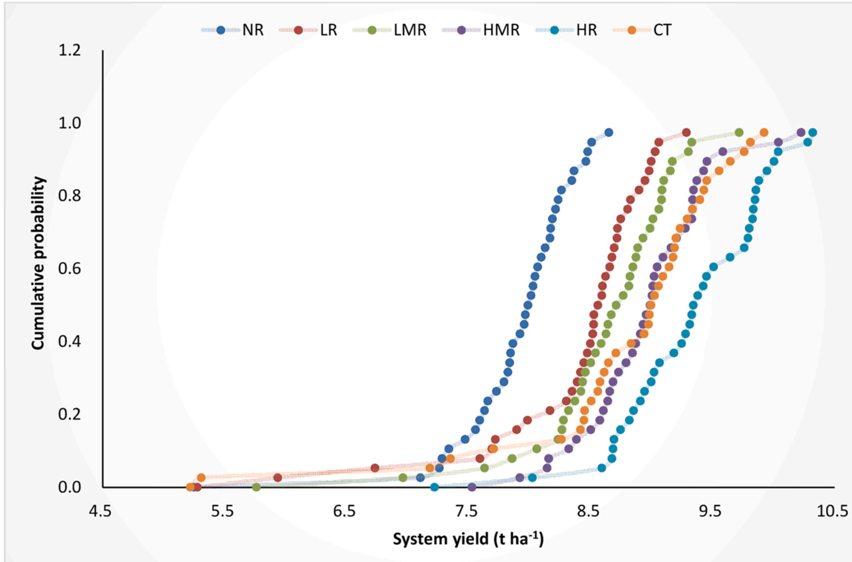

Fig. 7. Cumulative probability curve of total system productivity (TSP) of rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

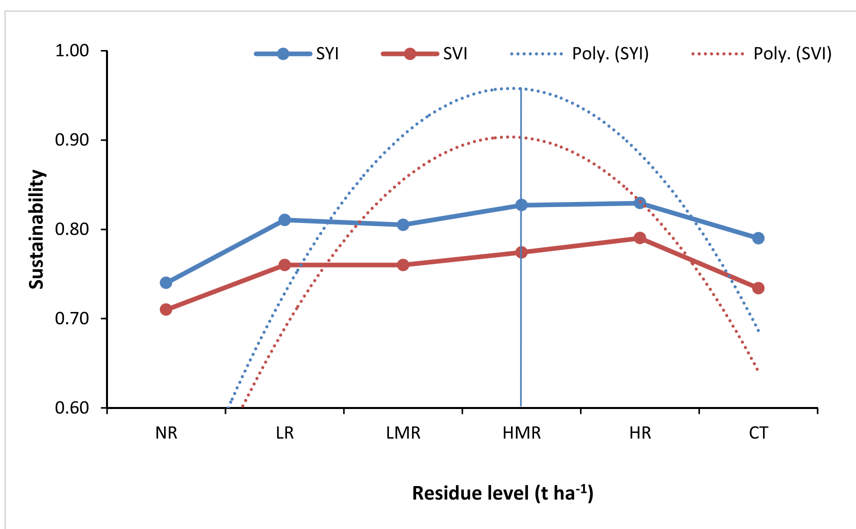

Fig. 8. Effects of long-term conservation agriculture portfolios on sustainability of rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

4. Discussion

4.1. Evaluation of APSIM in simulating the effects of CA in RWCS

APSIM simulated positive effects of surface residue retention on SP of RWCS consistent with the observed data (Figs. 1 and 2), and also with the other findings in similar environmental conditions (Balwinder-Singh et al., 2011; Balwinder-Singh et al., 2015; Gaydon et al., 2017; Bana et al., 2022). The higher predicted SP with mulch was associated with higher simulated transpiration, consistent with the findings of Balwinder-Singh et al. (2010), Balwinder-Singh et al. (2011) and Gaydon et al. (2017). Under IGP conditions, robustness for APSIM for the biomass production and grain yield simulations was found as good as the ORYZA2000 and CERES-Wheat models (Timsina and Humphreys, 2006; Balwinder-Singh et al., 2011).

4.2. System productivity and profitability

Mean SP was recorded higher under HR and HMR treatments of CA systems as compared to CT (Fig. 6). Though the mean yields under LMR and LR (lower residue levels) were less than CT, but during the years of poor monsoon (specifically, 1986, 1987, 1989, 2002, 2009), the productivity under all the CA systems were comparatively better than CT. CV of wheat and rice yields under CA were recorded as low as 6.1% and 6.0%, respectively as compared to ~ 6.9% in wheat and 26.5% in rice under CT (Figs. 3 and 5). The consistency in productivity of CA systems could be due to favorable factors of residue retention, namely, improved soil water dynamics and hydro-thermal regimes (Govaerts et al., 2009; Choudhary et al., 2017),), reduced competition to resources due to less weed density (Chauhan et al., 2007; Bana et al., 2020), improved phyllospheric microclimate and better soil physical properties (Jat et al., 2013; Bhattacharyya et al., 2015; Singh et al., 2016), and increased SOC, biomass C and N (Figs. 9 and 11) and nutrients compared to CT (Unger

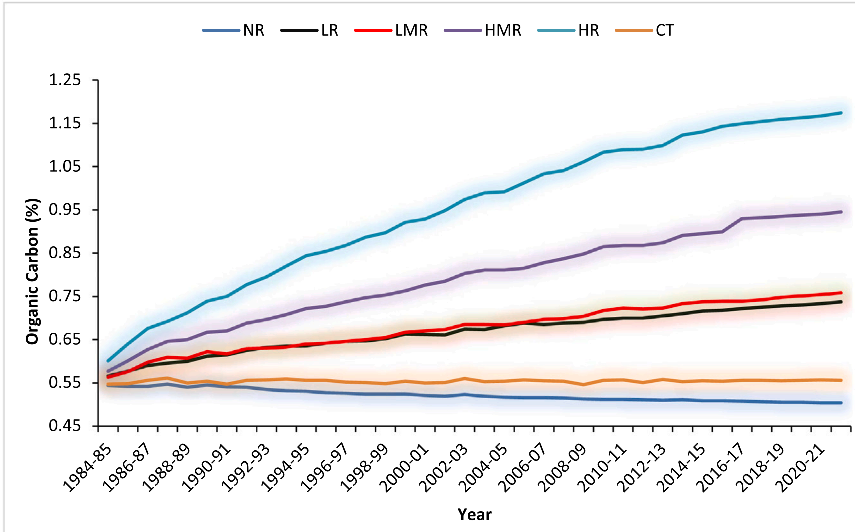

Fig. 9. Effects of long-term conservation agriculture portfolios on soil organic carbon changes from 1984 to 85–2021–22 under rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

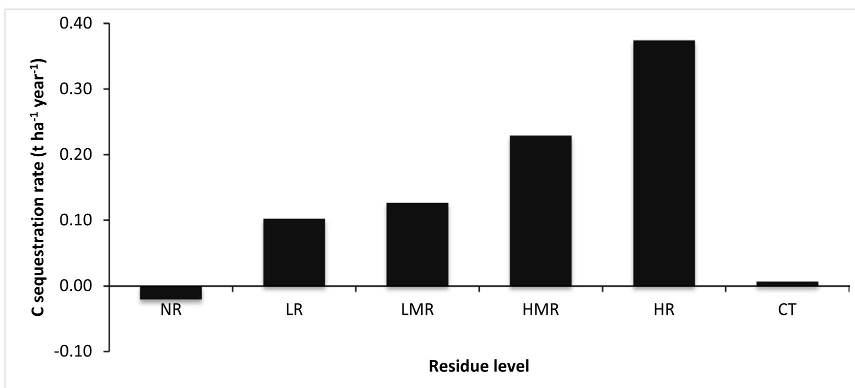

Fig. 10. Effects of long-term conservation agriculture portfolios on C sequestration rate in the rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

and Jones, 1998; Blanco-Canqui and Lal, 2009; Kaschuk et al., 2010; Parihar et al., 2017). Since scented rice is grown in the wet season and has a high water demand, therefore, annual yield variability and the influence of rainfall distribution was more notable in rice than wheat. The other reason for higher SP under CA is the longer vegetative phase in the CA system as a result of mulching, which led to more biomass production and better development of yield attributing characters (Balwinder-Singh et al., 2015).

SNR data analysis of RWCS over the years indicated that the income stability was higher under CA as compared to CT (Fig. 6). The coefficient of variation (CV) of SNR under LMR, HMR and HR was recorded between ~6–10%, which was significantly lower than CV of CT (~16%) scenario. In the cropping seasons of extremely low or higher than annual average rainfall, the decline in SNR under CA was expected to be comparatively less. The CA led to, ~ 9% higher SNR of RWCS as compared to CT. Residue retained scenarios provides comparatively better adaptations to harsh weather (Bana et al., 2016), therefore under CA, the income stability was comparatively higher. Several other researchers (Das et al., 2014; Choudhary et al., 2016; Bana et al., 2016) also reported that residue retention resulted in higher profitability as compared to no-residue retention in north-Indian conditions.

Higher values of sustainability indices under CA systems proved that CA was a sustainable crop establishment technique in long-run, both from productivity as well as economics point of view. The optima of SYI and SVI at HMR provide important information that based on the residue yields (Supplementary Fig. 2), 7.6 t ha^{-1} residue retention was sufficient to sustain the yield levels under CA. Though the SP was slightly more under HR than HMR but the crop residues are costly source of livestock fodder and there is always a trade-off between CA and farm animals for residues under crop-livestock based mixed farming systems. In such conditions, HMR would be an economically viable and sustainable option of residue management under CA-based mixed farming systems (Fig. 7).

4.3. SOC and SWP

Due to large quantum of residue retention for 37-years under CA scenarios, the SOC concentration was predicted to increase by ~ 30–95% in RWCS with a CSR of 0.1–0.37 t ha^{-1} yr^{-1} (Fig. 10). The advantage of residue retention and carbon sequestration for sustaining crop productivity by adopting CA practices have been well documented in temperate and sub-temperate regions (West and Post, 2002; Bhattacharyya et al., 2013). However, very few studies estimated SOC accumulation rates of residue retained CA and CT practices under tropical agro-ecosystems. In the present study, residue retention increased surface soil carbon compared to CT scenario (Fig. 9). Thus, the CA practices

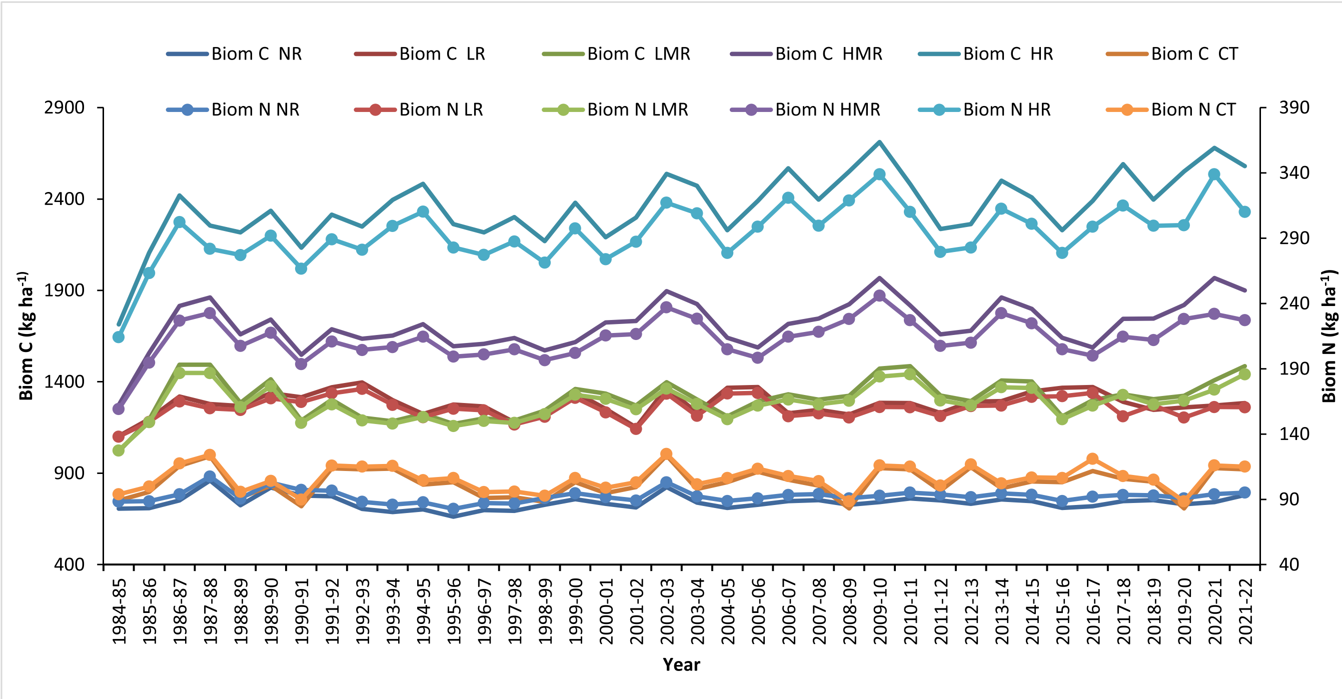

Fig. 11. Effects of long-term conservation agriculture portfolios on soil microbial biomass carbon and nitrogen (SMBC and SMBN) changes from 1984 to 85–2021–22 under rice-wheat cropping system. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

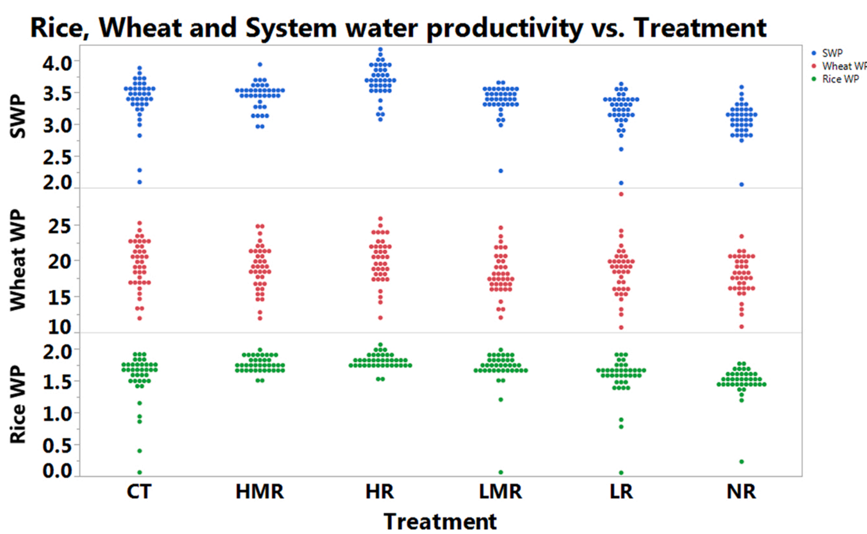

Fig. 12. Effects of long-term conservation agriculture portfolios on water productivity of rice and wheat. NR = No-residue; LR = Low residue; LMR = Lower-medium residue retention; HMR = Higher-medium residue retention; HR = High residue retention; CT = Conventional tillage.

have tremendous potential to increase SOC content in the RWCS of the region. The biomass C and N also increased significantly with residues retention (Fig. 11). Long-term CA adoption increases soil microbial activity as indicated by enhanced biomass C and N under CA scenarios. Growth rate of biomass C and N in soil is predicted to be ~ 4.8–23 kg ha^{-1} yr^{-1} and 0.6–2.6 kg ha^{-1} yr^{-1}, respectively under different residue levels. This was probably due to higher top layer soil microbial population in the residue retained and no-till conditions (Choudhary et al., 2014; Bhattacharyya et al., 2015).

On an average (37-years), SWP of RWCS under HR was recorded 3.68 kg ha^{-1} mm^{-1} which was ~10% higher than CT (Fig. 12). The SWP remained notably higher under CA during the years when precipitations were abnormal. Higher soil moisture retention and moderated soil thermal regime under CA resulted in higher grain yield and lowering of water use, resulted in more SWP. Higher SWP under residue retentions and ZT conditions under same agro-ecologies were reported by Das et al. (2014); Choudhary et al. (2016) and Bamboriya et al. (2017).

Crop residue burning is a common practice among the farmers and a big menace in RWCS region of IGP. The entire C in residues is lost due to burning (Gupta et al., 2004). As 1 t C accumulation equals 3.67 t CO_2 (Bhattacharyya et al., 2015), HR scenario adoption had the potential to emit ~1.36 t CO_2 ha^{-1} yr^{-1} less than CT scenario (farmers' practice) on an equivalent mass basis, as the CSR under HR was 0.37 t ha^{-1} $year^{-1}$. Thus, adoption of CA is a novel climate smart agriculture technique that reduces GHGs emissions and increases C-sequestration, WP, crop yields and profits.

5. Conclusions

This study suggests that long-term conservation agriculture in the RWCS enhances crop and water productivity in the IGP. The system productivity and system water productivity were higher under conservation agriculture (CA), specifically during unfavorable monsoon seasons, thus CA resulted in more stable yields and income. Residue retention led to more carbon sequestration and augmented soil organic carbon (SOC) compared to residue removal under zero-till, as well as under tilled conditions. The higher residue (HR) and higher-medium residue (HMR) scenarios were found economically profitable compared to conventional tillage (CT) practices. Retention of a 7.6 t ha^{-1} $year^{-1}$ residue load was optimum for long-term sustainability of CA in the IGP region. This work provides further evidences for us to promote CA under the RWCS in similar agro-ecologies of the tropics and sub-tropics under irrigated conditions. Possible impact of climate change in the near future under RWCS, synergies between residue retention and temperature fluctuations and cropping systems require further studies across locations for site-specific alterations/refinement in CA practices. Horizontal crop intensification with inclusion of legumes or short-duration forage crops, particularly summer cowpea (*Vigna unguiculata*), pearlmillet (*Pennisetum glaucum*) and mungbean (*Vigna radiata*) in between wheat and rice cropping seasons should be studied for developing a more sustainable CA-based rice-wheat production system.

CRediT authorship contribution statement

Ram Swaroop Bana: Conceptualization, Investigation, Writing – original draft. **Shanti Devi Bamboriya, Vipin Kumar**: Validation, Investigation, Writing – original draft. **Donald S. Gaydon, Alison M. Laing, Y.S. Shivay, Vijay Singh Meena**: Conceptualization, Writing – review & editing. **Samarth Godara, Deepak Singh**: Statistical analysis and Data visualisation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105745.

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