Field Crops Research 315 (2024) 109476

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Enhancing productivity, soil health, and reducing global warming potential through diverse conservation agriculture cropping systems in India's Western Indo-Gangetic Plains

M.K. Gora [a,b], H.S. Jat [b,*], J.K. Ladha [c], Madhu Choudhary [b], P.C. Sharma [b], A.K. Yadav [b], L.K. Singh [d], Tek B. Sapkota [e], Yadvinder Singh [d], Kailash Prajapat [b], R.K. Yadav [b], M.L. Jat [f], T.J. Krupnik [g], M.K. Gathala [g,*]

[a] *CCS Haryana Agricultural University, Hisar, Haryana, India*
[b] *ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India*
[c] *University of California, One Shields Avenue, Davis, USA*
[d] *International Maize and Wheat Improvement Center (CIMMYT), New Delhi, India*
[e] *International Maize and Wheat Improvement Center (CIMMYT), El-Batan, Mexico*
[f] *International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India*
[g] *International Maize and Wheat Improvement Center (CIMMYT), Dhaka, Bangladesh*

ARTICLE INFO

Keywords:
Crop diversification
Crop rotations
Greenhouse gas emissions
Indo-Gangetic Plains
Rice-wheat system
Soil quality

ABSTRACT

Context: The rice-wheat (RW) system, spanning 13.5 million hectares in South Asia, is crucial for food security and livelihoods. However, intensive conventional tillage-based practices have harmed soil and environmental health, decreased productivity trends and increased greenhouse gas emissions.
Objective: This study aims to develop resilient, climate-smart cropping systems within the RW system, focusing on soil and crop productivity, economic viability, and reduced greenhouse gas (GHG) emissions.
Methods: Over eight years, the study evaluated diverse parameters compared to farmer practices (FP) in seven scenarios (Sc), including one representing FP (Sc1) and six based on conservation agriculture (CA) principles. The study assessed system crop productivity, economic returns, soil quality (organic carbon; OC, nitrogen; N, phosphorus; P, potassium; K contents, bulk density; BD, soil aggregation, infiltration rates, microbial counts, and earthworm density), and GHG emissions.
Results: CA-based scenarios (Sc2 to Sc7) showed improved soil quality, lower bulk density, enhanced soil aggregation, and increased infiltration rates compared to Sc1. In the 0–15 cm layer, surface soil organic carbon (OC) and C stock were 63.7 % and 49.6 % higher, respectively, in CA-based scenarios. Additionally, available N, P and K contents in the surface layer increased by 10.2 %, 28.6 %, and 21.8 % under CA-based scenarios. Adoption of CA in intensified maize-based scenarios (Sc4 and Sc5) led to the increased system and economic yields, higher soil quality index (SQI), reduced GHG emissions and increased C stock compared to Sc1.
Implications: The study highlights that Conservation Agriculture (CA) practices and diversified crop rotations can address issues like falling crop productivity, reduced economic returns, soil degradation, and increasing environmental impacts in northwestern India's traditional rice-wheat system. However, widespread adoption requires government policies, including C credit payments and guaranteed markets with supportive pricing.

1. Introduction

The rice-wheat (RW) system occupies 13.5 million ha and is fundamental to food security, income, employment, and livelihoods for millions of rural and urban poor in South Asia. In recent decades, the high growth rates (wheat 3.0 %, rice 2.3 %) of the RW system have fatigued the natural resource base (Hobbs and Morris, 1996; Byerlee et al., 2003). The current intensification of RW rotations has led to resource degradation and productivity declines (Ladha et al., 2003a; Pathak et al., 2003; Jat et al., 2020a). Reduced productivity and low external input

* Corresponding authors.
E-mail addresses: hsjat_agron@yahoo.com (H.S. Jat), M.Gathala@cgiar.org (M.K. Gathala).

https://doi.org/10.1016/j.fcr.2024.109476
Received 4 February 2024; Received in revised form 2 June 2024; Accepted 15 June 2024
Available online 24 June 2024

use efficiency are frequently associated with declining soil organic matter (SOM) quantity, nutrient deficiencies and increasing C footprints (Bronson et al., 1998; Ladha et al., 2003b; Grace et al., 2003). Evidence shows that intensive tillage and frequent soil wetting-drying cycles in RW rotation have reduced SOM and system inefficiencies (George et al., 1992; Ladha et al., 2011). Classical approaches to overcome this productivity decline have failed to yield widespread benefits linked to the large biophysical and socioeconomic diversity of RW growing environments and to the inherent fragility of this solely cereal-based system (Gupta et al., 2003). Intensification strategies, such as intense tillage, increased fertilizer and water use, have failed to stabilize the fragile ecological equilibrium in these vulnerable production environments (Drechsel et al., 2015; Gathala et al., 2022). Intensive tillage together with crop residue burning causes depletion of SOC (Jat et al., 2023; Sapkota et al., 2017), available macronutrients (Jat et al., 2018), reduction in soil microbial diversity and enzymes (Choudhary et al., 2018), adverse soil physical properties (Parihar et al., 2016; Jat et al., 2023), and increases in greenhouse gas emissions (GHG) with consequent deterioration of soil quality (Roy et al., 2022; Jat et al., 2023). Soil improvement is thus necessary to break the negative spiral of degradation and make cropping systems sustainable and more profitable.

It is evident that any attempt to address the challenges of food and nutrition, and to diversify the rice-wheat production system must be accompanied by integrated resource-conserving measures (Ladha et al., 2003c, 2009). The most promising new trends are based on conservation agriculture (CA) practices: (a) reduced or no-tillage systems combined with soil surface residue cover or mulching, (b) crop diversification such as substitution of rice with an upland crop, and (c) integration of legumes in intensive cereal-based crop rotations (Ladha et al., 2016; Kumar et al., 2018; Jat et al., 2019, 2020b). However, there are no comprehensive medium to long-term studies evaluating various scenarios encompassing CA practices on soil biological, physical and chemical quality, GHG mitigation, and C balance in cereal-based rotations.

This 8-year field experiment evaluates the impact of CA practices and crop diversification on crop productivity, economic returns, soil quality, nutrient dynamics, and environmental footprint within rice-wheat rotations in the Indo-Gangetic Plains of India. We hypothesize that zero tillage with residue retention, transition season cropping, and increased crop diversity will improve productivity, soil health, reduce GHG emissions, and enhance the resilience of these cropping systems.

2. Materials and Methods

2.1. Site description and treatment details

The present study was carried out from an ongoing CA-based diversification research trial (2014–2022) at the experimental farm of ICAR-CSSRI, Karnal (29° 42″20.7′ N latitude, 76° 57″19.79′ E longitude) (Fig. 1a Supp. Table 1). This region belongs to semi-arid conditions with a sub-tropical climate. The area received cyclonic rains through a southwest monsoon with long-term average annual rainfall of 670 mm, 70–80 % of which occurs in the monsoon season (June to September). The characteristics of the experimental field were silty loam in texture, low in OC (0.56 %) with slightly alkaline pH (8.02) (Supp. Table 1). The experiment was set up in a randomized block design (RBD) with three replications, each plot size 12 m x 50 m (600 m^2). The full experimental details can be found elsewhere (Jat et al., 2020b; Gora et al., 2022).

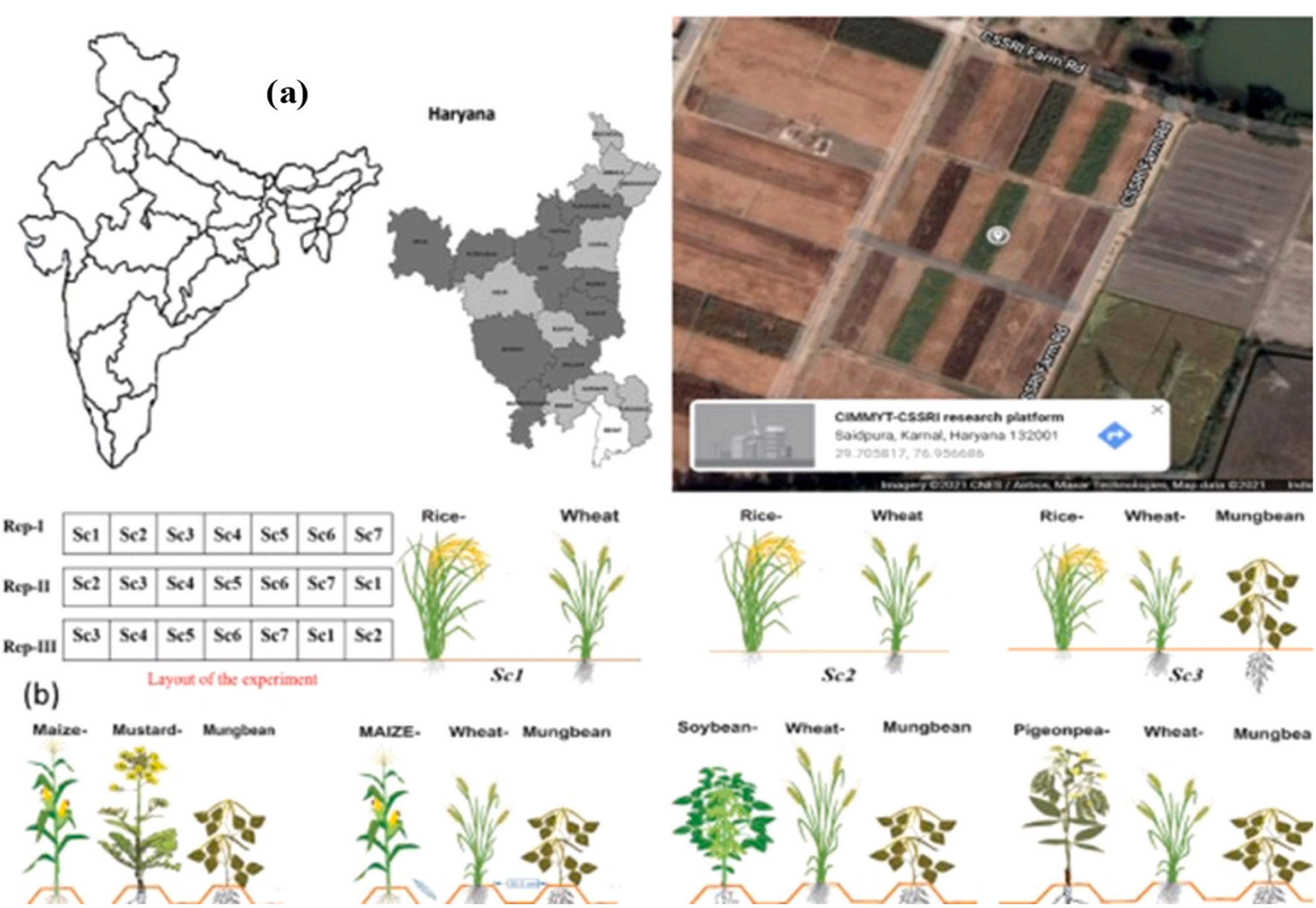

Fig. 1. Location of the experimental plots (a); Layout of the experiment and schematic diagram of different crops and cropping sequence in a year under different scenarios (b).

Seven treatments (referred to as scenarios: Sc) comprising crop rotations, tillage and residue management were designed with objectives to improve system productivity, soil quality, partial nutrient balances, and environmental footprints. Based on learning with time, the scenarios were adjusted after four years to enhance cropping intensity and diversification with superior management practices. Table 1 provides scenario descriptions for the first four (2014–2018) and the last four years (2019–2022), and Supp. Table 2 provides crop management details. Three cropping seasons in the area include the wet/rainy season (kharif; June to October), cool, dry winter season (rabi; November to March), and the hot, dry summer season (Late March to June). The rice (a wet season crop) in rotation with wheat (a dry season crop) along with summer fallow is predominant in the region. Scenario 1 features intensive tillage, crop establishment by seed broadcasting/manual transplanting, residue removal, and summer fallow, representing the current crop rotation and management practices known as farmer practice (FP) or conventional tillage-based scenario (CT-based). Scenario 2 simulated an improved farmer's practice where rice is grown as direct seeded rice with conventional tillage but wheat crop in rotation had conservation agriculture practices (no-till or zero-tillage, ZT with rice crop residue retention). Scenarios 1 and 2 were same through eight years. Whereas in other scenarios, either the rice (*Oryza* sativa) was substituted with maize (*Zea mays*) (Sc4 and 5), soybean (*Glycine max*) (Sc6) or pigeon pea (*Cajanus cajan)* (Sc7) and wheat (*Triticum* astivum) with mustard (*Brasssica juncea*) (Sc4). In addition, mung bean (*Vigna radiata)* was included in the summer season in Sc3, Sc4, Sc5, Sc6, and Sc7. To manage occasional flooding from rain in the wet season, upland crops (maize, soybean and pigeon pea) were grown on raised beds and maintained permanently (PB). Conservation agriculture, referred to as CA-based practices, was imposed in all crops in scenarios 3–7, and the soil surface was mulched with partial or full crop residue. The key details of field operations and crop management, including land preparation, tillage, variety, crop establishment, fertilizer, irrigation water, and pest, are provided in Table 1 & Supp. Table 2 (Fig. 1b).

2.2. Crop residue management under different scenarios

During 2014–2022, all the crop residues were removed from farmers' practices (Sc1). In Sc2, all rice residue was retained on the soil surface, but anchored wheat residue (20–25 % or about 2 Mg ha^{-1}) was incorporated through tillage operation before conventional-till direct seeded rice (DSR). In Sc3, all rice residue and about 25 cm anchored wheat residue were retained on the soil surface. In Sc4, crop residues were removed manually before planting, whereas in Sc5, Sc6 and Sc7, partial (~ 65 %) maize residues and anchored wheat stubbles (~ 30 %) were retained. Similarly, in Sc7, entire mung bean residue was retained on the soil surface and maize and wheat residue were managed as Sc5.

During 2018–2022, residue management in Sc1, Sc2, and Sc3 remained the same, but in Sc4, and Sc5, partial (60–65 %; ~150 cm below the cob height) maize stover and after combine harvest anchored wheat stubbles (25–30 %; ~15 cm from the surface) were retained on the soil surface, while in Sc4, mustard stubbles (60–65 %; ~100 cm from the surface) was retained. In Sc6 and Sc7, soybean (~25–30 %), pigeon pea (~20–25 %), and anchored wheat residues were retained on soil surface. In case of mung bean crop in Sc3 to Sc7, its full residue was retained on the soil surface.

During the 8 years (2014–2022) (Supp. Table 3), a total of 79.1, 80.5, 53.2, 84.0, 55.3, and 66.3 Mg ha^{-1} of crop residues were recycled (incorporated or retained on soil surface) in Sc2, Sc3, Sc4, Sc5, Sc6, and Sc7, respectively.

2.3. Weed management

The weeds were controlled through pre-emergence and post-emergence herbicides following the available recommendations. Glyphosate (1.25 l a.i. ha^{-1}) was applied to control on zero-till plots as a pre-plant herbicide. In DSR (CT/ZT) herbicides were applied: pendimethalin (1000 g a.i. ha^{-1}) as pre-emergence followed by post-emergence at 20–25 days after sowing (DAS) as Bispyribac Sodium + Pyrazosulfuron ethyl (8–10 g+ 6 g a.i. ha^{-1}, respectively) to control majority of all types of weeds (grassy and broad leaf weeds and sedges). In maize, the combination of pre-and post-emergence herbicides was used: atrazine (1000 g a.i. ha^{-1}) followed by Tembotrione (Laudis) 42 % SC (90 g a.i. ha^{-1}) and these applications were dependent on the infestation and diversity of weed species. In soybean and pigeon pea, pre- (2 DAS) and post-emergence (40 DAS) of pendimethalin (1500 ml ha^{-1}) and Imazethapyr in soybean and Quizalofop ethyl in pigeon pea (750 ml ha^{-1}) sprayed at 15–20 DAS, respectively. In wheat, tank mix post-emergence herbicides solution of Pinoxaden 5 % EC (50 g a.i. ha^{-1}) or Clodinafop ethyl + Metsulfuron (60+4 g a.i. ha^{-1}) was applied at 30–35 DAS to knock-down all types of weeds.

2.4. Soil sampling and analysis

Soil samples from the 0–15 and 15–30 cm depths from 3 sites in each plot were taken using a core sampler (7-cm diameter) at about the first week of June every year. The composite soil samples were mixed thoroughly using a poly bucket, and a subsample was taken from the mixed soil. One part of the fresh soil sample was kept moist in polyethylene bags at 4°C until the biochemical analysis. The remaining part of the soil was air-dried in shade, ground to pass through a 2-mm sieve, and stored in a plastic bag for chemical analysis. Soil bulk density, soil aggregate stability and infiltration rate were measured by core sampling (Blake and Hartge, 1986), wet sieving (Al-Maliki and Scullion, 2013), and double-ring infiltrometer (Gathala et al., 2011) methods, respectively. Soil penetration resistance (SPR) was determined to a depth of 30 cm at every 5 cm depth interval using a manual cone Penetrometer (Eijkelkamp Agrisearch Equipment, Germany). Soil pH and electrical conductivity (EC) (soil: water, 1:2) were analysed using the following standard methods (Jackson, 1973). Soil organic C, available N, available P and available K in soil were determined using wet oxidation method (Walkely and Black, 1934), alkaline permanganate method (Subbiah and Asija, 1956), sodium bicarbonate extraction method (Olsen et al., 1954) and flame photometer/neutral 1 N ammonium acetate extractant method (Jackson, 1973), respectively. Total N, P and K analyses were done by methods reported by Olsen and Sommers (1982); and Knudsen et al. (1982), respectively. Micronutrients (Fe, Mn, Zn and Cu) were determined using DTPA extractant atomic absorption spectrophotometer (Lindsay and Norvell, 1978). Soil organic C stock was calculated using the given formula.

$$Cstock\left(Mgha^{-2}\right) = C \quad \left(g \quad kg^{-2}\right) \times Bulk\ density\left(Mgha^{-3}\right) \times soil\ depth(m) \times 10 \tag{1}$$

2.5. Microbial and earthworm populations

The total bacterial counts in soil sample were made by pour plating method on a nutrient agar medium (Zuberer, 1994). After 3 days of incubation at 28°C bacterial colonies were counted. Fungal count was done on Rose bengal agar media supplemented with streptomycin (30 μg ml^{-1}) (Martin, 1950) after 5 days of incubation at 30 °C. All the plates were replicated thrice, and results were presented as colony forming units (CFU) g^{-1} dry soil. Sampling was done for earthworms during their activation period (morning) (Singh et al., 2020) during mid-September by digging and hand sorting method for two soil depths, i.e., 0–15 and 15–30 cm, from each replicate with three grid points. Soil blocks (25 cm×25 cm×15 cm) were removed from each plot. Similarly, soil blocks at depth of 15–30 cm were sampled (Abail and Whalen, 2018). Soil blocks were bagged, moved to the laboratory, and hand sorted. The density (no. m^{-2}) was determined for surface (0–15 cm) and sub-surface (15–30 cm) soil depths.

Table 1
Scenario details.

Scenario	Season	2014–2018			2019–2022		
		Wet	Dry	Summer	Wet	Dry	Summer
Sc1	Rotation	Rice	Wheat	Fallow	Rice	Wheat	Fallow
	Tillage	CT	CT	-	CT	CT	-
	CE	Transplanted	Broadcast	-	Transplanted	Broadcast	-
	Residue	Removed	Removed	-	Removed	Removed	-
Sc2	Rotation	Rice (DSR)	Wheat	Fallow	Rice (DSR)	Wheat	Fallow
	Tillage	CT	ZT	-	CT	ZT	-
	CE	Drill	Drill	-	Drill	Drill	-
	Residue	RR (F)	RR (P)	-	RR (F)	RR (P)	-
Sc3	Rotation	Rice (DSR)	Wheat	Fallow	Rice (DSR)	Wheat	Mung bean
	Tillage	ZT	ZT	-	ZT		
	CE	Drill	Drill	-	Drill	Drill	Drill
	Residue	RR (F)	RR (P)	-	RR (F)	RR (P)	RR (F)
Sc4	Rotation	Maize	Wheat	Fallow	Maize	Mustard	Mung bean
	Tillage	Raise beds, CT		-	Raise beds, ZT		
	CE	Drill	Broadcast	-	Drill	Drill	Drill
	Residue	Removed	Removed	-	RR (P)	RR (P)	RR (F)
Sc5	Rotation	Maize	Wheat	Fallow	Maize	Wheat	Mung bean
	Tillage	Raise beds, ZT		-	Raise beds, ZT		
	CE	Drill	Drill	-	Drill	Drill	Drill
	Residue	RR (P)	RR (P)		RR (P)	RR (P)	RR (F)
Sc6	Rotation	Maize	Wheat	Fallow	Soybean	Wheat	Mung bean
	Tillage	ZT	ZT	-	Raise beds, ZT		
	CE	Drill	Drill	-	Drill	Drill	Drill
	Residue	RR (P)	RR (P)	-	RR (P)	RR (P)	RR (F)
Sc7	Rotation	Maize	Wheat	Mung bean	Pigeonpea	Wheat	Mung bean
	Tillage	ZT	ZT	ZT	Raise beds, ZT		
	CE	Drill	Drill	Drill	Drill	Drill	Drill
	Residue	RR (P)	RR (P)	RR (P)	RR (P)	RR (P)	RR (F)

CE, crop establishment; CT, conventional tillage; ZT, zero or no tillage; RR (F), full residue retained; RR (P), partial residue retained.

2.6. Calculation of soil quality index

For soil quality indexing, we adopted the nonlinear method Bastida et al. (2006) described, using crop yield as the goal variable. We selected a minimum data set (MDS) of soil quality indicators that best represent soil functions, scored the MDS, and integrated it into a soil quality index (SQI). Following formula was used:

$$y = \frac{a}{\left(1 + \left(\frac{X}{X0}\right)^{-b}\right)} \tag{2}$$

where, a is the maximum value gained by the function, in this case, a =1, X is the unknown of the equation, corresponding to the parameter value in question in each case, X0 is the mean value of each parameter corresponding to the soils of different treatments, b is the value of the slope of the equation. We obtained curves that fit a sigmoidal tending to 1 for all the proposed parameters using different values of b for different selected parameters. The above value (y) gives variable curves that vary between 0 and 1. Different indicators were selected to get a "S" shaped curve to optimize the b value in the equation. Using the following equation MDS variables with weighted scores for each observation were added:

$$SQI = \sum WI\ SI \tag{3}$$

where S = indicator score, W = the weighing factor obtained from PCA, and i = 1.

Better soil quality or higher performance of soil function was associated with higher index scores.

2.7. Partial nutrient balance

Partial nutrient (N, P and K) balance sheets were constructed considering various inputs and outputs. In case of N, (a) inputs included N from fertilizer/urea, crop residue, biological nitrogen fixation, and irrigation water, and (b) outputs included N harvest through crop (grain plus above-ground plant material) and change in soil N. Nitrogen from irrigation water and pesticides was determined. Nitrogen input by rainfall was assumed to be zero. Inputs from biological nitrogen fixation in different crops were obtained from Peoples et al. (2021). Likewise, P and K balances included inputs from fertilizer, crop residue, and irrigation water, and outputs were from crop harvest and soil change. Negative nutrient balances indicate crop removal exceeds all sources' inputs, while positive balances suggest the opposite. If input exceeds output, the surplus nutrient either accumulates in the soil or is lost to the environment.

2.8. Estimation of greenhouse gases emissions and global warming potential

The CCAFS Mitigation Options Tool (CCAFS-MOT; Feliciano et al., 2017) was used to estimate GHG emissions from the production systems. The tool utilizes a combination of several empirical models to calculate GHG emissions in a production system, taking into account various factors that influence emissions (Feliciano et al., 2017). These factors include climatic conditions, soil characteristics, crop production inputs, and other relevant management practices. The CCAFS-MOT uses the (a) multivariate empirical model (MEM) of Bouwman et al., (2002) for nitrous oxide (N_2O), and nitric oxide (NO) emissions, (b) FAO/IFA (2001) model for ammonia (NH_3) emission, (c) IPCC Tier-1 emission factors for N_2O emission from crop residue, (d) the Eco-invent database for emissions related with production and transportation of fertilizers, (e) IPCC guidelines (Smith et al., 1997; Ogle et al., 2005) using updated factors based on the recent findings of Powlson et al. (2014); (2016) to account for SOC changes due to tillage intensity, farmyard manure, and residue retention/ incorporation, and the CO_2 emissions resulting from soil application of urea and lime (IPCC, 2006).

The net global warming potential (GWP) of different cropping systems was estimated considering all the sources and sinks of GHGs. All GHGs were converted into CO_2-equivalents (CO_2e) using the GWP (over 100 years) of 34 and 298 for CH_4 and N_2O, respectively (IPCC, 2013) and total GWP was calculated using following equation.

$$Total\ GWP\left(kgCO_{2eq.}ha^{-1}\right) = CO_2\quad\left(kgha^{-1}\right) + N_2O\quad\left(kg\ ha^{-1}\right)\times 298 + CH_4\quad\left(kg\ ha^{-1}\right)\quad\times 34 \tag{4}$$

2.9. System yield and economic returns

Rice and wheat were harvested and threshed either manually or using a combine harvester at a height of about 30 cm, leaving the anchored stubbles except in Sc1, which was harvested at ground level. Whereas, soybean, pigeon pea, maize and mustard crops were manually harvested and threshed. At maturity, the grain and straw yields of (a) wheat and rice were determined on an area of 100 m^2 from four samples of 25 m^2 each plot, and (b) maize, soybean, pigeon pea, mustard and mung bean were estimated from 108 m^2 area by harvesting from four locations of 27 m^2 from each plot. Grain yields reported were adjusted for seed moisture content: 140 g kg^{-1} for rice and maize, 130 g kg^{-1} for soybean and pigeon pea, 110 g kg^{-1} for mustard and 120 g kg $^{-1}$ for mung bean and wheat crops.

To evaluate system yield, we used the grain yield rice equivalent (GYRE) for all crops, rather than individual crop grain yields, measured in Mg ha^{-1}. This approach helps to neutralize the confounding effects of significant inherent differences in biomass and fluctuating market prices of the diverse crops involved in the GYRE calculations. The GYRE was calculated as

$$Grain\ yield\ rice\ equivalent\left(Mgha^{-1}\right) = \frac{Grain\ yield\ of\ non\ rice\ crop\left(Mgha^{-1}\right)\times MSP\ of\ non\ rice\ crop\left(USDMg^{-1}\right)}{MSP\ of\ rice\left(USDMg^{-1}\right)} \tag{5}$$

where, MSP is the minimum support price; (1 USD= Value of Purchasing Power Parity (PPP) to assess the yield per hectare in USD). PPP is defined as the rate of currency conversion that try to equalise the purchasing power of different currencies, by eliminating the differences in price levels between countries.

The full inventory of crop management inputs such as a number of tillage operations, fuel and electricity consumption, irrigations number and time required in each irrigation, seed, herbicide, fertilizer, labour use, pesticide application and their costs under each treatment were recorded for each crop using a standard data recording format (Supp. Table 4). All these associated costs were summated to calculate the total cost of production. The key inputs and outputs associated cost and value used for partial budgeting across the study period are presented in Supplementary Table 1. Gross economic returns were calculated as per the prevailing market prices of the commodity (grain and straw/stover) over the years. Net economic returns were determined by deducting the total cost of production from the gross returns.

2.10. Statistical analysis

The data recorded for various crop parameters were analyzed using analysis of variance (ANOVA) technique (Gomez and Gomez, 1984) for RBD using SAS 9.1 software (SAS Institute, 2002a). The scenario/-treatment means were compared using Tukey's honestly significant difference (HSD) at 5 % probability level of significance. SAS (13.2) JMP software was used for the separation of an interaction effect between scenarios and soil depth. The mean effects of cropping systems and tillage were determined using linear contrast or individual factor in the JMP (SAS Institute, 2002b). A contrast analysis offers additional insight into group differences, as it can test for more precise and specific differences among groups of data. Analyses of variance were done to test whether N balances in the different treatments were significantly different from zero.

Principal component analysis (PCA) and correlation matrix was prepared using JMP software (version 14.1). The results were submitted to PCA to evaluate the associate relationships between parameters. Data on earthworm population density, physical and chemical properties of soil had a greater coefficient of variation than 20 %, hence, were transformed through square-root ($\sqrt{(x+0.5)}$) method (Ribeiro-oliveira et al., 2018).

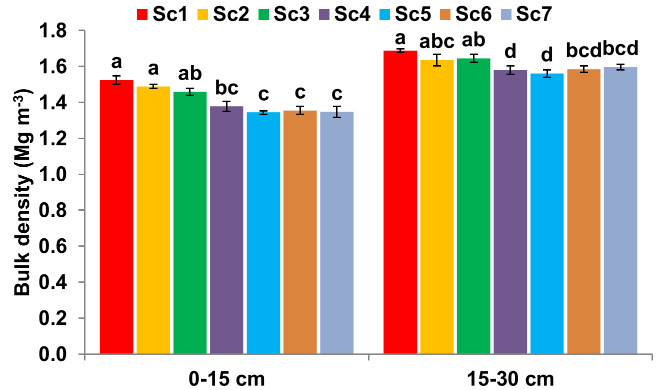

Fig. 3. Effect of CA-based cropping systems on bulk density under different scenarios after 8-years. [a]Refer Table 2 for scenario description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean). [b]Means followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. [c]Vertical bars indicate ±S.E. of mean of the observed values. [d]Indicates values that are significant at 95 % confidence level.

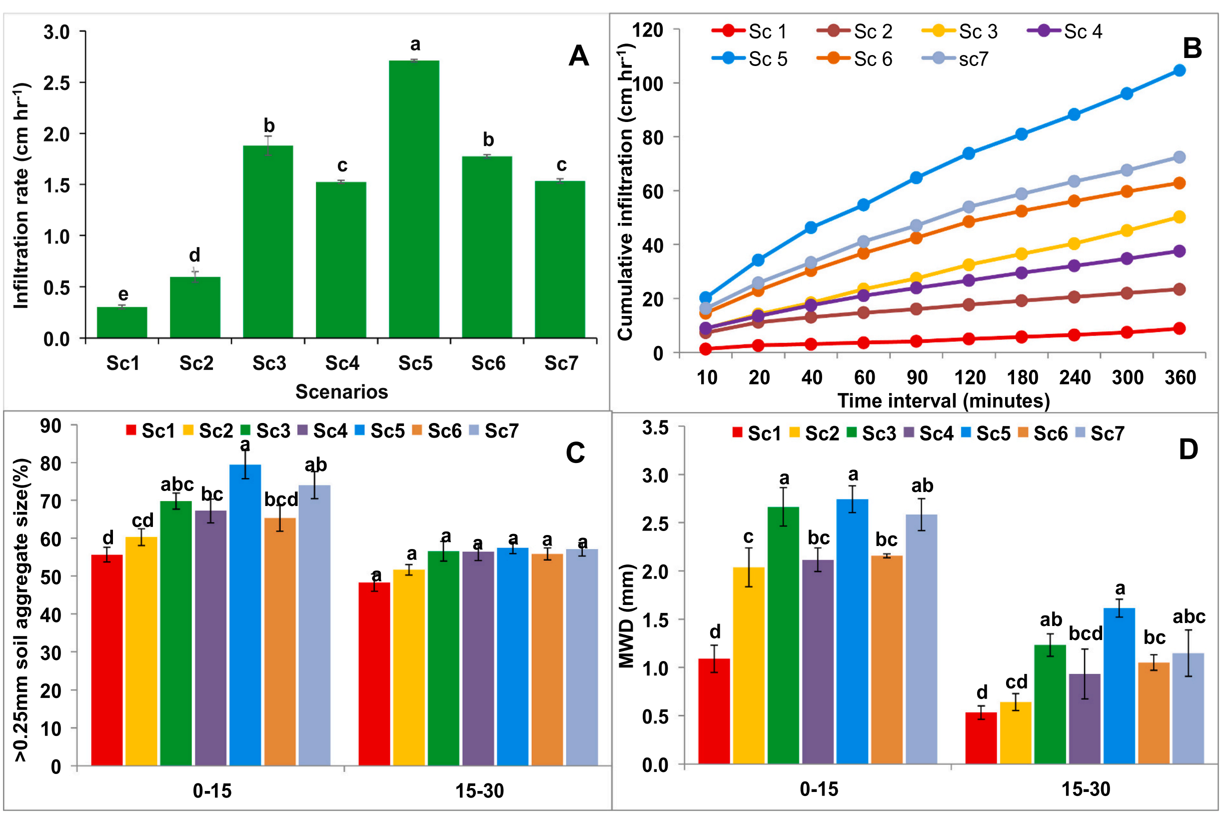

Fig. 2. Effect of CA-based cropping systems on infiltration rate, soil aggregate and mean weight diameter under different scenarios after 8-years. [a]Refer Table 2 for scenario description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean). [b]Means followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. [c]Vertical bars indicate ±S.E. of mean of the observed values. [d]Indicates values that are significant at 95 % confidence level.

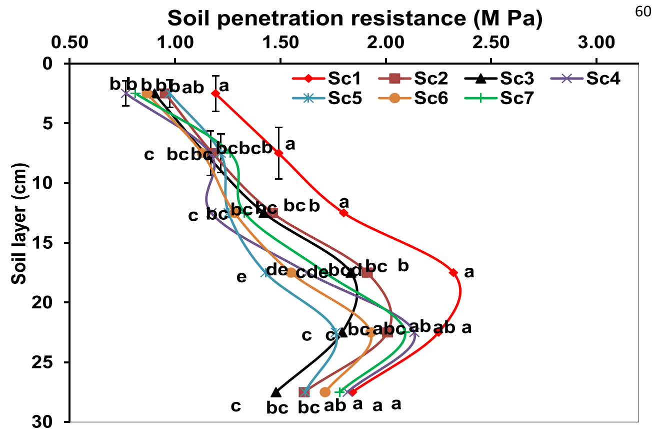

Fig. 4. Effect of CA-based cropping systems on soil penetration resistance under different scenarios. [a]Refer Table 2 for scenario description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean). [b]Means followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. [c]Vertical bars indicate ±S.E. of mean of the observed values. [d]Indicates values that are significant at 95 % confidence level.

3. Results

3.1. Soil physical properties as influenced by CA-based crop diversification

Soil physical parameters such as infiltration rate, cumulative infiltration, bulk density, soil penetration resistance and soil aggregate size distribution were significantly ($p<0.05$) influenced by different scenarios (Figs. 2–4) and interaction effects of years, scenarios, and soil layers were significant (Supp. Table 5). All the parameters showed improvements in all the CA-based scenarios (Sc2 to Sc7) compared to farmers practice (Sc1), though the quantity of improvements varied. Infiltration rate was highest in Sc5 (2.71 cm hr^{-1}) followed by Sc3 and Sc6 (1.88 and 1.77 cm hr^{-1}); Sc4 and Sc7 (1.53 and 1.53 cm hr^{-1}); Sc2 (0.60 cm hr^{-1}); and the lowest in the farmers practice (Sc1: 0.30 cm hr^{-1}) (Fig. 2a). However, the rates in Sc3 and Sc6, and Sc4 and Sc7 were not different. Successively, Sc2 to Sc7 had higher cumulative infiltration compared to Sc1 (Fig. 2b).

The >0.25 mm soil water stable aggregates size (WSA) in percentage and mean weight diameter (MWD) exhibited similar pattern of improvements. Compared to Sc1, CA-based scenarios (2−7) had 24.5 % and 15.6 % higher WSA (mean of the scenarios) and 118.7 % and 106.8 % higher MWD in surface and sub-surface soil layers, respectively (Fig. 2c, d). Both the parameters were the highest in Sc5: WSA, 42.7 % and 18.9 %, and MWD 151.7 % and 202.5 %, in surface (0–15 cm) and subsurface (15–30 cm) soil layers, respectively. The linear contrasts of WSA and MWD at surface and sub-surface layers were significant between Sc1 vs Sc2/Sc3, Sc1 vs Sc4-Sc7 (Supp. Table 5).

Soil bulk density in different scenarios varied from 1.34 to 1.52 and 1.56–1.69 Mg m^{-3} in the surface and subsurface soil layers, respectively (Fig. 3). It was the highest in Sc1 and lowest in Sc5 at both the soil depths (0–15 cm and 15–30 cm) (Fig. 3). Compared to Sc1 (1.52 Mg m^{-3}), BD of 0–15 cm soil reduced by 2.37 %, 4.31 %, 9.59 %, 11.79 %, 11.07 % and 11.59 % in Sc2, Sc3, Sc4, Sc5, Sc6 and Sc7, respectively. The linear contrast effects of BD at the surface and sub-surface layers were significant between Sc1 vs Sc4-Sc7, Sc2/Sc3 vs Sc4-Sc7 and non-significant between Sc1 vs Sc2/Sc3 (Supp. Table 5).

The SPR was significantly lower in CA-based scenarios than that of farmer practice (Sc1); the percent reductions were 26, 21, 27, 28, 13 and 9 at 0–5, 5–10, 10–15, 15–20, 20–25 and 25–30 cm soil depths, respectively (Fig. 4). The linear contrasts between Sc1 vs Sc2/Sc3, Sc1 vs Sc4-Sc7 and Sc2/Sc3 vs Sc4-Sc7 showed that effect of SPR at surface and sub-surface depth was significant (except surface layer in Sc2/Sc3 vs Sc4-Sc7) (Supp. Table 5).

3.2. Soil chemical properties as influenced by CA-based crop diversification

Except for the EC, CA-based interventions (Sc3-Sc7) significantly influenced soil pH, SOC content, C-stock, available N, P, K, Fe, Zn, Cu, and Mn (Tables 2 and 3). Soil pH ranged from 7.33 to 7.68 and 7.70–8.06 in the surface and sub-surface soil layers, respectively. Soil pH under CA-based scenarios (average of Sc3 to Sc7) after eight cropping cycles was lower by 0.28 and 0.20 units compared to Sc1 and Sc2 at the surface layer (7.67) and subsurface layers (8.03), respectively. The linear contrast effects of soil pH were significant between Sc1 (FP) vs Sc2/Sc3, FP vs Sc4-Sc7(PB) and Sc2/Sc3 vs PB both at the surface and sub-surface layers (expect FP vs Sc2/Sc3 at 15–30 cm soil depth) (Supp. Table 5). Interaction effects of scenarios, depth, year, year × depth and year × scenario was found to be significant in soil pH and EC but not significant between depth × scenario and year × scenario × depth in soil pH and EC (Supp. Table 5).

In the surface soil layer (0–15 cm), C both on gravimetric (%) and volumetric basis (C-stock, Mg ha^{-1}) were significantly higher in CA-based scenarios (Sc3-Sc7) compared to Sc1 (Table 2). On average, C percentage and C stock were 63.7 % and 49.9 % higher, respectively, in the surface layer over Sc1, measuring 0.54 % and 12.29 Mg ha^{-1}. The highest percentage of SOC was found in Sc3 (73.8 %), followed by Sc7 (72.1 %), Sc5 (63.4 %), Sc4 (58.1 %), Sc2 (57.5 %), and Sc4 (57.4 %). Similarly, the maximum soil C stock (Mg ha^{-1}) in the surface layer was observed in Sc3 (20.5), followed by Sc2 (18.9), Sc7 (18.7), Sc5 (17.7), Sc4 (17.6) and Sc6 (17.2). In sub-surface soil depth, both gravimetric and volumetric C were similar in Sc4 to Sc7 and higher than Sc1 (0.42 %

Table 2
Effect of CA-based cropping systems on soil electrical conductivity (dS m^{-1}), pH and soil organic carbon (%) and C- stock after 8- years.

Scenarios[a]	EC (dS m^{-1})		pH		C (%)		C- stock (Mg ha^{-1})	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Sc1	0.20[Ab]	0.17[Ab]	7.68[A]	8.01[AB]	0.54[D]	0.42 [F]	12.29[E]	10.57[D]
Sc2	0.20[A]	0.20[A]	7.66[A]	8.06[A]	0.85 [C]	0.47[D]	18.90[B]	11.51 [C]
Sc3	0.19[A]	0.19[A]	7.47[B]	7.90[BC]	0.93[A]	0.45[E]	20.45[A]	11.15 [C]
Sc4	0.17[A]	0.16[A]	7.40[BC]	7.86 [C]	0.85 [C]	0.50 [C]	17.57[D]	11.95[B]
Sc5	0.24[A]	0.19[A]	7.33 [C]	7.86 [C]	0.88[B]	0.54[A]	17.73[CD]	12.65[A]
Sc6	0.25[A]	0.15[A]	7.36 [C]	7.82[CD]	0.85 [C]	0.53[B]	17.21[D]	12.63[A]
Sc7	0.23[A]	0.18[A]	7.37 [C]	7.70[D]	0.93[A]	0.54[A]	18.71[BC]	12.90[A]

[b]Means followed by a similar uppercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test

[a] Refer Table 1 for treatment description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean)

Table 3
Effect of CA-based cropping systems on soil macro and micronutrient availability.

Scenarios[a]	Available N ($kg\ ha^{-1}$)		Available P ($kg\ ha^{-1}$)		Available K ($kg\ ha^{-1}$)		Fe ($mg\ kg^{-1}$)		Zn ($mg\ kg^{-1}$)		Cu ($mg\ kg^{-1}$)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Sc1	158.8 ^{C}	132.5^{D}	22.3 ^{C}	18.2^{Ab}	212.3^{D}	167.7^{E}	61.4^{A}	45.0^{A}	5.4^{AB}	2.8^{A}	6.5^{A}	3.3^{A}
Sc2	168.1^{B}	136.6^{BC}	26.7^{B}	20.1^{A}	254.6^{BC}	194.8^{A}	53.3^{B}	40.8^{A}	6.0^{A}	2.1^{A}	5.8^{AB}	3.5^{A}
Sc3	180.4^{A}	139.0^{AB}	28.1^{B}	19.2^{A}	260.7^{B}	192.6^{A}	46.6 ^{C}	42.9^{A}	6.2^{A}	2.2^{A}	5.4^{B}	3.5^{A}
Sc4	168.2^{B}	132.4^{D}	28.5^{AB}	18.9^{A}	256.7^{BC}	191.4^{AB}	38.5^{D}	29.5 ^{C}	1.8^{BC}	1.0^{B}	1.6 ^{C}	1.3^{B}
Sc5	169.1^{B}	136.0 ^{C}	32.1^{A}	22.4^{A}	275.6^{A}	180.9^{CD}	38.9^{D}	29.7 ^{C}	1.5 ^{C}	1.0^{B}	1.3 ^{C}	1.5^{B}
Sc6	180.6^{A}	141.0^{A}	29.1^{AB}	19.9^{A}	247.8 ^{C}	177.4^{D}	37.9^{D}	26.2 ^{C}	1.4 ^{C}	0.9^{B}	1.9 ^{C}	1.1^{B}
Sc7	183.1^{A}	141.1^{A}	27.0^{B}	18.3^{A}	256.0^{BC}	184.5^{BC}	38.1^{D}	35.2^{B}	1.7^{E}	1.1^{B}	2.0 ^{C}	1.3^{B}

[b]Means followed by a similar uppercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test
[a] Refer Table 1 for treatment description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean)

and 10.6 $Mg\ ha^{-1}$). Overall, % C and C-stock under CA-based cropping systems were significantly higher than Sc1 (Table 2). The linear contrasts between Sc1(FP) vs Sc2/Sc3, FP vs Sc4-Sc7(PB), and Sc2/Sc3 vs Sc4-Sc7 (PB) effect were significant in both gravimetric (0.54 %) and volumetric C (12.29 $Mg\ ha^{-1}$) in the two soil depths, respectively (Supp. Table 5). Interaction effects of years, scenario, sampling depth, year × scenario, year × sampling depth, scenario × sampling depth were also significant (Supp. Table 5).

All three available macronutrients (N, P and K) showed similar trends of significant positive changes and interactions in CA-based scenarios (Table 3).

Available nitrogen (N) in the 0–15 cm soil layer was significantly higher in CA-based scenarios (Sc2 to Sc7) compared to Sc1. Specifically, Sc3, Sc6, and Sc7 had a notable mean increase of 7.1 % in available N compared to Sc2, Sc4, and Sc5, and were 14.2 % higher than Sc1, which had 158.8 $kg\ ha^{-1}$ of available N. Additionally, available P and K in Sc2-Sc7 increased on average by 29 % and 22 %, respectively, with Sc5 recording the highest levels of P and K at 32.1 $kg\ ha^{-1}$ and 275.6 $kg\ ha^{-1}$, respectively. While soil available N and K had significant linear contrast differences between Sc1 vs Sc2/Sc3 and Sc3 vs Sc4-Sc7 (PB) in both soil profiles, available P only differed in the 0–15 cm soil (Supp. Table 5). Primarily, differences were prominent in the 0–15 cm soil, though there were some notable differences in subsurface soil (a) soybean and pigeon pea-based rotations (Sc6 and Sc7) had higher available N, and (b) available K tend to be in higher amounts in all CA-based scenarios. The overall results of available macronutrients tend to be linked to residue amendments in N and K.

Among the micronutrients studied, available Fe, Zn, and Cu showed similar responses across different scenarios and two soil depths. The interaction effects of year by scenario and sampling depth by scenario were significant (Supp. Table 5). The micronutrient levels decreased from Sc1 to Sc7 but were higher in the lowland-upland (rice-wheat)

Table 4
Cumulative N, P and K balance sheets for soil at 30-cm depth after 8 years (2014–2022).

Scenario[a]	[b]Crop Uptake (A)	[c]Fertilizer input (B)	[d]Other inputs (C)		[e]Balance (B+C) – A	Nutrient loss or gain $kg\ ha^{-1}\ year^{-1}$
			Residue	Irrigation water		
N $kg\ ha^{-1}$						
Sc1	1921^{D}	2644	0	169^{A}	892^{D}	112^{D}
Sc2	2029^{C}	2400	422^{BC}	149^{B}	941DE	118DE
Sc3	2026^{C}	2480	423^{B}	152^{B}	1029^{E}	129^{E}
Sc4	2558^{B}	2200	295^{E}	40^{E}	-23^{B}	-3^{B}
Sc5	2529^{B}	2480	406^{C}	42DE	399^{C}	50^{C}
Sc6	2813^{A}	1980	335^{D}	44^{CD}	-454^{A}	-57^{A}
Sc7	2561^{B}	1960	569^{A}	48^{C}	15^{B}	2^{B}
P $kg\ ha^{-1}$						
Sc1	407^{C}	410	0	10^{A}	13^{A}	2^{A}
Sc2	426^{B}	419	48^{B}	9^{B}	49^{B}	6^{B}
Sc3	436^{B}	489	51^{A}	9^{B}	113^{D}	14^{D}
Sc4	436^{B}	436	30^{D}	2^{C}	34^{B}	4^{B}
Sc5	439^{B}	489	49^{AB}	3^{D}	102^{CD}	13^{CD}
Sc6	481^{A}	524	36^{C}	3^{D}	82^{C}	10^{C}
Sc7	363^{D}	454	49^{AB}	3^{D}	143^{E}	18^{E}
K $kg\ ha^{-1}$						
Sc1	2265^{D}	0	0	962^{A}	-1302^{A}	-163^{A}
Sc2	2318^{D}	797	1195^{A}	849^{B}	523^{D}	65^{D}
Sc3	2098^{E}	797	1157^{A}	870^{B}	726^{E}	91^{E}
Sc4	2774^{B}	266	982^{B}	236^{D}	-1290^{A}	-161^{A}
Sc5	2901^{A}	797	1178^{A}	244^{D}	-682^{C}	-85^{C}
Sc6	2505^{C}	598	773^{D}	257^{CD}	-877^{B}	-110^{B}
Sc7	2516^{C}	598	905^{C}	276^{C}	-737^{C}	-92^{C}

[b]Means followed by a similar uppercase letter within a column are not significantly different at 0.05 probability level using Tukey's HSD test.
[a] Refer Table 1 for treatment description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean)
[b] Crop uptake includes grain plus straw harvested for all the crops in the system.
[c] Fertilizer input.
[d] other inputs include N, P and K from irrigation water and through residue for all the crops in the system.
[e] NPK balance (negative or positive) for the system.

rotation scenarios (Sc1, Sc2, and Sc3) compared to the upland-upland (maize, soybean, pigeon pea) rotations (Sc4-Sc7), as shown in Table 3. Notably, Zn and Cu were up to 72 % lower across two different soil layers. On averages, Sc1-Sc3 had 40 %, 264 % and 246 % higher Fe, Zn and Cu, respectively, than averages of Sc4-Sc7 (38.3, 1.6, 1.7 mg kg^{-1}). The three micronutrient trends and magnitude of differences were similar in the two soil depths.

3.3. Partial N, P and K balances as influenced by CA-based crop diversification

After eight years, the cumulative and mean annual partial balances of N, P, and K were significantly ($p<0.05$) affected by different scenarios, as detailed in Table 4. While N and K balances were both negative and positive in different scenarios, the P was always negative. Negative balances suggest that output (crop removal) exceeds input from all nutrient sources, while positive balances indicate the opposite. When input surpasses output, the excess nutrients either accumulate in the soil or are lost to the environment. Specifically, N loss is predominant due to its mobility, potentially being lost through denitrification or volatilization depending on soil, water, and climatic conditions. A positive N balance can indicate input from biological N_2 fixation. Conversely, a negative K balance may suggest uptake from deeper soil layers (below 30 cm), leading to soil K depletion.

Nitrogen balances were positive in all scenarios except Sc4 and Sc6, as shown in Table 4. The N balance for Sc4 was similar to that of Sc7. Notably, the N balance was significantly higher in Sc3 (DSR-wheat-mung bean system) compared to all other scenarios, with Sc2 (DSR-wheat) being the only exception, as it was comparable to Sc3. Scenarios 1–3 with rice-wheat rotation had large positive balances ranging from 112 to 129 kg ha^{-1} $year^{-1}$. Since the soils in rice-wheat (lowland-upland) rotation go through wetting-drying cycles, the system incurs with large losses of N, which are not considered in the present study. The total soil N showed a declining trend, suggesting minimal or no build-up of soil N; thus, it was largely considered lost. Our results show about 34–45 % loss of fertilizer N in Sc1 to Sc3, which is close to reported values in cereal-based systems. In upland-upland crop rotations (Sc4-Sc7), N balances were significantly lower – either marginally positive or negative (2 to −57 kg ha^{-1} $year^{-1}$, respectively) indicating lower losses and or additional inputs from biological nitrogen fixation, especially in Sc6 where soybean was in rotation with wheat. Much lower N balance to slightly negative balance (loss) in CA-based upland-upland crop rotations (Sc4-Sc7) can be explained because of favourable soil water regime is not conducive to leaching and denitrification plus some inputs from BNF. Our 8-year study on N balance suggests that soil wetting and altered physical conditions during the rice phase are primarily responsible for higher losses.

Phosphorus balances in all seven scenarios were positive, ranging from 2.0 to 18.0 kg ha^{-1} $year^{-1}$ (Table 4). This was consistent with the changes in available (final-initial) soil P values (Supp. Table 1; Table 3). Broadly, the CA-based scenarios (Sc3, Sc5, Sc6, and Sc7) had significantly higher (10–18 kg P ha^{-1} $year^{-1}$) soil build-up because of higher P input from fertilizer. When the amount of P applied from fertilizer and other sources of inputs (crop residue, organic manure, etc.) exceeds, the excess P will accumulate in soil. In the rice-wheat system, it's generally advised to apply P to wheat and other winter crops, while reducing or omitting its application to conventional puddled transplanted rice and other summer crops. These crops benefit from the increased availability of residual soil P due to high temperatures and reduced soil conditions. Our study indicates that long-term adoption of Sc3, Sc5, Sc6, and Sc7 is

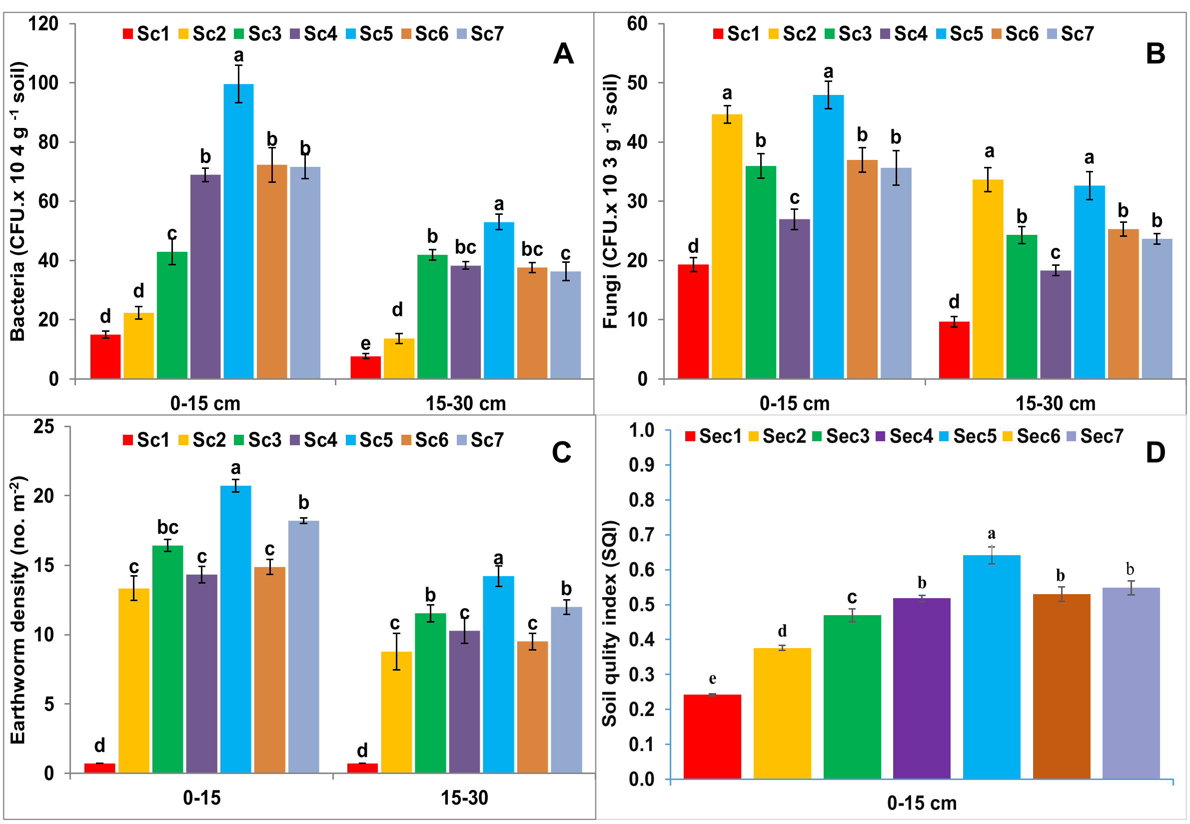

Fig. 5. Effect of CA-based cropping systems on bacterial and fungi colony counts, earthworm density and soil quality index under different scenarios after 8-years. [a]Refer Table 2 for scenario description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean). [b]Means followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. [c]Vertical bars indicate ±S.E. of mean of the observed values. [d]Indicates values that are significant at 95 % confidence level.

likely to result in P accumulation in the soil, suggesting that revisions to fertilizer P recommendations may be necessary.

Potassium balance, on the other hand, showed a mixed trend – it was negative in all scenarios except Sc2 and Sc3 which had positive balance (Table 4). The negative K balance ranged from 85 kg ha^{-1} year^{-1} in maize-wheat-mung bean (Sc4) to 163 kg ha^{-1} year^{-1} in rice-wheat system when all residues were removed (Sc1). In Sc2 and Sc3, the recycling of rice residue led to positive K balances. The scenarios with negative K balances suggest that the soil K pool was depleted, and the low level of K fertilization over the long-term may lead to K deficiency in these cropping systems, particularly where crop residues are removed. Despite low fertilizer K use by farmers, crop yields are often not reduced because soils in the region are rich in K-bearing minerals, releasing significant amounts of exchangeable K during crop growth.

3.4. Soil microbial properties as influenced by CA-based crop diversification

Both bacterial and fungal counts significantly increased in CA-based scenarios across both soil depths, with higher counts observed in the surface soil layer than in the subsurface layer (Fig. 5a, b). Bacterial and fungal counts doubled to quadrupled from CT-based (15×10^4 bacteria and 19×10^3 fungi CFU counts in Sc1) to CA-based (63×10^4 bacteria and 38×10^3 fungi CFU counts in Sc2 to Sc7) scenarios with the highest bacteria in Sc5 and the highest fungi in Sc3 and Sc5 (Fig. 5a, b). Linear contrasts between Sc1 vs Sc2/Sc4, Sc1 vs Sc4-Sc7, and Sc2/Sc3 vs Sc4-Sc7 effect were significant in both bacteria and fungi count at the surface and subsurface layer (Supp. Table 5).

Table 5
Effect of different scenarios on GHGs emissions, total SOC, global warming potential (GWP) and emission intensity (yield scaled emission) of different crops (based on 8-year average, 2014–22).

Scenarios	Total CH_4 kg (kg CO_2 eq. ha^{-1})	N_2O (kg CO_2 eq. ha^{-1})	GHG emissions due to energy consumption (kg CO_2 eq. ha^{-1})	Total SOC (kg CO_2 eq. ha^{-1})	Total GWP (kg CO_2 eq. ha^{-1}	Emission Intensity (kgCO_2 eq. kg^{-1} yield)
Kharif (Rice/maize/soybean/pigeon pea)						
Sc1	1972	422^{F}	2853^{A}	0	5247^{A}	0.832^{A}
Sc2	918	734^{CD}	2518^{B}	-247	3924^{B}	0.633^{B}
Sc3	697	687DE	2452^{C}	-190	3647^{C}	0.605^{B}
Sc4	228	816^{BC}	1062^{D}	-159	1947^{D}	0.288^{C}
Sc5	0	888^{B}	1009^{E}	-301	1596^{E}	0.203^{D}
Sc6	0	1463^{A}	729^{F}	-304	1888^{D}	0.323^{C}
Sc7	0	612^{E}	661^{G}	-317	956^{F}	0.200^{D}
Rabi (Wheat/mustard)						
Sc1	328	619^{C}	1284^{A}	0	2231^{A}	0.394^{A}
Sc2	0	694^{ABC}	1190^{B}	-308	1577^{B}	0.252^{BC}
Sc3	0	741^{AB}	1190^{B}	-337	1595^{B}	0.259^{B}
Sc4	35	427^{D}	918^{D}	-159	1221^{D}	0.212^{E}
Sc5	0	727^{AB}	1123^{C}	-301	1549^{B}	0.243^{D}
Sc6	0	670^{BC}	1143^{C}	-304	1508^{C}	0.245^{CD}
Sc7	0	757^{A}	1137^{C}	-319	1575^{B}	0.250^{C}
System						
Sc1	2299	1041^{D}	4138^{A}	0	7479^{A}	0.623^{A}
Sc2	918	1428^{C}	3709^{C}	-554	5500^{B}	0.441^{B}
Sc3	697	1500^{C}	3784^{B}	-715	5266^{C}	0.426^{C}
Sc4	263	1518^{C}	2135^{E}	-478	3438^{D}	0.258^{E}
Sc5	0	1695^{B}	2262^{D}	-762	3195^{E}	0.220^{F}
Sc6	0	2211^{A}	2003^{F}	-765	3450^{D}	0.278^{D}
Sc7	0	1741^{B}	2018^{F}	-955	2804^{F}	0.223^{F}

[a]Refer Table 1 for treatment description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean)
[b]Means followed by a similar uppercase letter within a column are not significantly different at 0.05 probability level using Tukey's HSD test.

3.5. Earthworm density as influenced by CA-based crop diversification

Compared to the CT-based scenario (Sc1), the earthworm density in all the CA-based scenarios (Sc2 to Sc7) increased several folds in both soil depths (Fig. 5c). Scenario 5 recorded the highest density of 333.3 and 165.3 individuals m^{-2} in the surface and sub-surface soil layers, respectively.

3.6. GHG emissions from soil, residue burning and energy consumption in different cropping system scenarios

Rice grown in wet season with either continuous flooding (Sc1) or alternate wetting-drying (Sc2 and Sc3) emitted much of the methane, but there was also some methane emission recorded from residue burning in scenarios where residue was removed specially in the first four years of cropping (Sc1 and Sc3; Table 5). Since crop residue burning is a common farmers' practice CT-based system in rice in the western IGP, GHG emission due to residue burning was estimated and accounted for (Sc1) and maize (Sc4 and Sc5). (Table 5). Scenario 1, with CT and residue burning, had the highest emission of methane 1972 kg CO_2 eq. ha^{-1}, which was reduced to 53.4 % in Sc2 with CT residue retention and to 64.7 % in Sc3 with ZT and residue retention. On a system basis, conventional rice-wheat rotation (Sc1) emitted the highest methane 2299 kg CO_2 eq. ha^{-1} and maize-wheat rotation (Sc4) had the lowest emission (263 kg CO_2 eq. ha^{-1}). No GHG emission was included due to burning where crop residues were retained/incorporated in CA-based management options under different scenarios.

The rice-wheat system in Sc1 with CT and continuous flooding had the lowest nitrous oxide in rice and system basis (422 and 1041 kg CO_2 eq. ha^{-1}, respectively). On a system basis, CA-based scenarios (Sc2 to Sc7) had significantly higher N_2O emissions (ranging from 1428 to 2211 kg CO_2 eq. ha^{-1}) than that of conventional scenario (Sc1, 1041 kg CO_2 eq. ha^{-1}). Scenarios 6 and 7 with maize-wheat rotation in the first four years and legumes (soybean-pigeon pea)-wheat rotation (Sc6 and Sc7) in the second four years had the highest N_2O of 2221 and 1741, kg CO_2 eq. ha^{-1} respectively.

Energy consumption associated with the production and transportation of fertilizers, as well as field operations such as tillage, seeding, and irrigation, drove GHG emissions, which showed a clear trend across both wet and dry season crops. GHG emissions for wet and dry seasons on a system basis were higher in the CT-based scenario (Sc1) compared to scenarios (Sc2 to Sc7) where conservation tillage was practiced-emissions decreased as tillage intensity was reduced. In the wet season, GHG emissions were the highest at 2853 kg CO_2 eq. ha^{-1} in Sc1, decreasing by 11.7 %, 16.4 %, and 62.8 % in Sc2, Sc3, and Sc4, respectively, and dropping to the lowest, 72.0 %, in Sc5 to Sc7 (Table 5). Similarly, in the dry season, emissions reduced from the highest of 1284 kg CO_2 eq. ha^{-1} in Sc1 to 7.3 % in Sc2 and Sc3, and to 18.9 % in Sc4 to Sc7.

3.7. Carbon storage from residue retention in different cropping system scenarios

Except for Sc1, which represents traditional farming practices where crop residue was removed or burned, the other scenarios (Sc2 to Sc7) involved partial (Sc2 and Sc3) or full (Sc4 to Sc7) retention of residues on the soil surface as mulch in CA-based scenarios (Sc3-Sc7). The INPUTS of C in soil S sequestration from residue retention, estimated through the CCAFS-MOT model, were considered as reductions in kg CO_2 eq. ha^{-1}. On a system-wide basis, these values ranged from 478 to 955 kg CO_2 eq. ha^{-1} in Sc2 to Sc7 (Table 5).

3.8. Total and yield-scaled global warming potential

Total global warming potential (GWP, expressed as kg CO_2 eq. ha^{-1}) and yield-scaled GWP (also referred to as GWP intensity or GWPi,

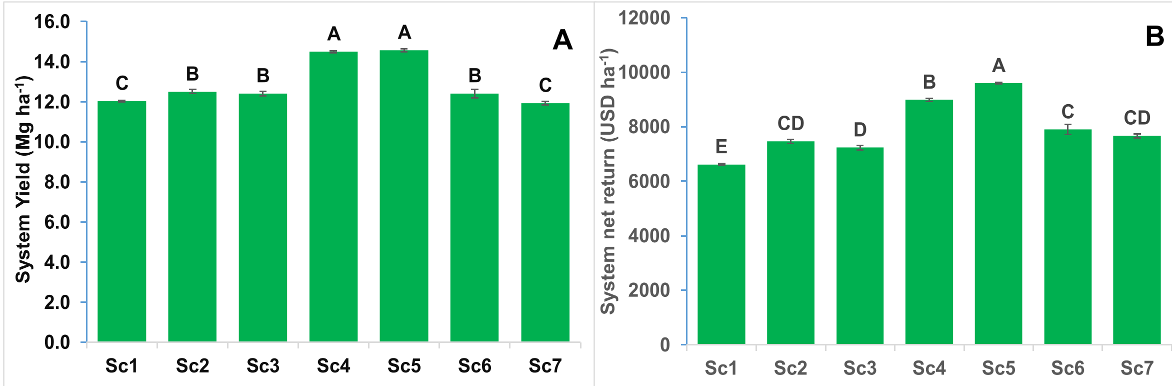

Fig. 6. Effect of CA-based cropping systems on system yield and system net return under different scenarios. [a]Refer Table 2 for scenario description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean). [b]Means followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. [c]Vertical bars indicate ±S.E. of mean of the observed values. [d]Indicates values that are significant at 95 % confidence level.

measured in CO_2 eq per metric ton of rice equivalent system yield) were calculated based on GHG emissions from soil and emissions associated with various inputs used during the cropping period, including fuel, electricity, fertilizers, herbicides, and pesticides. Both total and yield-scaled significantly differed in all the scenarios (Sc1 to Sc7; Table 5). On the cropping system basis, Sc1 had the highest total GWP (7479 kg CO_2 eq. ha^{-1}) and GWPi (0.62 CO_2 eq. Mg^{-1}). Rice-wheat-based rotation (Sc1 to Sc3) had 47–51 % higher total GWP and GWPi than other crop rotations including maize-wheat (Sc4 to Sc7). Of the total GWP of 311,32 kg CO_2 eq. ha^{-1} across seven scenarios, 49.1 % was contributed by emissions of CH_4 and N_2O from soil during crop cultivation, 64.3 % was from the other major sources (energy used for irrigation, fertilization, and pesticide) of emissions.

3.9. System yield and economic returns

System yield (rice equivalent; RE) and economic returns varied from 11.93 to 14.57 Mg ha^{-1} and 6616.3–9595.4 US$ ha^{-1}, respectively, amongst the scenarios (Fig. 6a, b).

The highest system yields and economic returns were observed in Sc5, followed closely by Sc4. In contrast, the lowest yields and returns were recorded in Sc1 (Fig. 6a, b). The system yield and economic returns of CA-based scenarios (Sc2-Sc7) increased by approximately 9 %, which equates to an increase of 1.02 Mg ha^{-1} and 620.3–2929.1 US$ ha^{-1}, respectively, compared to the CT-based scenario (12.03 Mg ha^{-1} and 6616.30 US$ ha^{-1}, respectively). The system yield and returns under the zero-tillage (Sc2 and Sc3) were 3.5 % and 11.1 % higher than Sc1 (farmers' practice). However, under permanent beds (Sc4 to Sc7), they were 11.0 % and 29.0 % higher, respectively. Nevertheless, system yields were similar across Sc1, 2, 3, and 7, and the economic returns were comparable in Sc2, 3, and 7. Crop diversification from a CT-based rice-wheat system to a CA-based maize-wheat/mustard-mung bean system increased the system yield by approximately 21 % and returns by 40.4 %.

3.10. Principal component analysis (PCA) and soil quality index (SQI)

Since the trends of soil quality indicators and soil quality index were very similar in two soil depths, we only discussed the upper soil layer (0–15 cm). In the PCA of 18 variables, three PCs were extracted with eigenvalues >1 that explained 90.59 % of the variance (Fig. 7a). Bacterial population in PC 1 (70. 1 %), C-stock in PC 2 (14.7 %) and fungi population in PC 3 (5.79 %) were selected as minimum data set (MDS) (Fig. 7b). After scoring, each score was multiplied by the respective weight obtained from PCA analysis. Then, the summation of these values given the soil quality indices for each treatment (Fig. 7b):

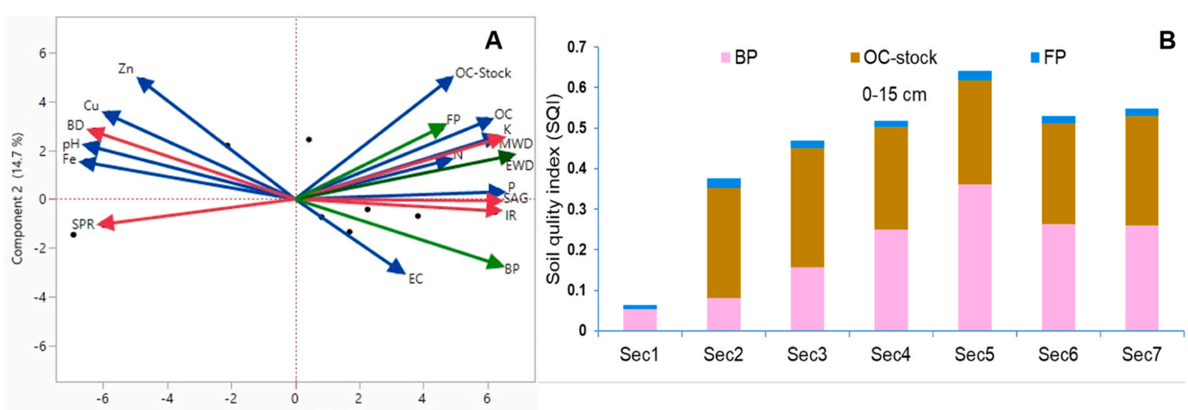

Fig. 7. (a) Principal component plot of soil physical, chemical and biological properties under long-term CA-based management practices (b) the contribution of individual key components on soil quality index under different scenarios. *Soil physical properties, chemical properties and biological properties are represented by red, blue and green colors, respectively. *Where*; pH- Soil pH; EC- Electric Conductivity; BD- Bulk density; SPR- Soil penetration resistance; IF- Infiltration rate; SOC- Soil organic carbon; SOC stock- Soil organic carbon stock; N- Available nitrogen; P- Available phosphorus; K- Available potassium; Fe- Available iron; Zn- Available zinc; Cu- Available copper; SAG- Soil aggregate size; EW- Earthworm density; BP- Bacteria population; FP- Fungi population.

SQI (0–15 cm) = $\sum$ (Bacterial population score × 0.399) + (Soil C-stock score × 0.299) + (Fungi population × 0.027).

Scenarios showed significant differences (Fig. 5d) for SQI. Sc5 had the SQI of 0.64, followed by Sc7 (0.55). The lowest SQI was scored by Sc1 (0.24) and Sc2 (0.38) due to lower values of soil physicochemical and biological properties.

The average individual contributions of each indicator in SQI across the treatments were 3.87, 42.89 and 53.24 % for fungi population, bacterial population, and OC-stock, respectively. The contribution of bacterial population to SQI was higher in CA-based scenarios (Sc3-Sc7) over FP. However, the contribution of soil C stock to SQI was higher in Sc1 (73.31 %) over the rest of the scenarios (mean of Sc2- Sc6) (53.29 %). The average contribution of the fungi population was more in ZT (mean of Sc2 and Sc3) (5.08 %) than in permanent raised beds (mean of Sc4 and Sc7) (3.49 %).

The results showed a strong and positive correlation between earthworm abundance (density for the 0–15 cm soil depth) and several parameters, including infiltration rate (IR), soil aggregate stability (SAG), mean weight diameter (MWD), soil organic carbon (SOC), SOC stock, and the nutrients N, P, and K (Supp. Table 6). Conversely, earthworm density at this soil depth negatively correlated with soil pH, bulk density (BD), soil penetration resistance (SPR), and the micronutrients Zn, Fe, and Cu. Specifically, in the topsoil layer, there was a significant positive correlation between earthworm density and SOC (r=0.94), SOC-stock (r=0.83), P (r=0.89), K (r=0.96), IR (r=0.83), SAG (r=0.88), and MWD (r=0.97). However, there was a significant negative correlation between earthworm density and pH (r=0.79), Fe (r=0.83), Cu (r=0.68), and SPR (r=0.84) (Supp. Table 6).

4. Discussion

In this eight years study, we explored how different conservation agriculture (CA)-based scenarios impact various soil physical, chemical, and biological properties compared to conventional farming practices. The results indicate significant improvements in soil infiltration rate, bulk density (BD), soil penetration resistance (SPR), and soil aggregate size distribution under CA-based scenarios (Sc2 to Sc7) compared to conventional tillage (CT) practices (Sc1). Notably, the infiltration rate was the highest in Sc5 and showed varying degrees of improvement across other scenarios. This suggests that minimal soil manipulation, crop residue retention, and diversification directly or indirectly enhance soil properties due to less disturbance and higher soil organic matter, which improves soil aggregation and pore distribution (Gathala et al., (2011); Thierfelder and Wall (2009).

Further, CA practices were associated with lower soil penetration resistance, a measure of soil compaction, across all soil depths compared to CT, primarily due to reduced bulk density and improved soil structure from no-till practices and residue recycling. These findings are consistent with prior research indicating that no-till and residue retention contribute to higher SOC content, enhancing mean weight diameter (MWD) and water-stable aggregates (WSA) (Gathala et al., 2011; Jat et al., 2013; Salem et al., 2015; Zhao et al., 2015; Somasundaram et al., 2020).

Chemical properties also improved under CA-based scenarios, with higher SOC and macronutrient availability (N, P, K). This enhancement can be attributed to the combination of crop residue retention and diversified uplands crops, inclusion of legumes and oilseeds, which provide a continuous supply of organic matter and nutrients through mineralization and biological N fixation, particularly in scenarios involving zero tillage and permanent raised beds (Dolan et al., 2006; Blanco-Canqui and Lal, 2008; Jat et al., 2018). The micronutrients (Fe, Zn, Cu) in the surface and subsurface layers were found to be more concentrated under rice-based scenarios (SC1-SC3) compared to diversified scenarios (SC4-SC7). This could be attributed to the application of ZnSO4 at a rate of 25 kg ha^{-1} during rice cultivation and the foliar spraying of $FeSO_4$ on the rice crop. Additionally, the prolonged submergence during rice cultivation may have enhanced the availability of Fe and Cu.

Microbial populations in the soil showed a substantial increase under CA scenarios, suggesting that the availability of organic matter and the reduction in soil disturbance create favourable conditions for microbial proliferation (Ghimire et al., 2014; Choudhary et al., 2018). This aligns with the observation that earthworm density, a key indicator of soil health, is also higher in CA scenarios. These earthworms contribute to nutrient cycling and organic matter decomposition, enhancing soil fertility (Rosas-Medina et al., 2010; Briones and Schmidt, 2017; Stroud, 2019). Furthermore, principal component analysis (PCA) indicated that microbial populations and soil C stock are critical drivers of soil quality variations (Das et al., 2021; Roy et al., 2022). The higher soil quality index (SQI) observed in CA scenarios underscores the potential of conservation practices to enhance soil health, further supported by the positive correlation between earthworm abundance and key soil quality parameters.

Regarding global warming potential (GWP), the study revealed that CA practices, especially those involving non-flooding and residue retention, significantly reduce methane emissions from rice paddies, which is a major concern in conventional rice-wheat systems (Adhya et al., 2014; Linquist et al., 2015). The reduction in GHG emissions is further supported by the higher C storage observed in CA scenarios, underscoring the role of conservation practices in enhancing C sequestration Jat et al. (2023). According to Ladha et al. (2016), energy use for irrigation, fertilizer, and pesticides also added significantly to the overall greenhouse gas pollution caused by soil emissions (CH_4 and N_2O) during crop production.

Economically, the highest system yield and returns were noted in scenarios with diversified cropping systems such as maize-mustard-mung bean (Sc4) due to better utilization of seasonal growth windows and efficient water use facilitated by residue mulching.

Overall, these results contribute to a better understanding of how CA-based management approaches can significantly improve soil quality, enhance productivity, and reduce environmental impacts, reinforcing the need for comprehensive management strategies that consider both biological and physicochemical aspects of soil health in agricultural systems. This study suggests that adopting CA-based, and notably, maize-based rotations could serve as a sustainable alternative to the traditional rice-wheat rotation (Sc1) prevalent in the Indo-Gangetic plains of northwestern India. Many researchers (2022; 2019; 2020; Parihar et al., 2016) have reported increases in yield, net economic returns and water productivity and reduction in global warming potential of CA-based maize-based systems compared to RW system. Choudhary et al. (2018) reported that maize-wheat-mung bean was the best alternative option to traditional RW system to achieve sustainable productivity while improving the SQI and conservation of natural resources and popularized all across RW domains in the IGP of South Asia. Considering the escalating water scarcity in the western region of India, diversifying cropping systems with maize-based rotations presents an opportunity to enhance water productivity (Yadvinder-Singh et al., 2014). However, the widespread adoption of such diversified rotations necessitates policy support from the government, such as payments for C credits and other societal benefits, including guaranteed markets at maximum support prices. The study's findings underscore that CA-based practices, coupled with diversified and intensive crop rotations, possess the potential to tackle the multifaceted challenges posed by decreasing crop productivity, diminishing economic returns, soil degradation, and escalating environmental footprints within the traditional rice-wheat system of northwestern India.

5. Conclusions

The results of this eight-year study underscore the substantial benefits of incorporating CA principles into cropping systems. Comparative

Table 6
Percent changes in key system performance parameters in CA-based scenarios (Sc2 to Sc7) over conventional farmers scenario (Sc1).

Scenarios comparison over Sc1[a]	System yield[b]	System Economic profits	SQI	Carbon stock	Apparent system N balance (input-output)	GWP
All CA (Mean Sc 2 to Sc7)	8.5[B]	23.0[B]	111.4[B]	49.6[AB]	-64.4[B]	-47.2[B]
Rice-based CA (Mean Sc 2 & Sc 3)	3.5 [C]	11.1 [C]	74.2 [C]	59.7[A]	10.4[A]	-28.0[A]
Maize-based CA (Mean Sc 4 & Sc 5)	20.7[A]	40.3[A]	138.4[A]	43.3[B]	-78.9 [C]	-55.6 [C]
Legume-based CA (Mean Sc 6 & Sc 7)	1.2 [C]	17.6 [C]	121.7[B]	45.9[B]	-124.6[D]	-58.1[D]

[a] Refer Table 1 for treatment description: Sc1=conventional till (rice-wheat); Sc2=conventional till (rice)-zero till (wheat); Sc3=zero till (rice-wheat-mung bean); Sc4=permanent bed (maize-mustard-mung bean); Sc5= permanent bed (maize-wheat-mung bean); Sc6=permanent bed (soybean-wheat mung bean); Sc7=permanent bed (pigeon pea-wheat-mung bean)

[b] Means followed by a similar uppercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test

analysis of CA-based scenarios (averages of Sc2 to Sc7) against the conventional RW system (Sc1) exhibited noteworthy benefits, including increases of 8.5 %, 23.0 %, 111 %, and 49.6 % in system yield, system economic return, soil quality index (SQI), and C stock, respectively (Table 6). Notably, CA-based scenarios led to a remarkable 47.2 % reduction in greenhouse gas emissions (GWP) and apparent N balance showed 64.4 % higher N output than input compared to Sc1. Further analysis demonstrated that maize-based rotations showcased the highest overall benefits, including a 20.7 % increase in system yield, a 40.3 % rise in economic yield, a 138 % boost in SQI, a 55.6 % decrease in GWP, and a 43.3 % increase in C stock. In contrast, the rice-based rotation exhibited relatively lower benefits, with gains of 3.5 % in system yield, 11.1 % in economic return, and a 28.0 % reduction in GWP, while achieving a substantial 74.2 % increase in SQI and a significant 59.7 % rise in C stock. The latter outcome is attributed to soil saturation, flooding, and mulching, facilitating C accumulation. Additionally, the legume-based rotation recorded the lowest system yield increase at 1.2 % yet exhibited the highest protein yield (data not shown). Legume-based rotation also had much lower N balance (-125 %), indicating significantly higher N output than N input resulting from symbiotic biological N_2 fixation. The results of this study will provide strong science-based evidence to the policymakers for appropriate policy decisions for crop diversification and to promote the conservation agriculture-based practices and attract the potential market for C credit farming in the region.

CRediT authorship contribution statement

Timothy Joseph Krupnik: Writing – review & editing, Resources, Project administration. **Jagadish Kumar Ladha:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Madhu Choudhary:** Writing – review & editing, Validation, Investigation. **Prabodh Chander Sharma:** Supervision, Resources, Project administration. **Arvind Kumar Yadav:** Investigation, Data curation. **Love Kumar Singh:** Writing – review & editing, Investigation, Data curation. **Tek Bahadur Sapkota:** Writing – review & editing, Formal analysis. **Yadvinder Singh:** Writing – review & editing, Formal analysis. **Kailash Prajapat:** Writing – review & editing, Investigation, Data curation. **Mangi Lal Jat:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Mahesh K Gathala:** Writing – review & editing, Supervision, Resources, Project administration. **Hanuman Sahay Jat:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Rakesh Kumar Yadav:** Writing – review & editing, Supervision, Project administration. **Manoj Kumar Gora:** Visualization, Validation, Investigation, Formal analysis, Data curation.

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.

Acknowledgments

The authors acknowledge the support from the ICAR-CSSRI, Karnal, and CIMMYT. The authors sincerely thank the Indian Council of Agricultural Research (ICAR) for Window-3 Funding to CIMMYT for Conservation Agriculture Research and The One CGIAR Integrated Regional Initiatives Transforming Agrifood Systems in South Asia (TAFSSA; https://www.cgiar.org/initiative/20-transforming-agrifood-systems-in-south-asia-tafssa). The authors also thank the Cereal Systems Initiative for South Asia (CSISA; https://csisa.org/) for receiving the technical support).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109476.

References

Abail, Z., Whalen, J.K., 2018. Corn residue inputs influence earthworm population dynamics in a no-till corn-soybean rotation. Appl. Soil Ecol. 127, 120–128.
Adhya, T.K., Linquist, B., Searchinger, T., Wassmann, R., Yan, X., 2014. Wetting and drying: Reducing greenhouse gas emissions and saving water from rice production. Working paper, installment 8 of creating a sustainable food future. World Resources Institute, Washington, DC.
Al-Maliki, S., Scullion, J., 2013. Interactions between earthworms and residues of differing quality affecting aggregate stability and microbial dynamics. Appl. Soil Ecol. 64, 56–62.
Bastida, F., Moreno, J.L., Hernández, T., García, C., 2006. Microbiological degradation index of soils in a semiarid climate. Soil Biol. Biochem. 38, 3463–3473.
Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute A, editor. Methods of soil analysis: part 1—physical and mineralogical methods. SSSA Book Ser. 5.1. Madison, WI, ASA and SSSA, pp. 363–375.
Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J. 72, 693–701.
Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Estimation of global NH_3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. Glob. Biogeochem. Cycles 16, 8-1.
Briones, M.J.I., Schmidt, O., 2017. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. Glob. Change Biol. 23, 4396–4419.
Bronson, K.F., Cassman, K.G., Wassmann, W., Olk, D.C., Van-Noorwijk, M., Garrity, D.P., 1998. Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, USA, pp. 35–57.
Byerlee, D., Ali, M., Siddiq, A., 2003. Sustainability of the rice-wheat system in Pakistan's Punjab: How large is the problem. ASA Special Publication No. 65. In: Ladha, J.K., Hill, J., Gupta, R.K., Duxbury, J., Buresh, R.J. (Eds.), Improving the productivity and sustainability of rice-wheat systems: issues and impacts. American Society of Agronomy, Madison, WI, USA, pp. 27–44. ASA Special Publication No. 65.
Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma 313, 193–204.
Das, S., Bhattacharyya, R., Das, T.K., Sharma, A.R., Dwivedi, B.S., Meena, M.C., Chaudhari, S.K., 2021. Soil quality indices in a conservation agriculture-based rice-mustard cropping system in North-western Indo-Gangetic Plains. Soil . Res. 208, 104914.

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M., Molina, J.A.E., 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage: residue and nitrogen management. Soil . Res. 89, 221–231.

Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R., Wichelns, D., 2015. Managing Water and Fertilizer for Sustainable Agricultural Intensification. International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). First edition, Paris, France.

Feliciano, D., Nayak, D.R., Vetter, S.H., Hillier, J., 2017. CCAFS-MOT-A tool for farmers, extension services and policy-advisors to identify mitigation options for agriculture. Agric. Syst. 154, 100–111.

Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Sharma, P.K., 2011. Effect of tillage and crop establishment methods on physical properties of a medium textured soil under a seven-year rice-wheat rotation. Soil Sci. Soc. Am. J. 75, 1851–1862.

Gathala, M.K., Mahdi, S.S., Jan, R., Wani, O.A., Parthiban, M., 2022. Sustainable Intensification in Eastern Gangetic Plains of South Asia via Conservation Agriculture for Energy, Water and Food Security Under Climate Smart Management System. In: Bahar, F.A., Anwar Bhat, M., Mahdi, S.S. (Eds.), Secondary Agriculture. Springer, Cham.

George, T., Ladha, J.K., Buresh, R.J., Garrity, D.P., 1992. Managing native and legume-fixed nitrogen in lowland rice-based cropping systems. In Biological Nitrogen Fixation for Sustainable Agriculture: Extended versions of papers presented in the Symposium, Role of Biological Nitrogen Fixation in Sustainable Agriculture at the 13th Congress of Soil Science, Kyoto, Japan, pp. 69-91.

Ghimire, R., Norton, J.B., Stahl, P.D., Norton, U., 2014. Soil microbial substrate properties and microbial community responses under irrigated organic and reduced-tillage crop and forage production systems. PLoS ONE 9, 103901.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research, 2nd ed. John Wiley and Sons, New York.

Gora, M.K., Kumar, S., Jat, H.S., Kakraliya, S.K., Choudhary, M., Dhaka, A.K., Jat, M.L., 2022. Scalable diversification options deliver sustainable and nutritious food in Indo-Gangetic plains. Sci. Rep. 12, 14371.

Grace, P.R., Jain, M.C., Harrington, L., Robertson, G.P., 2003. Long-term sustainability of the tropical and subtropical rice-wheat system: an environmental perspective. ASA Special Publication No. 65. In: Ladha, J.K., Hill, J., Gupta, R.K., Duxbury, J., Buresh, R.J. (Eds.), Improving the productivity and sustainability of rice-wheat systems: issues and impacts. American Society of Agronomy, Madison, WI, USA, pp. 27–44. ASA Special Publication No. 65.

Gupta, R.K., Hobbs, P.R., Jiaguo, J., Ladha, J.K., 2003. Sustainability of post-Green Revolution agriculture: The rice-wheat cropping systems of the Indo-Gangetic plains and China. In: Ladha J.K., Hill J., Gupta R.K., Duxbury J., Buresh R.J., (Eds), Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication No. 65. Madison, WI, USA, Am. Soc. Agron. pp. 27-44.

Hobbs P.R., Morris M.L., 1996. Meeting South Asia's future food requirements from rice-wheat cropping systems: priority issues facing researchers in the post-green era. NRG paper 96-01. Mexico, D.F. CIMMYT.

International Fertilizer Industry Association, 2001. Global estimates of gaseous emissions of NH3, NO and N2O from agricultural land. Food and Agriculture Organization of the United Nations (FAO).

IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. Institute for Global Environmental Strategies, Tokyo, Japan.

IPCC, 2013. Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson, M.L., 1973. Soil chemical analysis. Prentice Hall of India Pvt. Ltd, New Delhi.

Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A., Gerard, B., 2020a. Conservation agriculture for sustainable intensification in South Asia. Nat. Sustain. 3, 336–343.

Jat, H.S., Datta, A., Sharma, P.C., Kumar, V., Yadav, A.K., Choudhary, M., Choudhary, V., Gathala, M.K., Sharma, D.K., Jat, M.L., Yaduvanshi, N.P.S., Singh, G., McDonald, A., 2018. Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil incereal-based systems of North-West India. Arch. Agron. Soil Sci. 64, 531–545.

Jat, M.L., Gathala, M.K., Choudhary, M., Sharma, S., Jat, H.S., Gupta, N., Yadvinder-Singh, 2023. Conservation agriculture for regenerating soil health and climate change mitigation in smallholder systems of South Asia. Adv. Agron. 181, 183–277.

Jat, M.L., Gathala, M.K., Saharawat, Y.S., Tetarwal, J.P., Gupta, R., Singh, Y., 2013. Double no till and permanent raised beds in maize-wheat rotation of North-Western Indo-Gangetic Plains of India: effects on crop yields, water productivity, profitability and soil physical properties. Field Crops Res 149, 291–299.

Jat, H.S., Kumar, V., Datta, A., Choudhary, M., Kakraliya, S.K., Poonia, T., McDonald, A. J., Jat, M.L., Sharma, P.C., 2020b. Designing profitable, resource use efficient and environmentally sound cereal based systems for the Western Indo-Gangetic plains. Sci. Rep. 10 (1), 16.

Jat, H.S., Sharma, P.C., Datta, A., Choudhary, M., Kakraliya, S.K., Yadvinder-Singh, Sidhu, H.S., Gerard, B., Jat, M.L., 2019. Re-designing irrigated intensive cereal systems through bundling precision agronomic innovations for transitioning towards agricultural sustainability in North-West India. Sci. Rep. 9, 17929.

Knudsen, D., Peterson, G.A., Pratt, P.F., 1982. Lithium, sodium and potassium. In: Page, A.L., (Eds), Methods of soil analysis, Part 2. Madison. Wis. USA, Am. Soc. Agron., pp. 225-246.

Kumar, V., Jat, H.S., Sharma, P.C., Gathala, M.K., Malik, R.K., Kamboj, B.R., 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.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., 2003c. How extensive are yield declines in long-term rice–wheat experiments in Asia? Field Crop Res 81, 159–180.

Ladha, J.K., Hill, J.E., Duxbury, J.D., Gupta, R.K., Buresh, R.J., 2003a. Improving the productivity and sustainability of rice-wheat systems: issues and impact. ASA Special Publication 65. Madison, WI, USA, Am. Soc. Agron. pp. 211.

Ladha, J.K., Kumar, V., Alam, M.M., Sharma, S., Gathala, M.K., Chandna, P., Saharawat, Y.S., Balasubramanian, V., 2009. Integrating crop and resource management technologies for enhanced productivity, proftability, and sustainability of the rice-wheat system in South Asia. In: Erenstein, Hardy, O., Ladha, B., Yadvinder-Singh, J.K. (Eds.), Integrated crop and resource management in the rice-wheat system of South Asia. International Rice Research Institute, Philippines, pp. 69–108.

Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., Gupta, R.K., 2003b. Productivity trends in intensive rice-wheat cropping systems in Asia. In: Ladha J.K., Hill, J., Gupta, R.K., Duxbury, J., Buresh, R.J., (Eds.), Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication 65. Madison, WI, USA, Am. Soc. Agron. pp. 45-76.

Ladha, J.K., Rao, A.N., Raman, A.K., Padre, A.T., Dobermann, A., Gathala, M.K., 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, 1054–1074.

Ladha, J.K., Reddy, C.K., Padre, A.T., Kessel, C., 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. J. Environ. Qual. 40, 1756–1766.

Lindsay, W.L., Norvell, W.A., 1978. Development of a DTPA soil test for Zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42, 421–428.

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., Da Rosa, E.F., Van Kessel, C., 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Glob. Change Biol. 21, 407–417.

Martin, J.P., 1950. Use of acid, rose Bengal and streptomycin in the plate method for estimating soil fungi. Soil Sci. 69, 215–232.

Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72, 87–121.

Olsen, C.R., Cole, C.V., Wantanable, F.S., Dean, L., A., 1954. Estimation of available P in soil by extraction with sodium bicarbonate. USDA Circ. No. 939. Washington, DC, USDA, pp. 19.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Ed., Methods of Soil Analysis Part 2 Chemical and Microbiological Properties, American Society of Agronomy, Soil Science Society of America, Madison, pp. 403-430.

Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pradhan, S., Chakraborty, D., Jat, M.L., Jat, R.K., Saharawat, Y.S., Yadav, O.P., 2016. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. Soil Tillage Res 16, 116–128.

Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Yadvinder, Singh, Bijay, Kamra, S.K., Mishra, B., Sastri, A., Aggarwal, H.P., Das, D.K., Gupta, R.K., 2003. Climatic potential and on-farm yield trends of rice and wheat in the Indo-Gangetic plains. Field Crops Res 80, 223–234.

Peoples, M.B., Giller, K.E., Jensen, E.S., Herridge, D.F., 2021. Quantifying country-to-global scale nitrogen fixation for grain legumes: I. Plant reliance upon nitrogen fixation for soybean, groundnut and pulses. Plant Soil 469, 1–14. https://doi.org/10.1007/s11104-021-05167-6.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678–683.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174.

Ribeiro-oliveira, J.P., Santana, D.G., Pereira, V.J., 2018. Data transformation: an underestimated tool by inappropriate use. Acta Sci. Agron. 40, 35015.

Rosas-Medina, M.Á., León-González, F., Flores-Macías, A., Payán-Zelaya, F., Borderas-Tordesillas, F., Gutiérrez-Rodríguez, F., Fragoso-González, C., 2010. Effect of tillage, sampling date and soil depth on earthworm population on maize monoculture with continuous stover restitutions. Soil Tillage Res 108, 37–42.

Roy, D., Datta, A., Jat, H.S., Choudhary, M., Sharma, P.C., Singh, P.K., Jat, M.L., 2022. Impact of long-term conservation agriculture on soil quality under cereal based systems of North West India. Geoderma 405, 115391.

Salem, H.M., Valero, C., Munoz, M.A., Rodriguez, M.G., Silva, L.L., 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237, 60–70.

Sapkota, T.B., Jat, R.K., Singh, R.G., Jat, M.L., Stirling, C.M., Jat, M.K., Bijarniya, D., Kumar, M., Saharawat, Y.S., Gupta, R.K., 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. Soil Use Manag. 33, 81–89.

SAS Institute, 2002a. SAS/STAT User's Guide. Version 9.1. SAS Inst., Cary, NC.

SAS Institute, 2002b. JMP Statistics and Graphics Guide, Version 5. SAS Inst., Cary, NC.

Singh, S., Sharma, A., Khajuria, K., Singh, J., Vig, A.P., 2020. Soil properties changes earthworm diversity indices in different agro-ecosystem. BMC Ecol. 20, 1–14.

Smith, P., Powlson, D., Glendining, M., Smith, J., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long term experiments. Glob. Change Biol. 3, 67–79.

Somasundaram, J., Sinha, N.K., Dalal, R.C., Lal, R., Mohanty, M., Naorem, A.K., Hati, K. M., Chaudhary, R.S., Biswas, A.K., Patra, A.K., Chaudhari, S.K., 2020. No-till farming and conservation agriculture in South Asia–issues, challenges, prospects and benefits. Crit. Rev. Plant Sci. 39, 236–279.

Stroud, J.L., 2019. Soil health pilot study in England: Outcomes from an on-farm earthworm survey. PLoS ONE 14, 1–16.

Subbiah, B.V., Asija, G.L., 1956. A rapid procedure for the determination of available nitrogen in soils. Curr. Sci. 25, 259–260.

Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil . Res. 105, 217–227.

Walkely, A., Black, I.A., 1934. An experiment of the Degtjareff method for determination of soil organic matter and a proposed modification of the chronic acid titration method. Soil Sci. 37, 29–38.

Yadvinder-Singh, Kukal, S.S., Jat, M.L., Sidhu, H.S., 2014. Improving water productivity of wheat-based cropping systems in South Asia for sustained productivity. Adv. Agron. 127, 157–258.

Zhao, X., Xue, J.F., Zhang, X.Q., Kong, F.L., Chen, F., Lal, R., Zhang, H.L., 2015. Stratification and storage of soil organic carbon and nitrogen as affected by tillage practices in the North China Plain. PLoS ONE 10, e0128873.

Zuberer, D.A., 1994. Recovery and enumeration of viable bacteria. In: Weaver, R.W., Angle, S., Bottomley, P., Bezdicek, D., Smith, S., Tabatabai, A., Wollum, A., Mickelson, S.H. (Eds.), Methods of Soil Analysis: Part 2- Microbiological and Biochemical Properties. SSSA, Madison, WI, USA, pp. 119–144.