Sugar Tech (July-Aug 2017) 19(4):347–358
DOI 10.1007/s12355-016-0470-x

RESEARCH ARTICLE

Soil Carbon Sequestration and Crop Yields in Rice–Wheat and Sugarcane–Ratoon–Wheat Cropping Systems Through Crop Residue Management and Inoculation of *Trichoderma viride* in Subtropical India

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Received: 11 June 2016 / Accepted: 11 August 2016 / Published online: 23 August 2016

Abstract A field experiment was conducted at ICAR-IISR, Lucknow, in a split-plot design with two cropping systems and eight different crop residue management practices. In main plots, cropping systems, viz. CS_1—rice–wheat (R–W) and CS_2—sugarcane (plant crop)–ratoon–wheat (S–R–W) and subplots residue management practices, viz. residue removal (T_1-RR); residue burning (T_2-RB); residue incorporation (T_3-RI); residue incorporation + *Trichoderma* (T_4-RI + T), residue incorporation +25 % extra nitrogen application (T_5-RI + N), partial residue incorporation (T_6-PRI), partial residue incorporation + *Trichoderma* (T_7-PRI + T) and partial residue incorporation +25 % extra nitrogen application (T_8-PRI + N), were allocated. The observations on soil physical parameters indicated the lower mean bulk density (1.10 Mg m^{-3}) in sugarcane–ratoon–wheat system than the rice–wheat system (1.145 Mg m^{-3}). Increased porosity (58.68 %) was obtained in sugarcane–ratoon–wheat (S–R–W) system as compared to rice–wheat system (56.83 %). In S–R–W system, higher (19.51 %) SOC was recorded than the R–W system (16.31 Mg ha^{-1}) at 0–15 cm depth. After harvesting of wheat in both the cropping systems, higher total carbon sequestered (@1.42 Mg ha^{-1}) in S–R–W system than the R–W cropping system (0–15 cm soil depth). Higher contents of available nitrogen, phosphorous and potassium were recorded in S–R–W system than the R–W system after completion of crop cycle. The agronomic efficiency of rice, wheat and sugarcane crops indicated the higher level with residue incorporation along with *Trichoderma* application. Thus, it could be concluded that sugarcane–ratoon–wheat system acted as soil fertility restorer and crop reside management along with application of *Trichoderma* sustained the soil carbon level, crop productivity and agronomic/production efficiency of N for longer period.

Keywords Agronomic efficiency · Carbon sequestration · Rice–wheat cropping system · Sugarcane–ratoon–wheat system · Total soil carbon

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Introduction

The rice–wheat rotation is the principal cropping system in South Asian countries that occupies about 13.5 million hectares in the Indo-Gangetic Plains (IGP), of which 10.5 million hectares are in India (Gangwar 2010), 2.2 million hectares in Pakistan, 0.8 million hectares in Bangladesh and 0.5 million hectares in Nepal. This system covers about 33 % of the total rice area and 42 % of the total wheat area in the four countries as stated above, and account for one quarter to one-third of the total rice and wheat production. This cropping system is dominant in most Indian states, such as Punjab, Haryana, Bihar, Uttar Pradesh and Madhya Pradesh, and contributes to 75 % of the national food grain production (Mahajan and Gupta 2010). During the last three decades, India has witnessed significant rise in the cereal production, with less N-efficient rice–wheat systems dominating the cropping system and at the same time, there has been decline in N-efficient legumes crops. Wheat, rice and sugarcane crops have seen significant rise in areas, while the area under maize, pulses and oilseeds have observed a steep fall. As wheat and rice are exhaustive crops and heavily deplete the soil of its nutrient content, such a trend has led to setting of a negative balance of soil nutrients, loss of organic carbon and decline of factor productivity.

To increase the yield and to maintain sustainability of soil fertility through residue, recycling for nutrient management is one of the most vital factors. Since simple incorporation of rice residue causes nutrient immobilization and yield reduction in wheat, residue/stubble decomposition can be aided by inoculation of some cellulolytic fungi such as *Trichoderma*. Apart from low cost, the practice would be of eco-friendly and would improve soil health in contrast to supplementing nutrients through use of additional inorganic fertilizers.

Carbon is found in all living organisms and is the major building block for life on Earth. Carbon exists in many forms, predominantly as plant biomass, soil organic matter and as the gas carbon dioxide in the atmosphere and dissolved in seawater. Soil contains approximately 75 % of the carbon pool on land, 3× more than the amount stored in living plants and animals. Therefore, soil plays a major role in maintaining a balanced global carbon cycle. Over the past 150 years, the amount of carbon in the atmosphere has increased by 30 %. Most scientists believed that there is a direct relationship between increased levels of carbon dioxide in the atmosphere and rising global temperatures. One proposed method to reduce atmospheric carbon dioxide is to increase the global storage of carbon in soils. So there is a need to manage soils because soil contains more inorganic carbon than the atmosphere and more organic carbon than the biosphere. Soil is also considered to be an active and significant component in global carbon emission and sequestration potential. Soil carbon depletes when carbon output is more than carbon input. Sequestration occurs when carbon input > carbon output. Soil carbon sequestration is the process of transferring carbon dioxide from the atmosphere into the soil through crop residue and other organic solids and in a form that is not immediately remitted. Through the process of photosynthesis, plants assimilate carbon and return some of it to the atmosphere through respiration. The carbon that remains as plant tissue is the consumed by animals or added to the soil as litter when plants die and decompose. The primary way that carbon is stored in the soil is as soil organic matter. Carbon sequestration, taken as C-storage, can be achieved by various management practices, and the capacity of different management practices, to promote storage of soil C and provide a major sink for atmospheric CO_2, can be evaluated most convincingly from long-term studies that contribute unique information on soil C addition, losses and storage. But any predictions for change in C stock in soils depend on reliable estimates of net above ground biomass and the proportion of which is returned back to the soil. Increase in soil organic matter pool by 1t C/ha can increase additional annual 30–40 Mt of food production in developing countries (Lal 2006).

The great potential of C sequestration in crop land has provided a promising approach to reduce the atmospheric concentration of CO_2 for mitigating climate change. However, this approach depends on cropping systems, which may be defined as an operating system for growers to follow in their practices for crop production. An ideal cropping system for C sequestration should produce and remain the abundant quantity of biomass or organic C in the soil. The organic C concentration in the surface soil (0–15 cm) largely depends on the total input of crop residues remaining on the surface or incorporated into the soil. It decreases soil C greatly to remove crop top from the soil by cleaning up the land (Kuo and Jellum 2002). Therefore, to improve C sequestration, it is critical to increase the input of plant biomass residues. Biomass accumulation can be enhanced by an increase in cultivation intensity, growing cover crops between main crop growing seasons, reducing fallow period of land, crop rotations and intercropping systems. Biomass return to the soil can be improved by elimination of summer or winter fallow and maintaining a dense vegetation cover on the soil surface, which can also prevent soil from erosion for SOC loss. Potential of soil C sequestration in crop land of India has been estimated as 39–49 Tg Cyr^{-1} (Hutchinson et al. 2007).

In the proposed study, we intend to work out the carbon input output balance in sugarcane wheat cropping system, which is practiced in about 1 million ha area in Indo-Gangetic Plains of Uttar Pradesh. It is worth to mention here that rice–wheat cropping system where reports of depleting soil organic carbon are emerging also practiced in Indo-Gangetic Plain region of Uttar Pradesh. The proposed study may provide some clues to improve soil organic carbon status in these cropping systems to provide its long-term sustainability. Thus, a field experiment was planned and conducted on “Studies in carbon sequestration potential of sugarcane- and rice-based cropping systems under different crop residue management practices for sustaining soil health and crop productivity” with the following objectives (1) to study the impact of rice–wheat and sugarcane–ratoon–wheat cropping systems on carbon sequestration of soil (2) to enhance the carbon output input balance in different cropping systems and (3) to assess agronomic efficiency/production efficiency of crops with respect to N application in different cropping systems.

Materials and Methods

The Experimental Site and Soil

A field experiment was conducted for two cropping seasons of sugarcane (plant—first crop) and subsequent ratoon crop during 2010–12 and 2012–14 at ICAR-Indian Institute of Sugarcane Research, Lucknow, located at 26°56′N, 80°52′E and 111 m above sea level in semi-arid subtropical climate having dry hot summer and cold winter. There was a great variation in seasonal temperatures. Summer season prevails during April to June. The temperature during summer month goes up to 47 °C, and the climate becomes very hot and desiccating. Hot dry winds generally called "loo" blow in the summer month. Monsoon sets in the month of July with the arrival of south westerly monsoon winds and lasts till September. Lucknow receives annual rainfall about 101 cm. Winters starts from October and lasts till February. The minimum temperature during winter season in the month of December and January goes down up to 6 °C. Rainy season starts after onset of monsoon in third week of June and lasts till September. Rainy season is known for high temperature and high humidity (85–95 %) and is very much suitable for vertical growth of sugarcane crop.

Treatments

The field experiment was laid out in a split-plot design with two cropping systems (sugarcane–ratoon–wheat and rice–wheat) in main plots and eight crop residue management practices in subplot treatments. Rice, wheat and sugarcane crops were taken in the various cropping systems. Minimum plot size kept was 7.5 m × 6.0 m (45 m^2). Rice variety BPT 5204, wheat Cv. PBW 343 and sugarcane variety "CoSe 92423" were grown in the experiment. Rice–wheat system completed two cycles (rice–wheat–rice–wheat) and sugarcane–ratoon–wheat system completed one crop cycle during 2-year period.

In main plots, two cropping system, viz. CS_1—rice–wheat and CS_2—sugarcane (plant crop)–ratoon–wheat and in subplots eight residue management practices were allocated, viz. residue removal (T_1-RR); residue burning (T_2-RB); residue incorporation (T_3-RI); residue incorporation + *Trichoderma* (T_4-RI + T), residue incorporation +25 % extra nitrogen application (T_5-RI + N), partial residue incorporation (T_6-PRI), partial residue incorporation + *Trichoderma* (T_7-PRI + T) and partial residue incorporation +25 % extra N application (T_8-PRI + N). Thus, sixteen treatment combinations were applied in split-plot design under three replications. Recommended package of practices for each crop sugarcane, rice and wheat of the region was followed.

Soil Physical, Chemical Analysis and Agronomic Efficiency

The soil of the experimental field was sandy loam (17.5 % clay, 24.2 % silt and 58.3 % sand) of Indo-Gangetic alluvial origin, very deep (>2 m) well drained, flat and classified as non-calcareous mixed hyperthermic *udic ustochrept*. Before planting, soil samples from 0 to 15 and 15–30 cm depth were collected by core sampler of 8 cm diameter from five spots in the field. These samples were pooled together, and the representative homogeneous sample was analyzed for determination of soil organic carbon (Walkley and Black 1934), available N ($KMnO_4$ method), 0.5 M sodium bicarbonate ($NaHCO_3$, pH 8.5) extractable P and 1N NH_4OAC extractable K, following Jackson (1973). The initial organic carbon (14.87 and 11.88 Mg ha^{-1}), total carbon (20.31 and 17.82 Mg ha^{-1}), available N (245.2 and 234.4 kg ha^{-1}), available P_2O_5 (48.93 and 41.80 kg ha^{-1}) and available K_2O (326.4 and 312.1 kg ha^{-1}) of the experimental soil were determined in 0–15 and 15–30 cm depth, respectively. The observations on available nutrients contents in soil were recorded at the start and after completion of crop cycle in both the cropping systems.

Bulk density of the soil was determined by core sampler method (Blake 1965). Undisturbed samples were collected using a steel cylinder to determine soil bulk density and pooled for the subsequent evaluation of dry soil weight (105 °C). Porosity is a value that expresses the relative amount of pore space in the soil. It is not measured directly but is calculated from the bulk density and particle density (Brady and Weil 1996).

$$\text{Porosity/percent pore space} = 1 - (\text{bulk density/particle density}) \times 100$$

The weight per unit volume of the solid portion of soil is called particle density. Particle density of normal soils is 2.65 g cubic cm, and the same value was considered in the determination of porosity. Soil texture was determined by Bouyoucos hydrometer method (Bouyoucos 1936). Initial soil pH and electrical conductivity were measured in 1:2.5 soil water suspension by Beckman's Xeromatic pH meter (Jackson 1958) and electrical conductivity measuring machine, respectively. Soil samples were dried, sieved at 2 mm, and 10 g of sample were ground and sieved at 0.25 mm in order to determine C content. The total C content was determined by dry combustion, according to Nelson and Sommers (1982), using a CHNS Analyzer-EuroVector model EA 3000.

The C stock (Mg ha^{-1}) of each soil layer was calculated according to Eq. 1:

$$\text{C stock} = \text{C} \times \text{BD} \times \text{layer depth} \qquad (1)$$

where C is the C content (%), BD is the soil bulk density in Mg m^{-3} and layer depth is the layer thickness (cm).

Because samples were collected from fixed layers, the *C* stocks were adjusted for changes in bulk density that occurred as a result of changes in management. Therefore, the methodology described by Ellert and Bettany (1995) and Sisti et al. (2004) was used to correct soil *C* stocks to an equivalent soil mass, using the baseline area as reference. Carbon retention rates (Mg C ha^{-1} $year^{-1}$) in the 0–30 cm soil layer in all the treatments were calculated according to Eq. 2, using the baseline and the period of the two soil samplings.

$$\text{C retention rate} = [\text{C stock (Treatment wise)} - \text{C stock(baseline)}]2\ \text{(years)} \quad (2)$$

Agronomic efficiency of N was worked out with the following formula (Novoa and Loomis 1981)

$$\text{AE} = \text{kg biomass/kg N applied}$$

The data of each crop season were statistically analyzed separately. Various treatments were compared under split-plot design. The statistical analysis of the data was done through SAS software (IASRI 2015).

Results and Discussion

Soil Physical Parameters

Bulk density of soil in both the cropping systems decreased as compared to initial level after completion of crop cycle (Fig. 1a, b). Mean bulk density of rice–wheat system at the completion of crop cycle was determined as 1.145 vis-à-vis 1.10 Mg m^{-3} in sugarcane–ratoon–wheat system. Mean decline in sugarcane–ratoon–wheat system was higher (16.98 %) as compared to rice–wheat system (13.20 %) over the initial level (1.12 Mg m^{-3}). Crop residue management in the cropping systems also reduced BD level as compared to residue removal/burning (Fig. 2a, b). Bulk density of 15–30 cm depth was higher as compared to 0–15 cm depth in all the treatments. However, residue management level affected the BD in both the layers significantly. Incorporation of residues along with *Trichoderma*/25 % extra N showed the lowest BD in both the depths (0–15 and 15–30 cm). Partial residue incorporation also favored reduction in bulk density and soil compaction thereon.

Bulk density has been described by the researchers as a physical quality parameter for assessing soil health in cropping system. In our present study, on rice–wheat and sugarcane–ratoon–wheat system, we determined bulk density of the soil in two depths under different crop residue management practices. The effect of cropping system on bulk density of soil has been found variable. After completion of crop cycle, in rice–wheat system, bulk density decreased as compared to the initial level by 0.17 Mg m^{-3} in 0–15 cm depth and 0.19 Mg m^{-3} in

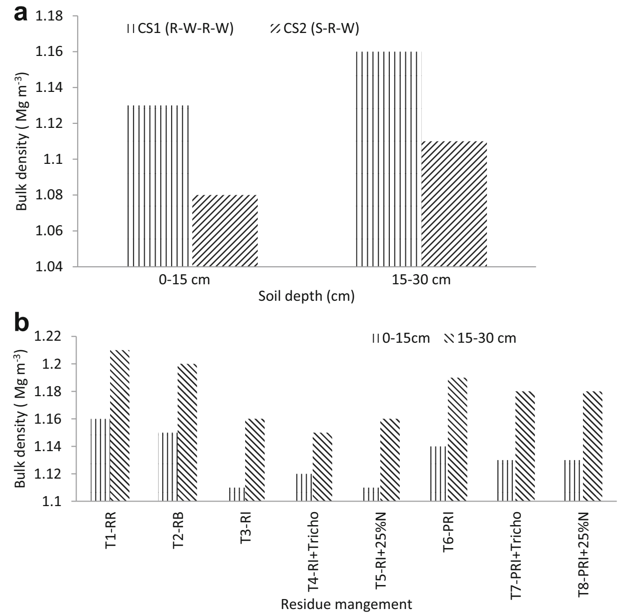

Fig. 1 **a** Effect of various cropping systems on bulk density of soil at different depths. **b** Effect of crop residue management practices on bulk density of soil at different depths

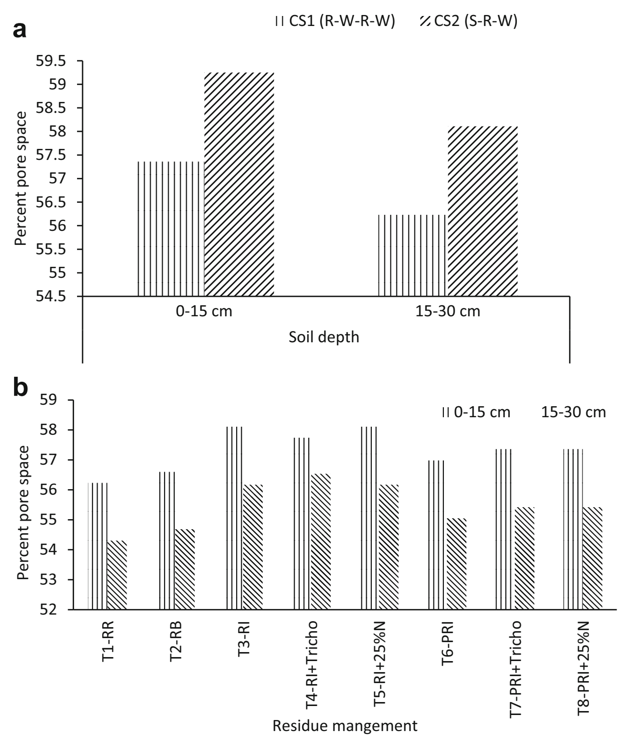

Fig. 2 **a** Effect of various cropping systems on percent pore space of soil at different depths. **b** Effect of crop residue management practices on percent pore space of soil at different depths

15–30 cm soil depth, whereas in sugarcane–ratoon–wheat system, after harvesting of wheat there was reduction in bulk density (0.22 Mg m^{-3} decreased in 0–15 cm and

0.24 Mg m^{-3} increased in 15–30 cm soil depth). Halvorson et al. (1999) reported that addition of organic manures and residues recycling improved soil organic carbon, aggregation and thus reduced bulk density.

Porosity of soil increased after completion of 2-year crop cycle in both the systems (rice–wheat and sugarcane–ratoon–wheat system). In sugarcane–ratoon–wheat system, at 0–15 cm soil depth, porosity percentage (59.25 %) was greater than the rice–wheat system (57.36 %). The mean porosity percentage (58.305 %) was 14.45 % higher than the initial porosity (50.94 %) at 0–15 cm depth and in subsurface soil depth (15–30 cm) effect was even higher (16.53 %) than upper layer. Among the treatments, full crop residue incorporation recorded the highest mean porosity than the partial residue incorporation/residue removal. Overall, residue removal/burning recorded the compaction and reduced porosity than the treatments with either full or partial residue management. Increased porosity improved aeration and therefore availability of nutrients and water holding capacity increased ultimately which improved the soil health status. Due to higher compaction in lower strata, porosity was reduced. Several workers reported the effect of residues retention on improving soil physical (structure, infiltration rate, plant available water capacity), chemical (e.g., nutrient cycling, cation exchange capacity, soil reaction) and biological (e.g., SOC sequestration, microbial biomass C, activity and species diversity of soil biota) quality (Beri et al. 1992, 1995; Power et al. 1986; Singh et al. 2005a, b, 2008).

Available Nitrogen, Phosphorous and Potassium in Soil

Higher levels of available nitrogen, phosphorous and potassium were recorded in S–R–W system than the R–W system (Table 1). The mean available NPK at 0–15 cm depth at harvest was 254.74 kg N ha^{-1}, 46.24 kg P_2O_5 ha^{-1} and 724.0 kg K_2O ha^{-1}, respectively. Available phosphorus in soil was higher in S–R–W system than R–W system (Table 1). At 0–15 cm depth, the P_2O_5 level (51.43 kg ha^{-1}) increased in S–R–W system compared to the initial status (48.93 kg ha^{-1}), whereas in 15–30 cm depth, the available P status decreased marginally (39.71 kg ha^{-1}) over the initial (41.80 kg ha^{-1}) level. Available potassium in soil increased in both the cropping systems, but the higher levels were recorded in S–R–W system than the R–W system (Table 1).

Among the different crop residue treatments, the highest available N (282.8 kg ha^{-1} N and 164.85 kg ha^{-1} at 0–15 and 15–30 cm depth, respectively) was determined in the treatment where full residue was incorporated with *Trichoderma*. At 0–15 cm depth, residue removal plots (210.77 kg ha^{-1} N) and at 15–30 cm depth residue burnt plots (163.55 kg ha^{-1} N) recorded the lowest available N. The highest available P was recorded at 0–15 and 15–30 cm depth (60.56 and 48.17 kg ha^{-1} P_2O_5, respectively) in the treatment where full crop residue was incorporated along with *Trichoderma,* whereas the lowest P_2O_5 (33.41 kg ha^{-1} P_2O_5) was recorded in the residue burnt plots at 0–15 cm depth. *Trichoderma* application with crop residues improved the available phosphorus at higher rates. However, additional application of N could not improve it significantly. The effect of full residue incorporation on P availability was higher as compared to partial residue incorporation. Residue removal plots showed the lowest availability of P_2O_5 in 15–30 cm depth. Inorganic form of extra N mineralized crop residue at faster rate and made nutrients available to crop plants, whereas *Trichoderma* showed positive effect on soil health as well as crop growth gradually. Under full residue incorporation also, inoculation of *Trichoderma* showed higher C fixation as compared to similar level with extra 25 % N. This higher carbon mobilized increased level of nutrients also which favored P availability. At 15–30 cm soil depth, residue removal plots showed the lowest (22.15 kg ha^{-1} P_2O_5) available P ha^{-1}.

The highest available K was recorded at 0–15 cm depth in the treatment where full residue was incorporated (603.55 kg K_2O ha^{-1}), whereas at 15–30 cm depth, residue incorporation with 25 % extra N-applied treatment recorded the highest available K (505.42 kg K_2O ha^{-1}). Burning of crop residues showed the lowest level of available potassium (309.03 kg ha^{-1}) in 15–30 cm depth, although mean of the available potassium (524.02 kg ha^{-1} in 0–15 cm depth and 385.07 kg ha^{-1} in 15–30 cm depth, respectively) was significantly higher over the initial level (326.4 and 312.1 kg K_2O ha^{-1}, respectively, in 0–15 and 15–30 cm depth).

While soil incorporation of crop residues is beneficial in recycling nutrients, plowing under required energy and time leads to temporary immobilization of nutrients (e.g., N), and the high C:N ratio needs to be corrected by applying extra fertilizer N at the time of residue incorporation (Singh et al. 2005a, b, 2008). Addition of organic manures and residue recycling improved organic carbon, aggregation and reduced bulk density of the soil (Halvorson et al. 1999). Trash mulching improved the soil organic carbon available and available P, thereby increasing the yield of the third ratoon crop. On the other hand, trash burning reduced the organic carbon (Yadav et al. 1994, 2009).

Table 1 Available nutrient content in soil after completion of crop cycle as influenced by cropping systems and residue management

Treatments	Available nitrogen (kg ha^{-1})		Available phosphorous (kg ha^{-1})		Available potassium (kg ha^{-1})	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Cropping systems						
CS_1 (R–W–R–W)	243.06	189.92	41.06	29.59	502.5	347.77
CS_2 (S–R–W)	266.42	201.1	51.43	39.71	545.68	422.37
SE	14.64	19.35	1.45	1.23	36.59	15.79
CD ($P = 0.05$)	NS	NS	6.22	5.31	NS	67.93
Residue management						
T_1-RR	210.77	173.95	35.13	22.15	503.62	371.27
T_2-RB	215.4	163.55	33.41	25.55	462.33	309.03
T_3-RI	268.05	202.65	46.96	31.64	603.55	499.55
T_4-RI + *Trichoderma*	282.8	224.85	60.56	48.17	586.22	331.05
T_5-RI + 25 % N	259.73	190.23	47.07	44.55	500.58	505.42
T_6-PRI	261.87	215.37	42.55	34.97	553.72	387.77
T_7-PRI + *Trichoderma*	278.6	185.37	57.35	41.73	517.05	350.72
T_8-PRI + 25 % N	260.72	208.1	46.92	28.48	465.09	325.75
SE	14.13	10.90	2.63	2.55	34.48	22.65
CD ($P = 0.05$)	28.94	23.33	5.39	5.23	70.62	46.39
Initial	245.2	224.4	48.93	41.80	326.4	312.1

CS_1 rice–wheat system, *CS_2* sugarcane–ratoon–wheat system, *RR* residue removal, *RB* residue burning, *PRI* partial residue incorporation, *RI* residue incorporation

Soil Organic Carbon and Total Carbon Sequestration

Soil organic carbon (SOC; Table 2) was greatly influenced by the cropping systems. S–R–W system recorded the higher SOC than the R–W system in both the depths. In S–R–W system, higher (19.62 %) SOC was recorded than the R–W system (16.31 Mg ha^{-1}) at 0–15 cm depth whereas in the subsurface depth in S–R–W system recorded higher rate of increase (20.02 %) than the R–W system (13.29 Mg ha^{-1}). Accumulation of soil organic carbon decreased at lower depth of soil in both the systems. The treatment where full residue along with 25 % extra N was incorporated and recorded the highest SOC (20.26 Mg ha^{-1}) at 0–15 cm depth of soil. However, the lowest SOC (12.56 Mg ha^{-1}) was analyzed where residue was removed. At 15–30 cm soil depth, the highest SOC was recorded in the treatment where partial residue was incorporated with *Trichoderma* (17.16 Mg ha^{-1}) and again the lowest SOC content was recorded in the treatment where residue was removed (10.74 Mg ha^{-1}).

After harvesting of wheat in both the systems, total carbon sequestered @1.42 Mg ha^{-1} year^{-1} in 0–15 cm soil depth under S–R–W system (Table 2) which was significantly higher than R–W cropping system (0.205 Mg ha^{-1} year^{-1}). Similar trend was also observed in 15–30 cm depth with lower values of C sequestered. Among the treatments of crop residue management, full or partial residue incorporation recorded the highest total carbon than the residue removal/burning. Crop residue management in both the cropping systems affected SOC sequestration significantly. The highest SOC sequestration was obtained under residue incorporation along with application of 25 % extra N (2.695 Mg SOC ha^{-1} year^{-1}) in 0–15 cm depth and 2.48 Mg SOC ha^{-1} year^{-1} in 15–30 cm depth). Residue removal declined SOC sequestration by 1.155 Mg ha^{-1} year^{-1} in 0–15 cm depth and 0.57 Mg SOC ha^{-1} year^{-1} in 15–30 cm depth, respectively, over the initial level (14.87 Mg ha^{-1} in 0–15 cm depth and 11.88 Mg ha^{-1} in 15–30 cm depth). Partial residue incorporation with *Trichoderma* sequestered higher SOC as compared to PRI alone. The SOC sequestration increased by 0.395 Mg ha^{-1} year^{-1} in 0–15 cm depth. However, PRI alone showed higher SOC sequestration rate in 15–30 cm depth.

The highest total soil carbon was sequestered under residue incorporation + *Trichoderma* (2.435 Mg ha^{-1} year^{-1}) in 0–15 cm depth and 1.175 Mg ha^{-1} year^{-1} in 15–30 cm depth. Partial residue incorporation was found better over residue removal/burning but sequestered at lower rate as compared to full residue incorporation. Partial residue incorporation with 25 % extra N reduced significantly lower amount of carbon as compared to partial residue incorporation + *Trichoderma*. Under full residue

Table 2 Soil organic carbon and total carbon sequestration (ha^{-1} $year^{-1}$) as influenced by different treatments after completion of the crop cycle

Treatments	SOC (Mg ha^{-1})		Total carbon (Mg ha^{-1})		SOC sequestered ha^{-1} $year^{-1}$		Total carbon sequestered ha^{-1} $year^{-1}$	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Cropping systems								
CS_1 (R–W–R–W)	16.31	13.29	20.72	16.44	0.72	0.705	0.205	−0.69
CS_2 (S–R–W)	19.51	15.95	23.15	17.88	2.32	2.035	1.42	0.03
SE	0.51	0.46	0.54	0.45	0.11	0.11	–	–
CD ($P = 0.05$)	1.52	1.42	1.62	1.42	0.34	0.32	–	–
Residue management								
T_1-RR	12.56	10.74	15.96	12.34	−1.155	−0.57	−2.175	−2.74
T_2-RB	14.82	12.32	18.2	13.95	−0.025	0.22	−1.055	−1.935
T_3-RI	18.21	16.39	24.91	20.59	1.67	2.255	2.3	1.385
T_4 RI + *Trichoderma*	19.09	17.16	25.18	18.17	2.11	2.64	2.435	0.175
T_5-RI + 25 % N	20.26	16.84	23.03	16.11	2.695	2.48	1.36	−0.855
T_6-PRI	19.2	15.34	24.2	20.06	2.165	1.73	1.945	1.12
T_7-PRI + *Trichoderma*	19.99	14.85	23.2	18.19	2.56	1.485	1.445	0.185
T_8-PRI + 25 % N	19.13	13.32	20.82	17.9	2.13	0.72	0.255	0.04
SE	0.75	0.62	0.59	0.38	0.10	0.11		
CD ($P = 0.05$)	1.42	1.26	1.20	0.86	0.24	0.24	–	–
Initial	14.87	11.88	20.31	17.82				

CS_1 rice–wheat system, *CS_2* sugarcane–ratoon–wheat system, *RR* residue removal, *RB* residue burning, *PRI* partial residue incorporation, *RI* residue incorporation

incorporation also, inoculation of *Trichoderma* showed higher C fixation as compared to similar residue level with 25 % added N.

Maintenance of a high concentration of soil organic carbon (SOC) is important for several reasons in agriculture to sustain the soil health for longer period. First, soil carbon has a profound effect on soil quality where it improved soil aggregation, increased water retention, nutrient supply and soil organism activities, soil fertility and productivity (Karlen et al. 1997). Thus, it ensures the long-term sustainability of an agroecosystem. Soil can also be a sink for atmospheric carbon dioxide (CO_2), and increased sequestration of carbon in agricultural soils has the potential to mitigate the global increase in atmospheric greenhouse gases. Verma and Bhagat (1992) have also recorded the maximum soil buildup of organic carbon under the rice straw chopped and incorporated with animal manure, followed by animal manure and straw mulch, while minimum organic carbon under rice straw burnt and rice straw removed.

Sugarcane–ratoon–wheat system sequestered higher soil organic carbon and total soil carbon than the rice–wheat system. Our observations on carbon sequestration in cropping system are further substantiated by Razafimbelo et al. (2006). Cerri et al. (2004) calculated that trash added 0.53 Mt C $year^{-1}$. In the present study, it was observed that full residue incorporation with incorporation of *Trichoderma* with 25 % extra N application resulted in the higher carbon sequestration in both the cropping systems. The higher root biomass and the associated rhizosphere helped in higher nutrient accumulation, organic carbon accumulation and thereby higher carbon sequestration. Earlier reports have established that increase in economic yield with best management practices results in simultaneous increase in the amount of crop residues and root biomass (Dwivedi et al. 2003; Singh et al. 2005a, b, 2010; Das et al. 2014). Thus, carbon sequestration potential in sugarcane–ratoon–wheat system increased. It was observed that rice–wheat system after completion of 2-year crop cycle recorded negative carbon balance in total carbon sequestration in 15–30 cm depth. Sugarcane-based system improved the soil in upper as well as lower strata also because of the deep root system than rice–wheat system. Higher total biomass produced in sugarcane-based system as compared to rice–wheat system ultimately improved the soil *C* stock.

Agronomic Efficiency and Crop Yields

Agronomic Efficiency in Rice–Wheat–Rice–Wheat System

In rice–wheat system, agronomic efficiency of rice with respect to N fertilization during first year was 36.25 kg grain kg^{-1} N applied at full recommended dose of N fertilizer applied (120 kg N ha^{-1}) and was 29.00 kg grain per kg nitrogen applied under 25 % extra nitrogen fertilizer application along with recommended dose of fertilizer (150 kg level of N; Table 3). In wheat, full residue incorporation with additional application of 25 % N exhibited agronomic efficiency of 32.7 kg grain kg^{-1} N applied with partial residue incorporation. However, the highest production efficiency (43.35 kg grain kg^{-1} N applied) was obtained with full residue incorporation. Full residue incorporation improved the production efficiency as compared to partial residue application. The lowest agronomic efficiency (32.15 kg grain kg^{-1} N applied) was obtained where partial residue incorporation was done with 25 % additional N application.

The agronomic efficiency of rice crop during 2013–14 indicated the highest level (39.38 kg grain kg N^{-1} applied) obtained with partial residue incorporation along with *Trichoderma* application (T_7). However, full residue incorporation along with *Trichoderma* application was also found at par with partial residue incorporation along with *Trichoderma* application (T_7). The lowest agronomic efficiency (29.78 kg grain/kg N applied) was obtained where residue was removed (T_1). Mean production efficiency (35.42 kg grain per kg N applied) of residue incorporation was 12.66 % higher than no residue (31.44 kg grain per kg N applied). In all the cases, additional N application decreased the production efficiency. Rao et al. (2014) reported that agronomic efficiency of N increased progressively with incremental doses of nutrients. This may be due to better utilization of nutrients from the available pool and consequent improvement in growth, yield attributes and yield.

The highest agronomic efficiency of wheat during 2013–14 (39.04 kg grain per kg N applied) was obtained in the treatment where full residue was incorporated. However, full residue incorporation along with *Trichoderma* application and partial residue incorporated treatments were also found at par. The lowest agronomic efficiency of wheat during 2013–14 (28.71 kg grain/kg N applied) was obtained where partial residue was incorporated along with 25 % extra nitrogen applied. Mean agronomic efficiency of residue incorporation was 35.48 kg grain per kg N applied over no residue was 30.38 kg grain per kg N applied. In all the cases, additional N application decreased the production efficiency. Sharma and Prasad (2008) reported that combining the application of wheat straw with *Sesbania* green manure or mung bean residues increased grain yield of cereal and agronomic N efficiency and improved the generally negative apparent N balances.

Crop Yields

Rice, wheat and sugarcane yields obtained in the cropping system have been presented in Table 4. During first year of experimentation, rice and sugarcane (plant crop) yielded 43.50 and 847.50 qtl ha^{-1}, respectively. After harvesting of rice crop, crop residue treatments were superimposed in succeeding wheat crop and during first year, wheat yield ranged from 42.45 to 52.03 qtl ha^{-1} in different treatments. Residue removal plots showed the lowest wheat yield (42.45 qtl ha^{-1}) as compared to the residue incorporation (52.03 1tl ha^{-1}). Again in rice–wheat cropping system, wheat stalk residues were also applied as per treatments before second year rice crop. During second

Table 3 Agronomic/production efficiency (kg yield/kg N applied) of various crops as influenced by different crop residue management treatments in rice–wheat and sugarcane–ratoon–wheat cropping systems

Treatments	Rice–wheat cropping system				Sugarcane–ratoon–wheat cropping system		
	Rice	Wheat	Rice	Wheat	Sugarcane	Ratoon	Wheat
T_1-Residue removal	36.25	35.38	29.78	29.04	565	430.0	30.05
T_2-Residue burning	36.25	36.82	33.10	31.71	565	461.2	29.17
T_3-Residue incorporation	36.25	43.36	34.56	39.04	565	498.2	31.53
T_4 Residue incorporation + *Trichoderma*	36.25	41.93	38.28	38.68	565	592.5	34.28
T_5-Residue incorporation + 25 % N	29.00	32.71	32.53	30.46	452	456.0	31.11
T_6-Partial residue incorporation	36.25	39.61	35.88	38.69	565	527.0	35.40
T_7-Partial residue incorporation + *Trichoderma*	36.25	38.23	39.38	37.28	565	557.5	35.57
T_8-Partial residue incorporation + 25 % N	29.00	32.15	31.91	28.71	452	391.2	25.91
SE	0.74	0.76	0.68	1.10	16.32	8.25	0.68
CD (P = 0.05)	1.84	1.68	1.45	2.45	36.45	18.96	1.45

CS_1 rice–wheat system, *CS_2* sugarcane–ratoon–wheat system, *RR* residue removal, *RB* residue burning, *PRI* partial residue incorporation, *RI* residue incorporation

Table 4 Crop yields (qtl ha^{-1}) in various cropping systems during the experimental period (2012–14)

Treatments	Rice–wheat cropping system				Sugarcane–ratoon–wheat cropping system		
	2012–13		2013–14		2012–14		
	Rice	Wheat	Rice	Wheat	Sugarcane	Ratoon	Wheat
T_1-Residue removal	43.50	42.45	35.74	34.85	847.5	860.0	36.06
T_2-Residue burning	43.50	44.18	39.72	38.05	847.5	922.3	35.00
T_3-Residue incorporation	43.50	52.03	41.47	46.85	847.5	996.3	37.84
T_4-Residue incorporation + *Trichoderma*	43.50	50.32	45.93	46.41	847.5	1185.0	41.13
T_5-Residue incorporation + 25 % N	43.50	49.06	48.80	45.69	847.5	1140.0	46.66
T_6-Partial residue incorporation	43.50	47.53	43.05	46.43	847.5	1054.0	42.48
T_7-Partial residue incorporation + *Trichoderma*	43.50	45.88	47.25	44.74	847.5	1115.0	42.68
T_8-Partial residue incorporation + 25 % N	43.50	48.23	47.87	43.07	847.5	977.9	38.87
SE	1.65	2.076	2.12	4.62	30.24	69.10	2.838
CD ($P = 0.05$)	3.56	4.452	4.43	10.052	66.45	147.80	6.087

CS_1 rice–wheat system, *CS_2* sugarcane–ratoon–wheat system, *RR* residue removal, *RB* residue burning, *PRI* partial residue incorporation, *RI* residue incorporation

year (2013–14), rice yield in different treatments ranged from 35.74 to 48.80 qtl ha^{-1}. The similar trend was observed in wheat crop also. Wheat crop during second year produced the highest yield (46.43 1tl ha^{-1}) with partial residue incorporation. However, residue incorporation with *Trichoderma* and residue incorporation with 25 % extra N was found at par.

Damodaran et al. (2005) reported significant increase in grain yield of rice in Tamil Nadu due to incorporation of *Trichoderma* culture. Increase in plant height of wheat with application of N has also been reported by Singh et al. (2002), Kumpawat and Rathore (2003) and Shah et al. (2004). Singh et al. (2002) also reported increase in number of tillers in wheat due to N application. Kumar et al. (1998) reported that in early growth stage of wheat, the higher dry matter accumulation was obtained with increasing levels of nitrogen. Nazirkar and Adsule (2002) also observed that N application significantly increased total dry matter production of wheat over the untreated control. Improvement in grain yield of wheat due to application of N has been reported by Srinivas et al. (1997); McGhie et al. 1998; Sharma et al. (2000).

Application of 15–20 kg N per ha as starter dose with straw incorporation increased yields of wheat and rice compared to either burning of straw or its incorporation in the soil. At recommended fertilizer N level, rice straw incorporation reduced rice yields than urea alone. Therefore, a higher dose of urea N application with rice straw incorporation is necessary to get good yields. Singh and Singh (2001) reported that application of 30 kg extra N per ha than the recommended fertilizer dose increased rice yields.

Agronomic Efficiency in Sugarcane (Plant)–Ratoon–Wheat Cropping System

Agronomic efficiency of sugarcane plant crop in first year was 565 kg cane per kg nitrogen applied (Table 3) where full recommended dose of fertilizer applied and was 452 kg cane per kg N applied where 25 % extra nitrogen fertilizer was applied along with recommended dose of fertilizer. The lowest agronomic efficiency of ratoon cane (430 kg cane kg^{-1} N applied) was obtained where residue was removed. However, the highest agronomic efficiency in ratoon cane (592.5 kg cane kg^{-1} N applied) was obtained in the treatment where full residue was incorporated along with *Trichoderma* application. Partial residue incorporation along with *Trichoderma* application recorded the lowest agronomic efficiency (391.2 kg ratoon cane per kg N applied). In all the cases, additional N application decreased the agronomic efficiency due to lower rate of increase in yield per kg N applied.

The lowest agronomic efficiency (25.91 kg grain kg N^{-1} applied) of wheat crop in sugarcane–ratoon–wheat cropping system was obtained where partial residue incorporation was done with 25 % additional N application. Residue burning plots also recorded the lower agronomic efficiency (29.17 kg grain per kg N applied) as compared to residue incorporation. The highest agronomic efficiency (35.57 kg grain kg N^{-1} applied) was obtained in partial residue incorporation along with *Trichoderma* application. Mean agronomic efficiency of wheat was obtained as 31.63 kg grain kg N^{-1} applied. Inoculation of *Trichoderma* with residue incorporation increased production efficiency wheat.

Mean sugarcane (plant crop) yield of 847.5 qtl ha^{-1} was obtained in sugarcane–ratoon–wheat cropping system (Table 4). Crop residue management in ratoon crop enhanced the yields up to 1185 qtl ha^{-1}. Residue application with inoculation of *Trichoderma* produced the highest ratoon yield (1185 qtl ha^{-1}). However, partial residue application also improved the ratoon yield up to 1115 qtl ha^{-1}. The residue removal plots produced the lowest ratoon yield. The similar trend was observed in succeeding wheat crop also. The highest wheat yield (46.66 qtl ha^{-1}) in sugarcane–ratoon–wheat cropping system was obtained with full residue incorporation + *Trichoderma*.

Sugarcane–ratoon–wheat cropping system also showed the positive effect of application of trash (residue) and inoculation of *Trichoderma*/25 % extra N. Sugarcane (plant) crop yielded about 847.5 qtl ha^{-1}. However, application of trash in ratoon crop brought forth significant positive effect on ratoon cane yield (Table 4). Ratoon yield in different treatments ranged from 860.0 to 1185 qtl ha^{-1}. Trash mulching (crop residue) along with *Trichoderma* in ratoon cane produced the highest ratoon yield (1185 qtl ha^{-1}). However, residue removal plots could produce only 860 qt ha^{-1}. Residue removal and their burning produced the results at par. Residue incorporation with 25 % extra N also showed the results at par with residue incorporation + *Trichoderma* (T_4). Mean yield of partial residue incorporation in sugarcane-based system was obtained as 1040.9 vis-à-vis 1107.1 qtl ha^{-1} in residue incorporated plots. Wheat yield in residue incorporated plots were also higher as compared to partial residue applied plots.

Yadav et al. (2009) reported increase in nutrient uptake by *Trichoderma* inoculation with incorporation of sugarcane trash mulch in a sugarcane–ratoon cropping system and described the stimulation of root system by *Trichoderma* application with larger mass of soil being exploited by the plant (Shukla et al. 2008) as a probable explanation. *Trichoderma* is known for releasing growth–promoting substances and might have enhanced uptake of nutrients and yield (Harman 2000; Yedidia et al. 2001). Application of *Trichoderma* enhanced the cane yield in all trash management practices. Application of *Trichoderma* enhanced the cane yield in all trash management practices. Improvement in soil fertility due to trash mulching with *Trichoderma* might have been responsible for such an effect. Yadav et al.(2009) also found significantly higher yields in the plots receiving *Trichoderma* compared to that in plots with no *Trichoderma* was probably due to the increases in SOC, SMBN and available nutrients and thus with better condition for both microorganisms and soil.

Conclusions

The two cropping systems (rice–wheat and sugarcane–ratoon–wheat system) under study with different residue management practices were shown to have positive effects on soil quality parameters. On carbon sequestration point of view, sugarcane-based system sequestered higher carbon (soil organic carbon and total soil carbon) than the rice–wheat system. Sugarcane–ratoon–wheat system incorporated higher amount of crop residue in the soil and thereby sequestered higher carbon than the rice–wheat system. Available nutrients after completion of crop cycle in sugarcane–ratoon–wheat system were higher than the rice–wheat system. The agronomic efficiency of sugarcane (plant crop) was significantly higher than ratoon crop. The increasing level of N decreased the agronomic/production efficiency of N. Thus, it could be concluded that sugarcane–ratoon–wheat system acted as soil fertility restorer and crop reside management along with application of *Trichoderma* sustained the soil carbon level, crop productivity and production efficiency of N for longer period.

Acknowledgments Authors are grateful to Director ICAR-Indian Institute of Sugarcane Research, Lucknow, for extending the facilities to provide research work at the Institute. Authors duly acknowledge the administrative and technical support of *Viswa Bharti Shiksha Niketan*, West Bengal.

Compliance with Ethical Standards

Conflict of interest The authors declare that they do have no conflict of interest.

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