Agricultural Water Management 232 (2020) 106067

Contents lists available at ScienceDirect

Agricultural Water Management

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

Long-term tillage and irrigation management practices: Strategies to enhance crop and water productivity under rice-wheat rotation of Indian mid-Himalayan Region

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ARTICLE INFO

Keywords:
Long-term
Zero tillage
Carbon sequestration
Water use
Rice-wheat yields

ABSTRACT

Since reckonable understanding of yield response under long-term (16 year) conservation management practices is the key to improve the productivity and physico-chemical indicators of rice-wheat rotation, impact of long-term tillage and irrigation levels on productivity, yield trend, soil organic carbon (SOC) fractions, carbon pools and sequestration under rice-wheat rotation on sandy clay loam soil of the mid-Himalaya were quantified. A field experiment started from 2001 through 2016 to assess the effect of tillage alterations conventional tillage (CT) and zero tillage (ZT) and four irrigation levels I_1: pre-sowing (PS), I_2: PS + crown root initiation (CRI), I_3: PS + CRI + panicle initiation (PI)/flowering (FL), and I_4: PS + CRI + PI/FL + grain filling (GF), applied at the critical growth stages to rice-wheat rotation. Results confirmed that irrigation management had a significant ($p = 0.001$) positive impact on grain yield of rice, wheat and system yield after 16 year continuous cropping.

We also recoded that, plot with four irrigation (I_4) had ~ 28, 40 and 35 % higher grain yield of rice, wheat as compared to single irrigation or I_1 (2.04, 2.99 and 5.05 Mg ha^{-1}), respectively. Rice yield declined significantly ($r = 0.68$; $p = 0.003$) by 70 kg ha^{-1} year^{-1} under ZT plots than CT plots (52 kg ha^{-1} year^{-1}). Decreasing trend of rice yield ranged from 42 kg ha^{-1} year^{-1} in four irrigations (I_4) to 75 kg ha^{-1} year^{-1} single irrigation (I_1). Whereas, wheat yield increased (58 kg ha^{-1} year^{-1}) non-significantly over the years under ZT plots whereas under CT plots (-13.6 kg ha^{-1} year^{-1}) it had declining trend with time. Unlike rice yield, impact of irrigation on wheat yield had positive trends or increasing trends with time. Plots under long-term ZT along with irrigation practice significantly increased total porosity and decreased pH and bulk density (BD) mainly in surface layer. Different pools of SOC were also significantly increased under ZT as compared to CT only in surface layer (0 − 15 cm).

We conclude that, ZT system increased yield of wheat and diminished rice yield after 16 years of experimentation. But apart from yield, ZT also improved physico-chemical indicators of soil and enhanced carbon sequestration. The WUE of rice and wheat (4.20 and 11.0 kg ha^{-1} mm^{-1}) had slightly higher under ZT as compared to CT. It is suggested that ZT is more desirable for efficient water utilization in such conditions. Frequent irrigation (I_4) was more desirable for maintaining optimum moisture condition for sustainable crop production.

1. Introduction

Rice-wheat system is the main production systems of South Asia. It is the source of livelihood, employment and income for hundreds of millions of rural and urban poor's. The rice-wheat rotation occupies approximately 26 M ha area in Asia, mainly with 13.5 M ha in the Indo-Gangetic plains (IGPs); covering approximately 32 % of the total rice area and about 42 % of the total wheat area in four IGP countries viz. India, Pakistan, Bangladesh and Nepal (Saharawat et al., 2012; Jat et al., 2014). Rice and wheat together contribute ~ 70 % of total cereals production in India with production of approximately 105 and 94 Mt, in about 44 and 30 M ha area, respectively (Agricultural Statistics at a Glance, 2016). Thus, the rice-wheat rotation is the keystone of India's food self-sufficiency. The conventional growing practices of rice-wheat rotation has aggravated soil degradation and decline productivity which ultimately are threats to sustainability and

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https://doi.org/10.1016/j.agwat.2020.106067
Received 8 May 2018; Received in revised form 1 February 2020; Accepted 1 February 2020
0378-3774/

profitability in cultivated regions and raise an immense question on system sustainability besides yield stagnation (Busari et al., 2015).

The soil and water are main components for conservation in Indian Himalayan Regions (IHR) where steep sloped land cause higher runoff losses during South-West monsoon (June-September) which have abundant rainfall and rest of months suffers from water scarcity (Panday et al., 2018). The adoption of conservation management practices (CMPs) will help in achieving sustainable and productive agricultural systems along with preservation of nutrient and moisture in the soil. This is particularly true for the Himalayan soils that are highly prone to water erosion. CMPs are important agronomic practices which are concerned about agricultural sustainability and has progressively augmented globally to cover ~ 11 % of the globe's ~ 158 M ha cultivable land (Choudhary et al., 2016, 2018). The conservation agriculture based CMPs have been found effective for increasing crop productivity and soil sustainability.

However, along with CMPs, sustainable use of irrigation water is also needed in the context of currently shrinking water resources. Consequently, irrigation management practices (IMPs) are important to understand soil-water dynamics throughout the profile and these help to increase the productivity with per drop more crop. CMPs such as zero tillage (ZT) system retain higher moisture content for longer time and are important for enhanced WUE than conventional tillage (CT) system. Preservation of SOC is important to sustain long-term soil sustainability (Sapkota et al., 2017) and ecosystem functionality. However, potential of SOC storage or carbon sequestration or accumulation under different cropping systems may be changed or influenced by several agricultural practices like ZT, CT, irrigation, farm yard manure (FYM), fertilization, crop residues, and mulching. The advantage of preserving SOC for sustainable agriculture ecosystem is well recognized and its accumulation has been measured as a possible solution to mitigate climate change, in which atmospheric carbon is converted into soil carbon that is long-lived (Minasny et al., 2017). Consequently, adoption of such CMPs which improve storage of atmospheric carbon (Powlson et al., 2016; Samal et al., 2017) may help in reducing greenhouse gas emissions and mitigating climate change (Chen et al., 2015; Lal, 2015) as well as improving soil structure, quality (Lal, 2016) and fertility (Dignac et al., 2017).

Many studies provided evidence on the rice-wheat production as exaggerated by tillage and irrigation in Himalayan ecosystem after 4 and 9 years of cultivation by Panday et al. (2008) and Bhattacharyya et al. (2013), respectively. However, precise information on the long-term (16 year) effects of tillage and irrigation on productivity, yields trend, physico-chemical indicators of soil, soil organic carbon (SOC) pools and carbon sequestration under rice-wheat system of the region is lacking. In the context of deteriorating soil quality, stagnation of yield in rice-wheat system has been recorded across Indo-Gangetic plains (IGP) and Indian Himalayan Regions (IHR) (Busari et al., 2015). A long-term field experiment was initiated during 2001 through 2016 with following objectives: (i) to determine the effects of tillage and irrigation on crop water productivity and trends of yield under rice-wheat system, (ii) to know the response of physico-chemical indicators of soil under long-term tillage and irrigation practices and (iii) to study the impact of tillage and irrigation on SOC pools and requisitioning.

2. Materials and methods

2.1. Experimental site

A field experiment was conducted for 16 years (2001–2016) at the experimental farm of the ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Hawalbagh (29°36´N; 79°40´E at 1250 m above MSL) of Almora, India on a sandy clay loam soil. The region is characterized by a sub-temperate climate with a dry summer (March–June), wet monsoon season (June–September) and a cool, dry winter (October–February). Mean annual maximum and minimum air temperature during study period were 26⁰C and 10⁰C, respectively. Average annual rainfall was 921 mm during study period (2001–2016) of which ~ 73 % was received during the monsoon season. The surface soil (0 – 15 cm) of the experimental field had sandy clay loam type soil having bulk density (BD) of 1.34 Mg m^{-3}, soil organic carbon 6.6 g kg^{-1}, 0.5 M $NaHCO_3$ extractable phosphorus 11.5 kg ha^{-1} and 1 N CH_3COONH_4 extractable potassium 127 kg ha^{-1}. The sub-surface soil (15 – 30 cm) had BD of 1.36 Mg m^{-3} and soil organic carbon 6.15 g kg^{-1}.

Table 1
Experimental details and agronomic practices of the experiment.(2001–2016)

Experimentation period	2001 to 2016	
Cropping system followed	Rice (*Oryza sativa* L)	Kharif season
	Wheat (*Triticum aestivum* L)	Rabi season
Experimental design	Split plot design	
Treatments	(a) Main plots: Tillage managements	
	CT: Conventional tillage	
	ZT: Zero tillage	
	(a) Sub plots: Irrigation management	
	I_1: pre-sowing (PS),	
	I_2: PS + active tillering (AT)/crown root initiation (CRI),	
	I_3: PS + AT/CRI + panicle initiation (PI)/flowering (FL),	
	I_4: PS + AT/CRI + PI/FL + grain filling (GF)	
Crop varieties used	Rice	*VL Dhan* 82
	Wheat	*VL Wheat* 804
Replication	04	
Sowing time	Rice	First to second week of June
	Wheat	Last of week of October to first week of November
Fertilizer applied ($N-P_2O_5-K_2O$ kg ha^{-1})	Rice	100-60-40
	Wheat	100-60-40
Irrigation application rate	50 mm per irrigation	
Harvesting time	Rice	Last week of October
	Wheat	Last week of April/May

2.2. Experimental design and treatments

The experiment was laid out in permanent plots in split plot design with tillage (ZT in the form of no disturbance of the soil and CT in the form of two diggings with a spade to 15 cm layer to pass with rotary tiller for seed bed preparation for both rice and wheat as main plot treatments) and four levels of irrigation as sub-plots with four replications (Table 1). Irrigations {I_1: pre-sowing (PS), I_2: PS + active tillering (AT)/crown root initiation (CRI), I_3: PS + AT/CRI + panicle initiation (PI)/flowering (FL), and I_4: PS + AT/ CRI + PI/FL + grain filling (GF)} were applied at critical growth stages of both the crops.

2.3. Crop management

Rice was sown (seed rate 100 kg ha^{-1}) manually (direct seeding rice; DSR) in the first to third week of June and wheat was sown (100 kg ha^{-1}) in last week of October to first week of November during different year of experimentation. In rice crop, full dose of phosphorus (as di-ammonium phosphate) and potassium (as muriate of potash) were applied at the time of field preparation by broadcasting before seeding. Nitrogen (as urea) was applied half as a basal dose at field preparation and remaining half in two equal splits at the tillering and panicle initiation stages of crop growth. The fertilizer source for NPK in wheat was the same as that of rice.

2.4. Soil sampling and analysis

Soil sampling was done after harvesting of wheat crop in 2016-

Table 2
Soil carbon fractions and their method of analysis of long-term field experiment.

Soil parameters	Methods	References
DOC	Centrifugation method followed by wet combustion method	Walkley and Black (1934)
MBC	Fumigation extraction method	Vance et al. (1987)
POC	Wet sieving method	Cambardella and Elliott (1992)
Cumulative CO_2-C	Alkali trap method	Anderson (1982)
$KMnO_4$-C	0.33 *M* $KMnO_4$ oxidation method	Islam and Weil (1999)
WBC	Wet combustion method	Walkley and Black (1934)

2017. Soil samples were collected from each plot from 0 to 15 and 15 − 30 cm soil layers using a core sampler. Immediately after sampling, visible root fragments and stones were manually removed and the soil sample was divided into two parts. Method of estimation for different soil carbon and its fractions are given in Table 2.

2.5. Soil organic carbon fractionation and sequestration calculations

The SOC concentration was distributed into different fractions determined by the modified Walkley–Black method as described by Chan et al. (2001) using 5, 10, and 20 ml of 36 *N* H_2SO_4 that resulted in 12, 18 and 24 *N* H_2SO_4 and by added 1 N dichromate solution and back titration with FAS using diphenylamine indicator. The three acid solution ratios allow the separation of SOC into the following four fractions (P) according to decreasing oxidizability / lability.

P_1 (Very labile fraction): Organic carbon oxidizable under 12 N H_2SO_4

P_2 (Labile fraction): Difference in oxidizable organic carbon extracted between 18 *N* and 12 *N* H_2SO_4 (18-12 *N* H_2SO_4)

P_3 (Less labile fraction): Difference in oxidizable organic carbon extracted between 24 *N* and 18 *N* H_2SO_4 (24-18 *N* H_2SO_4)

P_4 (Non-labile fraction): Difference in organic carbon extracted with 24 *N* H_2SO_4 and TOC determined by CHN analyzer (TOC- 24 *N* H_2SO_4)

P_1 and P_2 together constitute the active pool, while P_3 and P_4 constitute together the passive pool. Carbon sequestration (CS) (Mg C ha^{-1}) = C (%) × bulk density (Mg m^{-3}) × soil depth (m) × 100.

The carbon sequestration rate (CSR) was calculated as:

CSR (kg C ha^{-1} $year^{-1}$) = $\{(CS_f - CS_i)/T\} \times 1000$;

Where, CS_f is carbon sequestration (Mg ha^{-1}) in 2016 and CS_i is carbon sequestration (Mg ha^{-1}) in 2001 and T is the time of experiment (16 years).

2.6. Water use efficiency (WUE)

$$\text{Water use efficiency (WUE)} = \frac{Y}{TEMU}$$

Where Y is yield (kg ha^{-1}); TEMU is total eff ;ective moisture (mm) used by the crop in the form of rainfall + irrigation + profile moisture use)

2.7. Statistical analyses

Analysis of variance (ANOVA) (Gomez and Gomez, 1984) was performed to determine the effects of treatments using the IBM SPSS statistical package 20 (SPSS, Inc., Chicago, IL, USA) to quantify and evaluate source of variation. All parameters were analysed as a split--plot model (tillage as main effect, irrigation as split-plot effect).. To test the hypothesis on yield and WUE trends, a simple linear regression analysis of grain yields and WUE (slopes and the P values) over the years was done to determine a time trend variable.

$$Y = a + b\,t$$

Where: Y = grain yield (kg ha^{-1}) or WUE (kg ha^{-1} mm^{-1}), a = the constant, t = year, and b = slope or magnitude of the yield or WUE trend (yield or WUE changes per year).

3. Results

3.1. Rice, wheat and rice-wheat system productivity and yield trend

The tillage system had non-significant impact on mean grain yield of rice, wheat and system yield after 16 year of continuous cropping. Plots under CT recorded slightly greater mean yield of rice than ZT plots (Table 3). The wheat crop performed better under ZT and had slightly higher yield than CT. Rice-wheat system yield was slightly higher under CT plots than ZT. Unlike tillage, irrigation management had a significant (p = 0.001) impact on grain yield of rice, wheat and system. Plot under I_4 had nearly 28, 40 and 35 % higher grain yield of rice, wheat and system as compared to I_1 plots (2.04, 2.99 and 5.05 Mg ha^{-1}), respectively. A significant interaction effect between tillage and irrigation was observed for rice, wheat and system yield.

Linear regression analysis of rice grain yield revealed that declining trends in tillage and irrigation treatments after 16 years of experimentation. Rice yield declined significantly (r = 0.68; p = 0.003) by

Table 3
Initial yield, mean yield of rice, wheat and rice-wheat system as influenced by 16 year long-term tillage practices and different irrigation levels.

Treatments[†]	¥Initial grain yield (Mg ha^{-1})			Mean (2001–2016) grain yield (Mg ha^{-1})		
	Rice	Wheat	Rice-wheat system	Rice	Wheat	Rice-wheat system
Tillage						
CT	2.90 ± 0.34^a	3.71 ± 0.08^a	6.61 ± 0.24^a	2.35 ± 0.05^a	3.63 ± 0.10^a	5.98 ± 0.13^a
ZT	3.12 ± 0.21^a	3.67 ± 0.07^a	6.78 ± 0.36^a	2.31 ± 0.07^a	3.64 ± 0.13^a	5.95 ± 0.17^a
P value	0.09	0.21	0.25	0.19	0.74	0.46
Irrigation						
I_1	3.09 ± 0.23^a	3.25 ± 0.04^d	6.34 ± 0.26^b	2.04 ± 0.05^d	2.98 ± 0.17^d	5.03 ± 0.19^d
I_2	2.80 ± 0.33^a	3.69 ± 0.05^c	6.50 ± 0.35^b	2.25 ± 0.06^c	3.53 ± 0.09^c	5.77 ± 0.13^c
I_3	3.06 ± 0.17^a	3.85 ± 0.08^b	6.91 ± 0.17^a	2.42 ± 0.05^b	3.86 ± 0.12^b	6.28 ± 0.14^b
I_4	3.08 ± 0.34^a	3.97 ± 0.13^a	7.05 ± 0.42^a	2.62 ± 0.06^a	4.18 ± 0.07^a	6.80 ± 0.13^a
P value	0.31	0.001	0.004	0.001	0.001	0.001
T × I $_{(LSD)}$	0.53	0.15	0.65	NS	NS	NS
P value	0.001	0.001	0.001	0.44	0.37	0.60

[†] Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent (p ≤ 0.05) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant. [¥] Initial grain yield considered yield recorded at the time of initiation of experiment 2001-02.

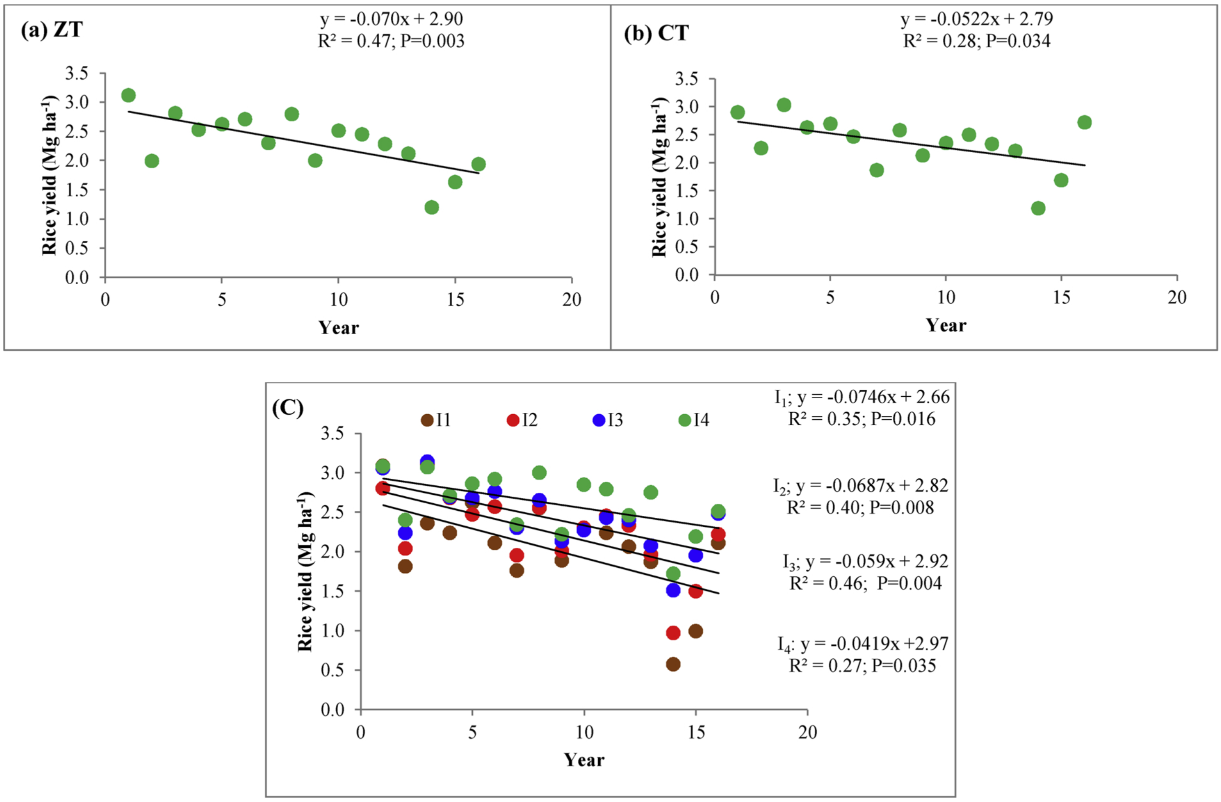

Fig. 1. Regression analysis of the 16-year trends of rice yield under different tillage (a, b) and irrigation levels (c) (for treatment details refer to Table 1).

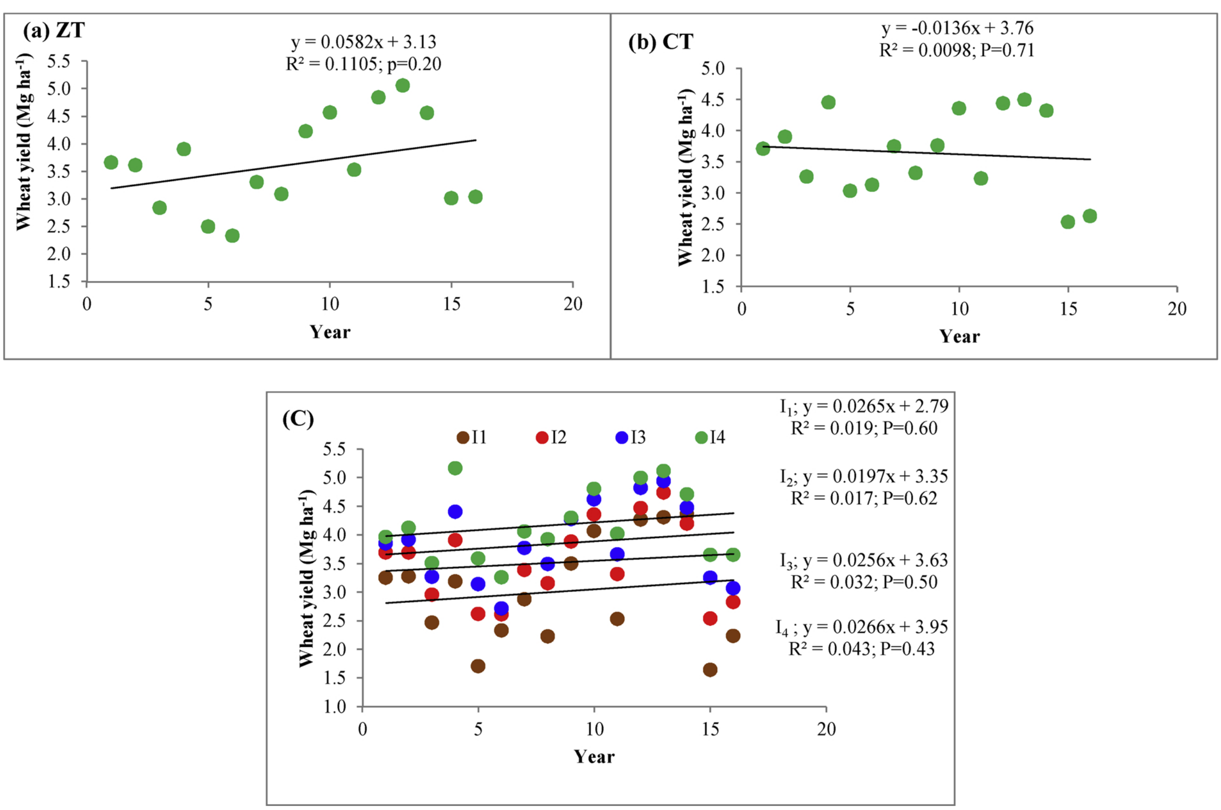

Fig. 2. Regression analysis of the 16-year trends of wheat yield under different tillage (a, b) and irrigation levels (c) (for treatment details refer to Table 1).

70 kg ha^{-1} year^{-1} under ZT plots and 52 kg ha^{-1} year^{-1} in CT plots. (Fig. 1a, b). Like tillage, in the irrigation plots also significantly negative rice yield trends was observed over the years. Rice yield trends over the years declined more ranging from 42 to 75 kg ha^{-1} year^{-1} under different irrigation levels (Fig. 1c) and the decrement rate was the highest in I_1 (75 kg ha^{-1} year^{-1}) plots followed by I_2 and I_3 and the

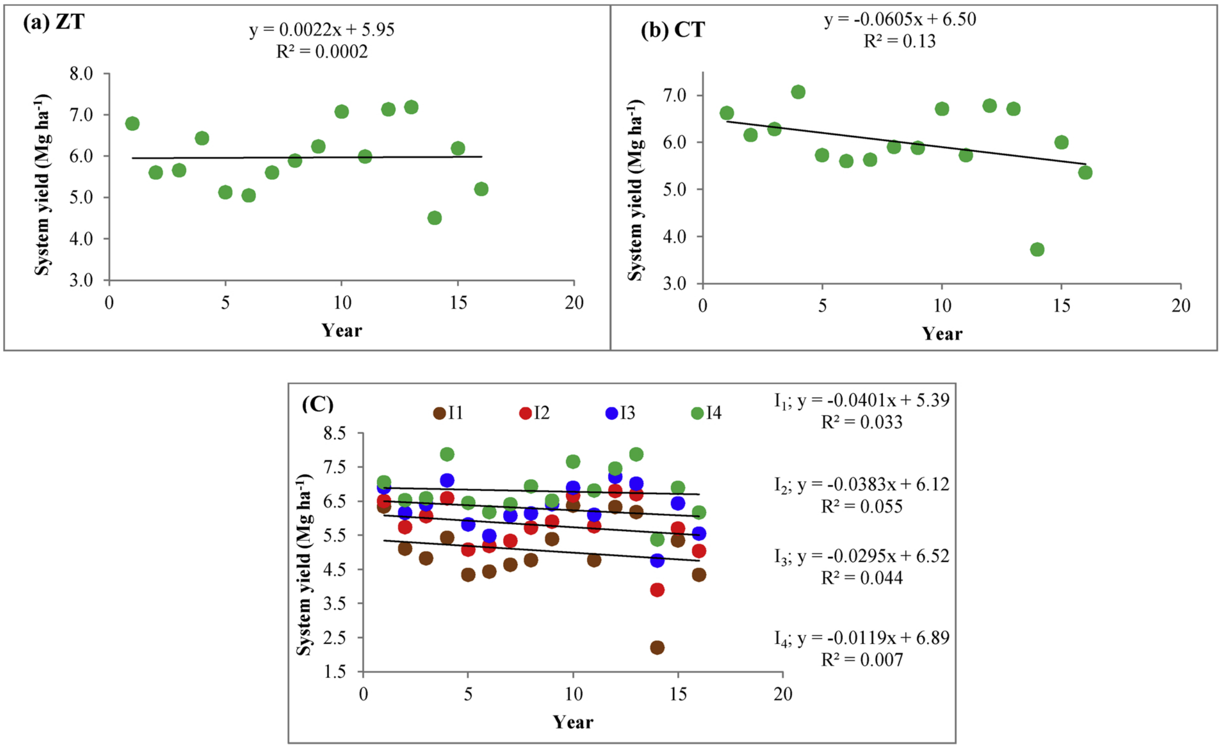

Fig. 3. Regression analysis of the 16-year trends of rice-wheat system yield under different tillage (a, b) and irrigation levels (c) (for treatment details refer to Table 1).

lowest under I_4 plot (42 kg ha^{-1} year^{-1}). Wheat yield increased (58 kg ha^{-1} year^{-1}) over the years under ZT plots; however it had declining trends under CT plots (-13.6 kg ha^{-1} year^{-1}) (Fig. 2a, b). Unlike rice yield, impact of irrigation on wheat yield had increasing yield trends over time (Fig. 2c). The wheat yield increment over the years was the highest under I_4 plot (27 kg ha^{-1} year^{-1}) and lowest under I_2 (19 kg ha^{-1} year^{-1}). The RWCS had positive yield trends over the years under ZT while CT and irrigation treatments had negative trends. The system yield decreased by ~61 kg ha^{-1} year^{-1} under CT whereas in ZT system yield increased by 2.2 kg ha^{-1} year^{-1} (Fig. 3a, b). The system yield decrement over the years was the highest under I_1 plots (40 kg ha^{-1} year^{-1}) and lowest under I_4 plots (12 kg ha^{-1} year^{-1}) (Fig. 3c).

3.2. *Effect of tillage and irrigation on the physico-chemical indicators of soils*

The pH of soil under ZT plots had significantly (p = 0.001) lower than CT plots in 0 – 15 cm soil layer while in 15 – 30 cm soil layer, both ZT and CT had similar effect on soil pH (Table 4). In the surface layer (0–15 cm) the pH of soil after harvest of wheat was lower under I_1 than I_4, I_3 and I_2. However, impact of irrigation was not statistically significant on soil pH under sub-surface (15 – 30 cm) soil and both soil layers had following order of soil pH: $I_1 > I_2 > I_3 > I_4$. Soil pH increased with depth under both ZT and CT plots. The soil under CT plots was more compacted than ZT plots in 0–15 and 15 – 30 cm soil layers after wheat harvest (Table 4). Bulk density under CT plots had greater

Table 4
Soil pH, bulk density (BD) and total porosity (*f*) under different soil depths as influenced by tillage practices and different irrigation levels.

Treatments[†]	pH		BD (Mg m^{-3})		*f* (%)	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
Tillage						
CT	5.32 ± 0.36^b	6.08 ± 0.38^a	1.28 ± 0.014^b	1.32 ± 0.052^a	51.46 ± 0.52^b	50.20 ± 1.94^a
ZT	5.02 ± 0.36^a	6.02 ± 0.31^a	1.25 ± 0.032^a	1.29 ± 0.055^a	52.64 ± 1.20^a	51.48 ± 2.06^a
P value	0.05	0.34	0.02	0.18	0.02	0.17
Irrigation						
I_1	4.98 ± 0.42^a	5.94 ± 0.39^a	1.29 ± 0.020^b	1.32 ± 0.020^a	51.22 ± 0.77^b	50.18 ± 0.75^a
I_2	5.11 ± 0.33^a	6.07 ± 0.28^a	1.28 ± 0.046^{ab}	1.31 ± 0.074^a	51.56 ± 1.75^{ab}	50.47 ± 2.81^a
I_3	5.18 ± 0.30^a	6.02 ± 0.39^a	1.26 ± 0.012^{ab}	1.29 ± 0.079^a	52.45 ± 0.44^{ab}	51.06 ± 3.00^a
I_4	5.42 ± 0.40^a	6.18 ± 0.32^a	1.24 ± 0.013^a	1.28 ± 0.039^a	52.97 ± 0.49^a	51.63 ± 1.46^a
P value	0.25	0.05	0.06	0.69	0.06	0.69
T × I $_{(LSD)}$	NS	NS	NS	NS	NS	NS
P value	0.94	0.23	0.81	0.99	0.81	0.99

[†] Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent (p ≤ 0.05) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant.

Table 5
Dissolve organic carbon (DOC), microbial biomass carbon (MBC), cumulative CO_2-C, permanganate oxidizable carbon ($KMnO_4$-C), particulate organic carbon (POC), Walkley Black carbon (WBC) and soil organic carbon (SOC) in different soil layers under different tillage and irrigation levels.

Treatments[†]	DOC (mg kg^{-1})		MBC (g kg^{-1})		Cumulative CO_2-C (mg kg^{-1})		$KMnO_4$-C (g kg^{-1})		POC (g kg^{-1})		WBC (g kg^{-1})		SOC (g kg^{-1})	
	Soil depths (cm)													
	0–15	15-30	0–15	15-30	0–15	15-30	0–15	15-30	0–15	15-30	0–15	15-30	0–15	15-30
Tillage														
CT	36 ± 2.91^{b}	20 ± 1.51^{b}	0.26 ± 0.02^{b}	0.21 ± 0.02^{b}	638 ± 29^{b}	440 ± 48^{b}	0.72 ± 0.04^{b}	0.49 ± 0.02^{b}	2.36 ± 0.04^{b}	1.97 ± 0.06^{a}	7.86 ± 0.52^{b}	7.22 ± 0.30^{b}	11.76 ± 0.51^{b}	10.36 ± 0.39^{b}
ZT	41 ± 3.04^{a}	22 ± 1.56^{a}	0.32 ± 0.02^{a}	0.24 ± 0.02^{a}	730 ± 72^{a}	522 ± 94^{a}	0.79 ± 0.04^{a}	0.53 ± 0.03^{a}	2.66 ± 0.05^{a}	2.02 ± 0.09^{a}	8.84 ± 0.41^{a}	7.54 ± 0.27^{a}	13.08 ± 0.56^{a}	11.24 ± 0.43^{a}
P value	0.001	0.020	0.001	0.001	0.001	0.020	0.001	0.020	0.001	0.18	0.001	0.025	0.001	0.001
Irrigation														
I_1	34 ± 4.04^{c}	19 ± 1.91^{b}	0.26 ± 0.01^{c}	0.20 ± 0.01^{c}	586 ± 55^{c}	408 ± 52^{b}	0.69 ± 0.05^{c}	0.48 ± 0.03^{b}	2.32 ± 0.03^{d}	1.87 ± 0.07^{c}	7.70 ± 0.29^{c}	6.91 ± 0.25^{c}	11.35 ± 0.36^{c}	10.19 ± 0.40^{b}
I_2	38 ± 3.27^{b}	20 ± 0.96^{b}	0.29 ± 0.02^{b}	0.22 ± 0.01^{b}	640 ± 42^{c}	457 ± 65^{b}	0.74 ± 0.03^{bc}	0.48 ± 0.03^{b}	2.41 ± 0.04^{c}	1.93 ± 0.06^{c}	8.15 ± 0.57^{bc}	7.18 ± 0.18^{bc}	12.09 ± 0.52^{b}	10.42 ± 0.34^{b}
I_3	38 ± 1.86^{b}	21 ± 1.52^{b}	0.30 ± 0.02^{b}	0.23 ± 0.02^{ab}	719 ± 48^{b}	496 ± 51^{ab}	0.78 ± 0.03^{ab}	0.52 ± 0.02^{a}	2.61 ± 0.05^{b}	2.03 ± 0.12^{b}	8.82 ± 0.40^{ab}	7.56 ± 0.30^{ab}	13.02 ± 0.46^{a}	10.72 ± 0.41^{b}
I_4	43 ± 2.73^{a}	24 ± 1.75^{a}	0.33 ± 0.02^{a}	0.25 ± 0.02^{a}	790 ± 57^{a}	562 ± 114^{a}	0.83 ± 0.04^{a}	0.54 ± 0.03^{a}	2.70 ± 0.06^{a}	2.16 ± 0.04^{a}	8.72 ± 0.61^{a}	7.87 ± 0.41^{a}	13.22 ± 0.78^{a}	11.89 ± 0.5^{a}
P value	0.001	0.001	0.001	0.001	0.001	0.020	0.001	0.002	0.001	0.001	0.003	0.001	0.001	0.001
T × I $_{(LSD)}$	NS	2.58	0.028	NS	NS	NS	NS	NS	0.084	NS	0.81	NS	1.10	NS
P value	0.67	0.049	0.03	0.18	0.87	0.85	0.71	0.85	0.01	0.78	0.05	0.75	0.04	0.62

[†] Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent (p ≤ 0.05) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant.

values than ZT plots at both surface and subsurface soil layers. Tillage had significant impact on the BD at surface layer while similar effect at sub-surface layer. In the soil layers (0–15 and 15 − 30 cm layer), BD after wheat harvest was lower under I_4 than I_3, I_2 and I_1. BD gradually increased with depth, regardless of the tillage and irrigation system imposed. Total porosity was significantly ($P < 0.05$) higher under ZT plots (52.64 %) than CT plots (51.47 %) in surface layer whereas in sub-surface layer the increase was non-significant (Table 4). Higher total porosity was also estimated after harvest of wheat in I_4 plots as compared to I_3, I_2 and I_1 in both the soil layers.

3.3. Soil organic carbon (SOC) and its fractions

3.3.1. Soil organic carbon (SOC)

Results in Table 5 showed that total SOC concentration was significantly affected by tillage and irrigation practices in the both the soil layers. Plots under ZT had ∼11 and 9 % greater total SOC concentration than CT (11.76 and 10.13 g kg^{-1}) in the 0–15 and 15 − 30 cm soil layers, respectively. Plots under I_4 had ∼18 and 16 % higher total SOC concentration than I_1 plots, in the 0–15 and 15 − 30 cm soil layers, respectively. The SOC concentration was higher in surface layer than sub-surface layer in both tillage as well as irrigation systems. The tillage and irrigation interaction effect was only significant ($p = 0.04$) for SOC only in the surface soil layer.

3.3.2. Dissolve organic carbon (DOC)

DOC comprised a very small proportion (0.15–0.35 %) of SOC and was significantly influenced by tillage and irrigation practices (Table 5). Plots under ZT had significantly (∼14 and 10 %) higher DOC than CT plots (35 and 20 mg kg^{-1}) in the 0–15 and 15 − 30 cm soil layer, respectively. Like tillage, irrigation had a significant impact on DOC in both the soil layers (Table 5). I_4 plots had (∼28 and 22 %) higher DOC as compared to I_1 plots (34 and 19 mg kg^{-1}) in the 0–15 and 15 − 30 cm soil layers, respectively. Depth-wise distribution of DOC decreased from surface to sub-surface layer. The interaction effect between tillage and irrigation was non-significant for surface layer but it was significant ($p = 0.045$) for sub-surface layer.

3.3.3. Microbial biomass carbon (MBC)

The MBC of the soil under different tillage and irrigation regimes varied significantly ($p < 0.05$) in both the soil layers. Data shown in Table 5 revealed that plots under ZT had significantly ∼23 and 12.5 % greater MBC than CT (0.26 and 0.21 g kg^{-1}) plots in the 0–15 and 15 − 30 cm soil layers, respectively. Plots under I_4 had significantly ∼27 and 25 % higher MBC than plot under I_1 (0.26 and 0.20 g kg^{-1}) and ∼14 and 13 % higher MBC than plot under I_2 (0.29 and 0.22 g kg^{-1}) in the 0–15 and 15 − 30 cm soil layers, respectively. It was observed that the distribution of MBC content declined with depth. A significant ($P < 0.05$) interaction effect was observed between tillage and irrigation only for surface layer.

3.3.4. Permanganate oxidizable carbon ($KMnO_4$-C)

The $KMnO_4$-C concentration of the soil was significantly affected by tillage and irrigation practices in both the soil layers (Table 5). In the ZT plots, the $KMnO_4$-C concentration was 10 and 6 % higher compared to the CT plots (0.72 and 0.49 g kg^{-1}) in the 0–15 and 15–30 cm layers, respectively. Meanwhile, plots under I_4 had ∼20 and 12 % greater $KMnO_4$-C concentration than plots under I_1 (0.69 and 0.48 g kg^{-1}) in the 0–15 and 15 − 30 cm layers.

3.3.5. Particulate organic carbon (POC)

The POC concentration of soil was significantly affected by tillage and irrigation in both soil layers. Plots under ZT had significant by ∼13 and 3 % higher POC concentration than CT plots (2.36 and 1.97 g kg^{-1}) in the surface soil layer and subsurface soil layer, respectively (Table 5). Plots under I_4 had ∼16 and 15 % higher POC concentration than I_1

(2.32 and 1.87 g kg^{-1}) and ~12 and 11 % higher POC concentration than I_2 plots (2.41 and 1.93 g kg^{-1}) in the 0–15 and 15 – 30 cm soil layers, respectively. A perusal of results revealed that POC concentration decreased with depth. A significant ($P < 0.05$) interaction was observed between tillage and irrigation in the surface layer in the present study.

3.3.6. Walkley Black carbon (WBC)

Plots under ZT had significantly ($p < 0.05$) greater accumulation of WBC concentration (8.84 and 7.54 g kg^{-1}) as compared to plots under CT (7.86 and 7.22 g kg^{-1}) in 0–15 and 15 – 30 cm soil layers, respectively (Table 5). It was ~12 and 4 % greater in ZT than CT plots in 0–15 and 15 – 30 cm soil layers, respectively. Plots under I_4 had ~13 and 14 % higher WBC concentration in the 0–15 and 15 – 30 cm soil layer compared to I_1 plots (7.70 and 6.91 g kg^{-1}), respectively. Similarly, plots under I_3 had ~ 8 and 5 % higher WBC concentration in 0–15 and 15 – 30 cm soil layers as compared to I_2 plots (8.15 and 7.18 g kg^{-1}), respectively. Irrespective to treatments, WBC concentration diminished with increasing soil depth. In the surface soil layer, WBC concentration was more pronounced under ZT than CT plots and it was 17 % higher than sub-surface layer. While in CT plots, WBC was about 9 % higher in surface layer than the sub-surface layer. There was a significant ($p = 0.035$) interactive effects of tillage and irrigation on WBC concentration only in surface soil layer.

3.3.7. Cumulative CO_2-C (Mineralizable carbon)

Cumulative CO_2-C varied significantly ($p < 0.05$) under different tillage systems from 638 to 730 mg CO_2-C mg kg^{-1} and 440–522 mg CO_2-C kg^{-1} soil in 0–15 and 15 – 30 cm soil layers, respectively after 28 days of incubation (Table 5; Fig. 4a–d). Plots under ZT evolved significantly ($p < 0.05$) ~15 and 18 % higher cumulative CO_2-C than CT (638 and 440 mg CO_2-C kg^{-1}) in 0–15 and 15 – 30 cm soil layers, respectively. Irrigation had significant impact on CO_2 evolution. Plots under I_4 and I_3 evolved nearly 35 and 23 % greater cumulative CO_2 than I_1 (586 mg CO_2-C kg^{-1}) in the 0 – 15 cm soil layer. In the 15 – 30 cm soil layer, I_4 and I_3 evolved about 38 and 22 % greater CO_2 than I_1 (408 mg CO_2-C kg^{-1}), respectively. Higher cumulative carbon mineralization was recorded under surface soil as compared to sub-surface layer under different tillage and irrigation treatments.

3.4. Carbon pools

The CT plots had significantly ($p < 0.05$) lower very labile pool (P_1) than ZT plots in both soil layers (Table 6). Plots under ZT also had nearly 15 and 3 % greater labile pool (P_2) than CT plots (2.27 and 2.18 g C kg^{-1}) in the 0–15 and 15 – 30 cm soil layer, respectively. No significant impact of tillage on labile pool (P_2) was noticed in 15 – 30 cm soil layer. In ZT plots, the less labile pool (P_3) ~10 and 4 % higher as compared to CT plots (2.15 and 2.07) in 0–15 and 15 – 30 cm soil layers, respectively. Similar to labile pool (P_2), the less labile pool (P_3) also changed non-significantly with tillage in 15 – 30 cm soil layer. Non-labile pool (P_4) of SOC varied significantly ($p < 0.05$) under different tillage and irrigation levels in both the soil layers. In the 0–15 and 15 – 30 cm soil layers, plots under ZT had nearly 8.70 and 18 % greater non-labile SOC than CT plots (3.90 and 3.15 g C kg^{-1}). Apart from labile pool (P_2) and less labile pool (P_3), plots under I_4 had greater SOC concentration of very labile (P_1) and non-labile pool (P_4) than I_3 in both the soil layers. Irrespective of tillage and irrigation treatments, layer wise distribution of SOC concentration in pool was higher in the 0 – 15 cm layer as compared to 15 – 30 cm soil layer. The tillage and

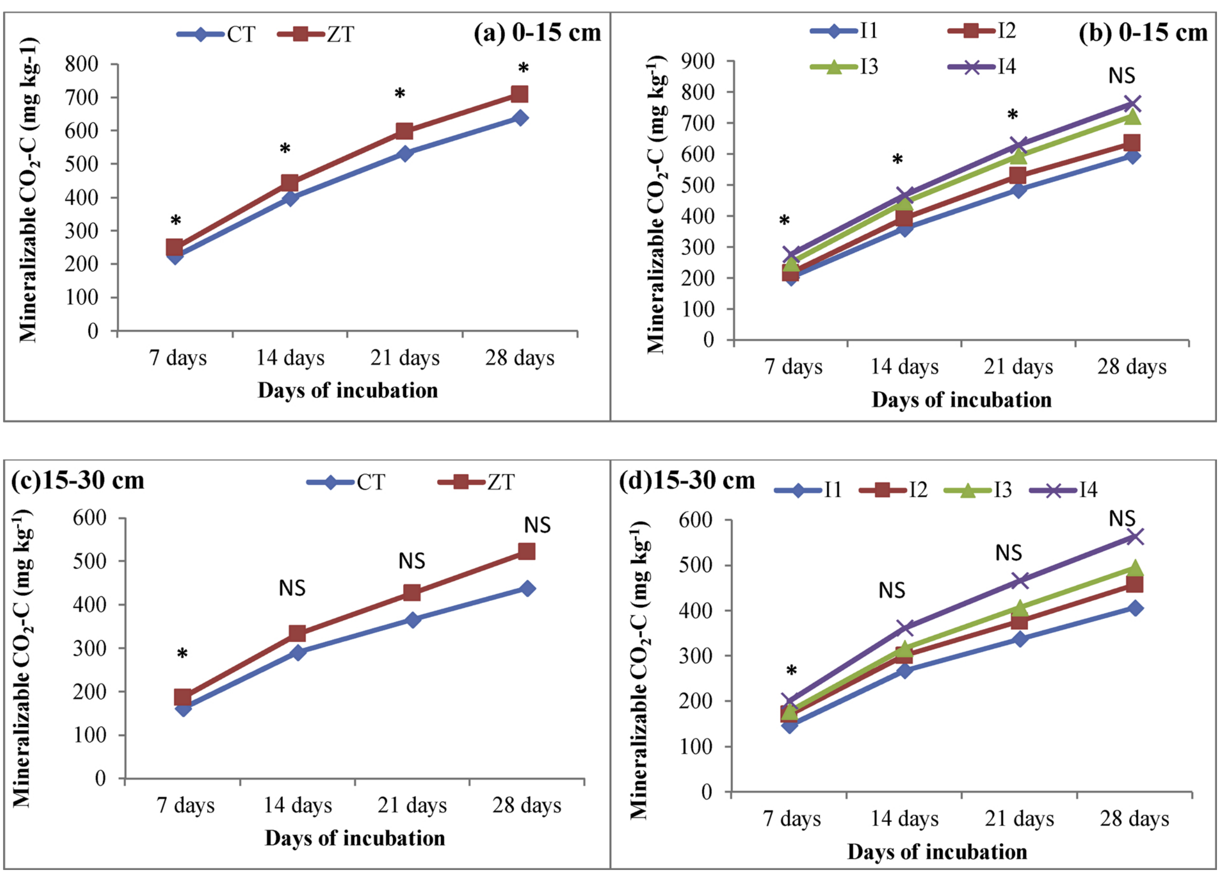

Fig. 4. Cumulative CO_2-C of soil under different tillage and irrigation levels in 0–15 (a and b) and 15 – 30 cm (c and d) of RWCS. Symbol * denotes significant differences between the treatments at $p \le 0.05$ according to Duncan Multiple Range Test for separation of means; NS indicates not significant (for treatment details refer to Table 1).

Table 6
Different soil organic carbon pools in 0–15 and 15 – 30 cm soil layers different tillage practices and irrigation levels.

Treatments†	Soil Organic Carbon Pools (g kg^{-1})							
	†P_1		P_2		P_3		P_4	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
Tillage								
CT	3.69 ± 0.15^{b}	2.96 ± 0.08^{b}	2.27 ± 0.21^{b}	2.18 ± 0.15^{a}	2.15 ± 0.20^{b}	2.07 ± 0.38^{a}	3.90 ± 0.18^{b}	3.15 ± 0.37^{b}
ZT	3.86 ± 0.17^{a}	3.15 ± 0.12^{a}	2.61 ± 0.18^{a}	2.24 ± 0.13^{a}	2.37 ± 0.12^{a}	2.15 ± 0.34^{a}	4.24 ± 0.31^{a}	3.70 ± 0.41^{a}
P value	0.021	0.001	0.001	0.34	0.005	0.65	0.002	0.007
Irrigation								
I_1	3.29 ± 0.17^{d}	2.85 ± 0.09^{c}	2.27 ± 0.14^{b}	2.12 ± 0.16^{b}	2.15 ± 0.07^{b}	1.94 ± 0.37^{a}	3.64 ± 0.22^{c}	3.27 ± 0.16^{b}
I_2	3.53 ± 0.13^{c}	2.95 ± 0.11^{c}	2.41 ± 0.23^{ab}	2.18 ± 0.14^{ab}	2.20 ± 0.21^{ab}	2.06 ± 0.35^{a}	3.93 ± 0.21^{bc}	3.24 ± 0.31^{b}
I_3	3.87 ± 0.11^{b}	3.15 ± 0.14^{b}	2.56 ± 0.21^{a}	2.24 ± 0.12^{ab}	2.39 ± 0.13^{a}	2.18 ± 0.33^{a}	4.21 ± 0.20^{ab}	3.17 ± 0.32^{b}
I_4	4.41 ± 0.21^{a}	3.29 ± 0.08^{a}	2.52 ± 0.20^{a}	2.31 ± 0.14^{a}	2.30 ± 0.23^{ab}	2.27 ± 0.38^{a}	4.51 ± 0.36^{a}	4.02 ± 0.77^{a}
P value	0.001	0.001	0.08	0.14	0.11	0.49	0.001	0.01
T × I (LSD)	0.26	NS	NS	NS	NS	NS	NS	NS
P value	0.003	0.44	0.19	0.83	0.11	0.98	0.25	0.53

† Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent ($p \leq 0.05$) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant. (†P_1 = Very labile pool; extracted with 12 N H_2SO_4, P_2 = Labile pool; extracted between 18 - 12$N H_2SO_4$, P_3 = less labile pool; extracted between 24-18$N H_2SO_4$, P_4 = non-labile pool; extracted with TOC- 24 $N H_2SO_4$).

irrigation interaction effect was significant (p = 0.002) for the very labile pool and that for surface layer only.

Non-labile pool (P_4) constituted the highest (32.17–34.32%) across the tillage and irrigation levels as compared to rest of the pools. The very labile pool (P_1) constituted a higher proportion (29.24–33.80 and 27.72–29.37%) of total SOC concentration than P_2 and P_3 across the treatments in 0–15 and 15 – 30 cm soil layers, respectively (Fig. 5a, b). The percentage carbon concentration distribution of different pools to total SOC was in the order: $P_4 > P_1 > P_2 > P_3$ in 0 – 15 cm soil layer whereas P_2 and P_3 were more or less similar in 15 – 30 cm soil layer.

3.5. Carbon sequestration (CS) and carbon sequestration rate (CSR)

The tillage and irrigation had significant ($p < 0.05$) impact on carbon sequestration (CS) in the surface and subsurface layers. Plots under ZT had ~ 9 and 6 % higher carbon sequestration as compared to CT plots (22.68 and 20.50 Mg ha^{-1}) in the 0–15 and 15 – 30 cm soil layers, respectively (Table 7). Irrespective of tillage, CS was found higher under I_4 than I_3, I_2 and I_1 plots in the 0–15 and 15 – 30 cm soil layers, respectively. Data shown in Table 7 revealed that CSR varied significantly ($p < 0.05$) under tillage and irrigation treatments. The CSR was higher under ZT plots (459 and 333 kg C ha^{-1} year^{-1}) as compared to CT plots (339 and 259 kg C ha^{-1} year^{-1}) in the 0–15 and 15 – 30 cm soil layers, respectively. The CSR also varied significantly

Table 7
Carbon sequestration (CS) and carbon sequestration rate (CSR) in 0–15 and 15 – 30 cm soil layers under different tillage practices and irrigation levels.

Treatments†	C-sequestration (Mg ha^{-1})		C-sequestration rate (kg C ha^{-1} year^{-1})	
	0 – 15 cm	15 – 30 cm	0 – 15 cm	15 – 30 cm
Tillage				
CT	22.68 ± 0.98^{b}	20.50 ± 1.07^{b}	339 ± 61^{b}	259 ± 67^{b}
ZT	24.62 ± 1.49^{a}	21.70 ± 1.45^{a}	460 ± 93^{a}	333 ± 91^{a}
P value	0.003	0.046	0.003	0.046
Irrigation				
I_1	22.01 ± 0.59^{b}	20.16 ± 0.69^{b}	297 ± 37^{b}	237 ± 43^{b}
I_2	23.31 ± 1.78^{ab}	20.47 ± 1.12^{b}	378 ± 111^{ab}	257 ± 70^{b}
I_3	24.61 ± 1.01^{a}	20.85 ± 1.62^{b}	459 ± 63^{a}	281 ± 99^{b}
I_4	24.68 ± 1.57^{a}	22.89 ± 1.62^{a}	464 ± 98^{a}	408 ± 101^{a}
P value	0.012	0.009	0.014	0.003
T × I (LSD)	NS	NS	NS	NS
P value	0.210	0.89	0.210	0.89

† Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent ($p \leq 0.05$) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant.

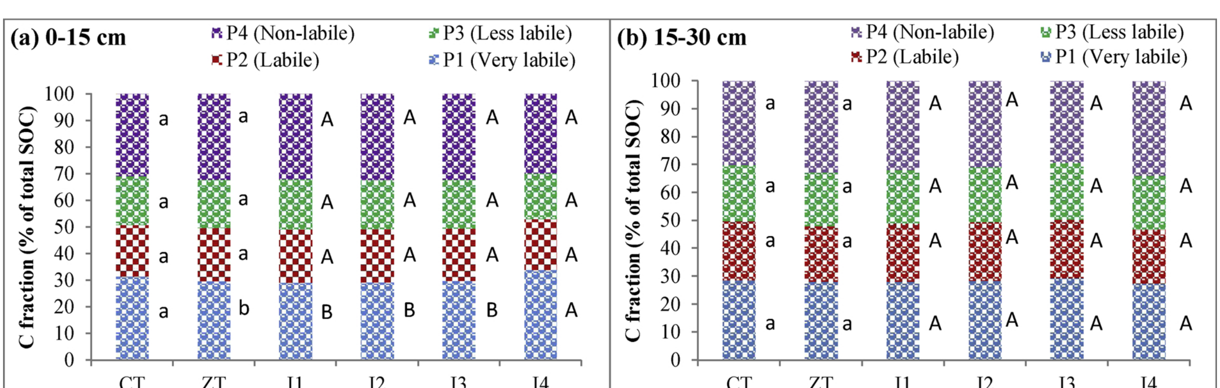

Fig. 5. Distribution of carbon fractions of different lability (as % of total SOC) in 0–15 (a) and 15 – 30 cm (b) soil layers under different tillage and irrigation levels. Bars followed by the same letter for a given fraction (small letter used within tillage and capital letter for irrigation treatments) are not significantly different ($P < 0.05$) (for treatment details refer to Table 1).

Table 8
Initial water use efficiency (WUE), pooled WUE of rice and wheat as influenced by 16 year long-term tillage practices and different irrigation levels.

Treatments[†]	[¥]Initial WUE (kg ha^{-1} mm^{-1})		Pooled (2001–2016) WUE (kg ha^{-1} mm^{-1})		WUE trend (kg ha^{-1} mm^{-1} $year^{-1}$)	
Tillage	Rice	Wheat	Rice	Wheat	Rice	Wheat
CT	230.75	12.08	4.18 ± 0.94[a]	10.7 ± 2.47[a]	–112.8	–160.9
ZT	306.51	10.43	4.20 ± 1.02[a]	11.0 ± 2.56[a]	–150.5	+71.3
P value			NS	NS		
Irrigation						
I_1	339.38	11.85	4.11 ± 1.22[a]	11.0 ± 3.37[c]	–166.9	–100.3
I_2	306.64	11.90	4.22 ± 1.13[a]	11.4 ± 2.78[d]	–150.6	–58.4
I_3	248.53	10.91	4.20 ± 0.88[a]	10.7 ± 2.21[b]	–121.6	–19.8
I_4	254.68	10.16	4.22 ± 0.78[a]	10.4 ± 1.62[a]	–125.0	+45.4
P value			NS	0.05		
T × I (LSD)			0.16	0.44		
P value			NS	NS		

[†] Refer to Table 1 for treatment details. Mean (± values are standard deviations from means) followed by similar letter within a column for a particular management practices are not significant diff ;erent (p ≤ 0.05) among the treatments according to Duncan Multiple Range Test. LSD indicates least significant difference and NS indicates not significant. [¥] intercept value is considered as initial WUE.

($p < 0.05$) under contrast irrigation regimes from 297 to 464 kg C ha^{-1} $year^{-1}$ in the 0 – 15 cm layer and 237–408 kg C ha^{-1} $year^{-1}$ in the 15 – 30 cm soil layer. Apart from treatments, layer wise distribution of CS and CSR was also higher in the 0 – 15 cm layer as compared to15 – 30 cm soil layer. Irrespective of tillage, CS was found higher under I_4 than I_3, I_2 and I_1 plots in the 0–15 and 15 – 30 cm soil layers, respectively.

3.6. Water use efficiency (WUE) and its trend

The plots under ZT showed numerically a higher WUE value in rice and wheat (Table 8) as compared to CT. As there were no statistically yield differences between ZT and CT in both crops, so WUE values were also similar. WUE values of rice in the plots under different irrigation treatments were not statistically different, but in wheat there were statistically different, even though there were significant yield differences in irrigation treatments in both the crops. Results revealed that WUE values were found higher under I_4 than I_3, I_2 and I_1 plots in the both crops.

After analyzed of 16 year data of WUE disclosed that negative WUE trend over the years ranging from 112 to 150 kg ha^{-1} mm^{-1} $year^{-1}$ in tillage and 121 to 170 kg ha^{-1} mm^{-1} $year^{-1}$ in irrigation treatments in rice whereas in wheat it was positive under ZT and I_4 treatments and negative trends in CT as well as all three irrigation treatments (Figs. 6 and 7).

3.7. Correlation among different physico-chemical indicators, SOC fractions with rice and wheat yield

Significant correlation was observed of soil, rice and wheat yield in the surface layer of soil while non-significant in the sub-surface layer. Both, soil pH and total porosity had positive correlation with rice yield (r = 0.38; p = 0.031 and r = 0.43; p = 0.014), while a significant negative correlation (r = -0.43; p = 0.014). Wheat yield had significant positive correlation with total porosity (r = 0.43; p = 0.012) while significant negative correlation with bulk density (r = -0.44; p = 0.012). Different fractions and pools of SOC were significantly correlated with rice and wheat yield (except P_2 and P_3 in 0–15 and P_3 and P_4 in 15 – 30 cm soil layers). CS had significant positive correlation with rice (r = 0.43; p = 0.014 and r = 0.48; p = 0.005) and wheat yield (r = 0.47; p = 0.007 and r = 0.49; p = 0.004) under 0–15 and 15 – 30 cm soil layers, respectively (Table 9).

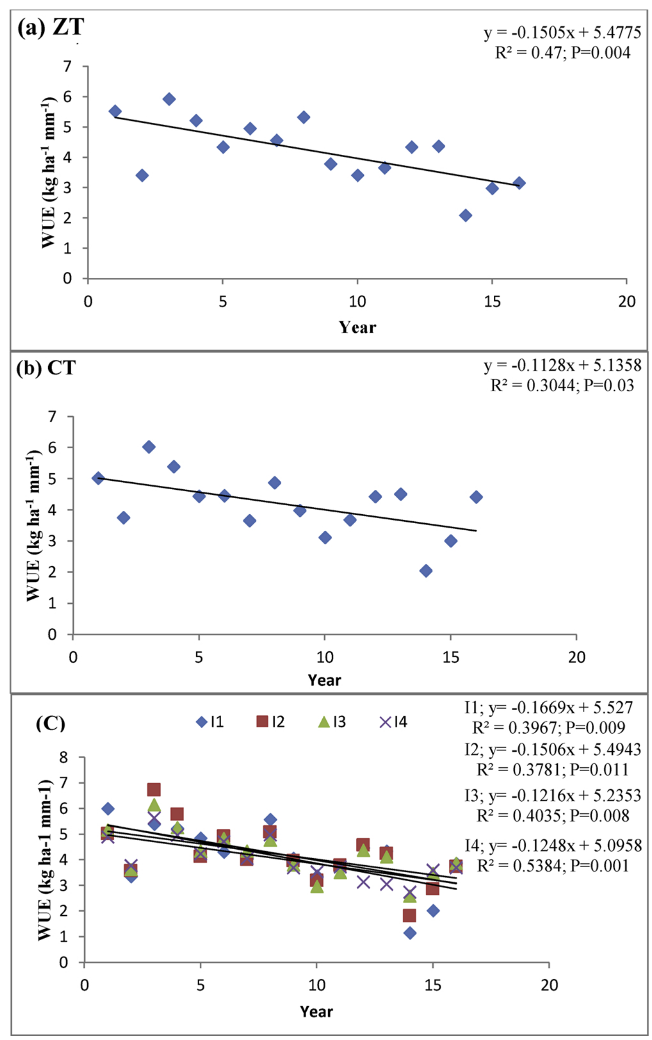

Fig. 6. Regression analysis of the 16-year trends of WUE of rice under different tillage (a, b) and irrigation levels (c) (for treatment details refer to Table 1).

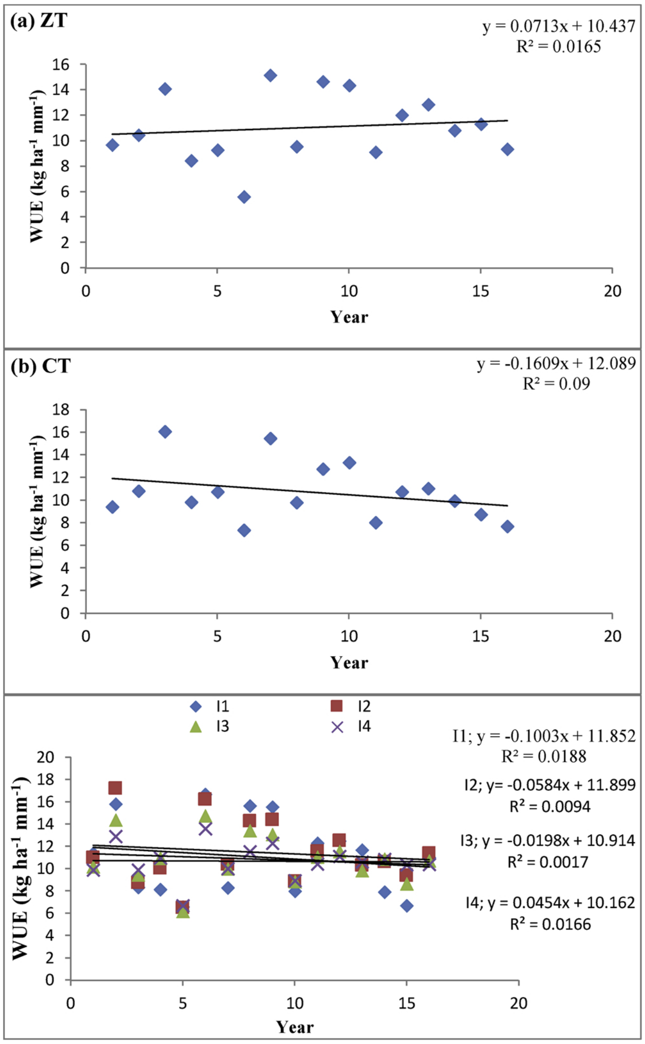

Fig. 7. Regression analysis of the 16-year trends of WUE of wheat under different tillage (a, b) and irrigation levels (c) (for treatment details refer to Table 1).

4. Discussion

4.1. Effect of tillage and irrigation on grain yield and yield trends

Consequently, the rice yield reduced under both the ZT and CT system. In ZT, surface layer had light crop residue and no disturbance (Stanley et al., 2018) along with high weed infestation during season as compared to season (Gathala et al., 2016); this was the another cause of more rice yield reductions in ZT as compared to CT. However, wheat yield to a certain extent sustained and increased under ZT but declined slightly under CT plots after long term cultivation (Gathala et al., 2011). No significant difference was reported in the yields of rice and wheat under ZT and CT system after 9 (Bhattacharyya et al., 2013) and 16 years (in the present study) of experimentation.

Linear regression analysis revealed a downward trend in rice grain yield both in the tillage and irrigation treatments after 16 years of crop cultivation. This might be due to the long term cultivation of rice-wheat leading to the degradation of soil quality and health as well as tropical humid climates leading to weeds, pests, or disease pressure proportionately which are largely contributing to yield declines (Pittelkow et al., 2015). Recommended dose of fertilizers were not enough to sustain long-term crop production under cereal-cereal cropping system. Similar results tuned with Singh et al. (2015) and Kim et al. (2016). In the present study, for wheat, plots under ZT had positive yield trends over the years as compared to CT. Our results are accorded with others findings such as Song et al. (2016); Singh et al. (2016), and Jat et al. (2014). Application of four irrigations (I_4) increased moisture content in soil profile and speed up of exchange of nutrient process and availability of nutrients improved in soil overall yield of rice and wheat increased as compared to limited irrigations (I_1 or I_2 or I_3).

4.2. Effect of tillage and irrigation on physico-chemical indicators of soils

Significantly lower than CT in 0–15 and 15 − 30 cm soil layers respectively (Table 4). Tillage increased bulk density and penetration resistance of the soils as compared to no or minimum tillage. No significant change in was also reported by Bhattacharyya et al. (2013). Frequent irrigation under I_4 treatment had lower bulk density value as compared to few irrigation (I_2 and I_1) might be due to adequate soil moisture condition had better root growth and increased air permeability of soil. Total porosity was higher under I_4 plots which might be due to improved soil aggregation coupled with more root and stubble biomass.

4.3. Effect of tillage and irrigation on soil organic carbon (SOC) and its fractions

In addition to the minimizing breakdown of macro aggregates (Gathala et al., 2011) in the frequently irrigated plots (I_4), the effects of higher root and stubble biomass might have contributed to increased SOC concentration (Jat et al., 2014; Sapkota et al., 2017). According to Meena et al. (2015), ZT resulted in a net increase of 16–27 % in soil carbon concentration over CT under maize-based cropping systems. Prasad et al. (2016) stated that after 10 years, the SOC concentration in 0–20 cm soil layer with minimum tillage (MT) was 11 % higher than with CT in rainfed finger millet-pigeonpea cropping system. Similar findings also in tune with Song et al. (2016); Souza et al. (2016) and Liu et al. (2014). DOC is the primary energy source for soil micro-organisms and is an indicator of the carbon availability to soil micro-organisms (Stevenson, 1994). The results showed that DOC concentration was higher under ZT plots as compared to CT. It might be due to the preservation of easily available carbon from oxidation. DOC is potentially mobile in soils, so the proportion of DOC may be an indicator of translation or turnover rates of whole size of SOC. Generally, in both soil layers, DOC was greater in the I_4 plots over I_3, I_2 and I_1 plots. The significant tillage and irrigation interaction effect suggested that these dependent variables responded differently to tillage treatments within the four irrigation treatments under sub-surface layer studied. Naresh et al. (2016) reported that furrow irrigated raised bed (FIRB) and ZT enhanced the DOC as compared to CT. The highest DOC concentrations were measured in 0–15 cm soil layer and decreased with soil depth (Hao et al., 2013; Liu et al., 2014).

The CMPs such as ZT have higher MBC concentration than CT and this parameter was negatively affected when the soil was disturbed (Figueiredo et al., 2013 and Souza et al., 2016). A repeated tillage operation break down soil aggregates and exposes protected organic matter to microbial decomposition and increase the loss of carbon from CT plots as compared to ZT plots. Similar findings were also reported by Heidari et al. (2016); Liu et al. (2014) and Liu et al. (2010). Water regimes had significant effect on MBC in both the soil layer and this might be due to the reason that optimum moisture content caused favorable microclimate for proliferation of soil microorganism and their activity was increased in soil (Quanying et al., 2014; Souza et al., 2016). The higher concentration of $KMnO_4$-C in I_4 plots may be due to the decomposition of root biomass and higher accumulation of $KMnO_4$-C from non-labile pools (P_4) than I_3, I_2 and I_1 plots. Our findings are in tune with Chen et al. (2009); Bhattacharyya et al. (2013) and Liu et al. (2014). Higher POC recorded in I_4 might be due to the higher moisture content that led to formation of stable macroaggregates finally leading

Table 9
Pearson correlation among rice yield (RY), wheat yield (WY), pH, bulk density (BD), total porosity (f), total organic carbon (TOC), dissolve organic carbon (DOC), microbial biomass carbon (MBC), permanganate-oxidizable carbon (KMnO4-C), Cumulative CO_2-C, particulate organic carbon (POC), Walkley–Black carbon (WBC), different soil organic carbon pools (P) and carbon sequestration (CS) in the 0–15 and 15 − 30 cm soil layers (n = 32).

Soil parameters	Pearson's correlation coefficients (r)															
	RY	WY	pH	BD	f	TOC	DOC	MBC	$KMnO_4$-C	CO_2-C	POC	WBC	P_1	P_2	P_3	P_4
	0 − 15 cm Soil layer															
WY	0.98**	1														
pH	0.38*	0.33	1													
BD	−0.43*	−0.44*	0.15	1												
f	0.43*	0.43*	−0.15	−0.99**	1											
TOC	0.55**	0.59**	−0.15	−0.35	0.34	1										
DOC	0.55**	0.61**	−0.04	−0.34	0.34	0.65**	1									
MBC	0.47**	0.54**	−0.29	−0.35*	0.36*	0.77**	0.73**	1								
$KMnO_4$-C	0.65**	0.73**	0.03	−0.34*	0.35	0.62**	0.53**	0.63**	1							
CO_2-C	0.68**	0.71**	−0.04	−0.49*	0.47*	0.62**	0.57**	0.70**	0.71**	1						
POC	0.64**	0.69**	−0.18	−0.59**	0.59**	0.79**	0.68**	0.83**	0.74**	0.81**	1					
WBC	0.42*	0.44*	−0.09	−0.31	0.31	0.90**	0.59**	0.68**	0.53**	0.56**	0.69**	1				
P_1	0.82**	0.85**	0.25	−0.46**	0.46**	0.54**	0.66**	0.54**	0.75**	0.73**	0.72**	0.47**	1			
P_2	0.30	0.32	−0.47**	−0.42*	0.42*	0.70**	0.33	0.62**	0.38*	0.43*	0.61**	0.67**	0.33	1		
P_3	0.25	0.25	−0.08	−0.17	0.17	0.62**	0.42*	0.47**	0.33	0.36*	0.42*	0.57**	0.23	0.27	1	
P_4	0.65**	0.69**	−0.02	−0.50**	0.50**	0.69**	0.47**	0.63**	0.72**	0.55**	0.76**	0.47**	0.64**	0.45**	0.42*	1
CS	0.43*	0.47**	−0.10	−0.01	0.01	0.94**	0.57**	0.69**	0.54**	0.51**	0.63**	0.84**	0.41*	0.58**	0.59**	0.56**
	15 − 30 cm Soil layer															
WY	0.98**	1														
pH	−0.04	−0.05	1													
BD	−0.20	−0.22	0.18	1												
f	0.20	0.22	−0.19	−0.99**	1											
TOC	0.62**	0.64**	−0.42*	−0.23	0.23	1										
DOC	0.60**	0.56**	−0.34	−0.19	0.19	0.65**	1									
MBC	0.55**	0.58**	−0.36*	−0.09	0.09	0.58**	0.39*	1								
$KMnO_4$-C	0.48**	0.50**	−0.26	−0.30	0.31	0.51**	0.57**	0.55**	1							
CO_2-C	0.49**	0.51**	0.01	−0.37*	0.38*	0.51**	0.41*	0.32	0.49**	1						
POC	0.73**	0.75**	−0.13	−0.19	0.19	0.68**	0.66**	0.41*	0.41*	0.51**	1					
WBC	0.68**	0.68**	−0.11	−0.08	0.08	0.70**	0.52**	0.63**	0.51**	0.36*	0.70**	1				
P_1	0.71**	0.72**	−0.24	−0.33	0.33	0.76**	0.63**	0.67**	0.63**	0.59**	0.72**	0.67**	1			
P_2	0.42*	0.41*	−0.05	−0.11	0.11	0.35	0.57**	0.33	0.49**	0.39*	0.34	0.27	0.42*	1		
P_3	0.29	0.29	−0.34	−0.37*	0.37*	0.16	0.01	0.06	0.17	0.22	0.23	0.05	0.28	−0.16	1	
P_4	0.32	0.35	−0.03	−0.12	0.12	0.54**	0.33	0.34	0.41*	0.71**	0.47**	0.35	0.46**	0.33	0.08	1
CS	0.48**	0.49**	−0.31	0.34	−0.34	0.84**	0.51**	0.52**	0.32	0.27	0.55**	0.63**	0.55**	0.26	−0.05	0.46**

** Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

to greater POC than dryer conditions or I_3, I_2 and I_1 plots.

The higher WBC concentration in the plots under ZT than CT plots might be attributed in part to less disruption of the soil structure, aggregates and due to less soil/residue interaction with ZT and another side was higher decomposition rates and carbon redistribution with CT plots (Du et al., 2010). The effects of higher root and stubble biomass might have contributed to increased WBC concentration along with higher levels of moisture content in I_4 and I_3 than I_2 and I_1.

Carbon mineralization process represents decomposition of organic matter in soil and is reflected as an indicator of microbial activity probably largely governed by the higher root biomass and crop residue addition available for microorganism growth and higher soil respiration as compared to dried conditions.

4.4. *Effect of tillage and irrigation on carbon pools and carbon sequestration (CS)*

Results shown in Table 7 indicated that higher CS and CSR under ZT plots may be due to (i) higher soil surface residue retention leading to greater carbon inputs or (ii) preservation of SOC without disturbance of soil and decomposition. Chen et al. (2009) reported that reduced tillage (RT) contained 7.3 % more SOC stocks than plough tillage (PT) in the 0–20 cm layer. CS increased in topsoil of double rice-cropping systems with increases in experimental duration (Chen et al., 2014).

4.5. *Effect of tillage and irrigation on water use efficiency (WUE)*

The mean (of 16 years) WUE for both rice and wheat in the plots under tillage were not statistically different with each other but higher numerical values were observed under ZT as compared to CT. Results indicated that ZT may be more needed than CT in terms of water budget and efficiency. Frequent irrigation (I_4) was also supportive for maintaining optimum moisture condition for higher yield production as compared to small number of irrigation. Similar results were observed by Jat et al. (2009) and Parihar et al. (2017).

4.6. *Relationship between physico-chemical indicators, SOC, rice and wheat yield*

These results revealed a decline of these SOC and its fractions with increased soil depths. Different fractions and pools of SOC were significant and positively correlated with rice and wheat yield. Such correlations suggested that SOC as a core parameter to the soil fertility and play an important role in the improvement of soil quality. Similarly, depletion in different SOC fractions and pools could also give an early indication for decline of soil fertility (Chen et al., 2009)

5. Conclusions

Our results from a 16-year old experiment confirmed that plots under ZT increased wheat yield and reduced rice yield while the rice yield was increased and wheat yield was decreased in CT system. Irrigation had also negative rice yield trends and positive trends of wheat yield over the years. These findings indicate that ZT may be more desirable than CT for wheat cultivation, physico-chemical indicators of soil and carbon sequestration significantly improved under ZT system along with frequent irrigation (I_4 or I_3) than CT system and small number of irrigation (I_1 or I_2). Adoption of ZT is the better management option for soil carbon improvement than CT, whereas CT may be more productive in case of rice cultivation according to current scenario. A minimum of four irrigations in both the crops is necessary for maintaining sustainable production along with improvement of physico-chemical indicators of soil. The WUE of rice and wheat had higher under ZT as compared to CT. It is suggested that ZT is more desirable for efficient water utilization in such conditions. Frequent irrigation (I_4) was more desirable for maintaining optimum moisture condition for sustainable crop production.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

We thank the ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan (http://vpkas.icar.gov.in), under project "Integrated Water & Soil Management for Enhancing Production and Input Use Efficiency" (IXX08505) for providing necessary facilities. Authors express their thankfulness to Mr. Narayan Ram and Sanjay Kumar Arya, technical Officer of the institute for helping in field management and soil analysis.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106067.

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