Journal of Soil Science and Plant Nutrition (2024) 24:451–466
https://doi.org/10.1007/s42729-023-01555-2

ORIGINAL PAPER

Soil Carbon Mineralization and Aggregate Distribution in Various Tillage Practices of Rice–Wheat Cropping System: A Field and Laboratory Study

Naeem Ahmad[1,2] · Ahmad Latif Virk[3] · Muhammad Bilal Hafeez[1,2] · Zheng-Rong Kan[4] · Zujiao Shi[1,2] · Rui Wang[1,2] · Hafiz Muhammad Waleed Iqbal[5] · Muhammad Ishaq Asif Rehmani[6] · Xiaoli Wang[1,2] · Rattan Lal[7] · Jun Li[1,2]

Received: 15 February 2023 / Accepted: 10 November 2023 / Published online: 30 November 2023

Abstract
Different tillage and residue management practices can strongly impact soil structure stability and soil organic carbon (SOC) sequestration. However, the detailed information about the aggregate stability, SOC protection, and mineralization within aggregates are still lacking. Using aggregate fractionation with laboratory incubation, we investigated aggregate-associated SOC, soil structural stability, and SOC mineralization in rice–wheat rotation under different tillage treatments: CT0 (puddled rice, conventional wheat − residue); CTR (puddled rice, conventional wheat + residue); NT0 (direct rice seeding, zero-tilled wheat − residue); and NTR (direct rice seeding, zero-tilled wheat + residue). NTR significantly enhanced the large macro-aggregate fraction (> 2 mm) at the 0–45 cm soil layer and macro-aggregate-associated SOC at the 0–15 cm soil layer. However, CTR enhanced the macro-aggregate-associated SOC at the 15–30 cm layer. Notably, the mean weight diameter (~8%) and geometric mean diameter (~24%) were higher under NTR than those under other treatments, and the effect was more pronounced in 30–45 cm layer. The highest average cumulative carbon mineralization C_m (~9%) was observed in macro-aggregates (> 2 mm) than micro-aggregates (< 2 mm). With regard to tillage systems, the C_m was higher under NTR compared to other treatments. However, C_m at the 15–30 cm layer was higher (~22%) under CTR than that in other treatments. Notably, a positive relationship was found between total carbon input and soil aggregation. Specifically, carbon input of NT0, NTR, and CTR increased > 2 mm aggregates at 0–15 cm, while carbon input of CTR increased > 2 mm at 15–30 cm soil depth. Overall, no tillage with residue return (NTR) could enhance the soil macro-aggregation and associated SOC accumulation by decreasing SOC mineralization in rice–wheat double cropping system.

Keywords Carbon mineralization · Aggregate distribution · Tillage · Residue returning · Rice–wheat rotation

1 Introduction

By the end of twenty-first century, the average temperature rise by 3.7 °C due to unprecedented rise in the atmospheric carbon dioxide (CO_2) has accelerated the global warming and climate change (IPCC 2013). Globally, crop production is a significant source of greenhouse gasses (GHGs) emission (Carlson et al. 2016) but also has potential to sequester soil organic carbon (SOC) and mitigate change in climate (Lal 2004; Lal 2016). Therefore, offsetting atmospheric

✉ Jun Li
junli@nwsuaf.edu.cn

1 College of Agronomy, Northwest A&F University, Yangling 712100, Shaanxi, China

2 Key Laboratory of Crop Physi-ecology and Tillage Science in Northwestern Loess Plateau, Ministry of Agriculture, Yangling 712100, Shaanxi, China

3 State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou, China

4 College of Agriculture, Nanjing Agricultural University, Nanjing 21009, China

5 Department of Agronomy, Muhammad Nawaz Shareef, University of Agriculture, Multan 66000, Pakistan

6 Department of Agronomy, Ghazi University, Dera Ghazi Khan, Pakistan

7 CFAES Rattan Lal Center for Carbon Management & Sequestration, The Ohio State University, 210 Kottman Hall, 2021 Coffey Rd, Columbus, OH 43210, USA

carbon (C) in terrestrial ecosystem and mitigating GHGs emissions are among key solutions to addressing climate change (IPCC 2018; Yang et al. 2023). Soil aggregates physically protect SOC and almost 90% of its sequestration occurs in soil aggregates (Andruschkewitsch et al. 2014; Somasundaram et al. 2017). Each aggregate fraction has capacity to encapsulate the SOC with varying magnitude of physical protection against microbial degradation and moderated by different farmland management techniques (e.g., tillage and residue returning) (Spohn and Giani 2010; Gelaw et al. 2015). Furthermore, the buildup and turnover of SOC in farmlands based on the balance between carbon inputs primarily sources from crop residue retention (above-ground, root biomass, and rhizodeposition) and outputs via SOC mineralization by microbes (Malhi et al. 2011; Xie et al. 2017). Thus, it is pertinent to evaluate the distribution, stabilization, and SOC mineralization in different proportions of soil aggregates to understand the mechanism of aggregate formation and SOC protection within aggregate classes.

Soil conservation practices (no tillage and residue retention) affect nutrient distribution and effectively transform SOC and aggregate stability (Zhao et al. 2015; Somasundaram et al. 2018). Conventional tillage (CT) has been reported a major cause to physically disrupt large aggregates, making finer aggregates, thus destroying SOC binding in carbon-rich macro-aggregates and promoting SOC microbial degradation (Álvaro-Fuentes et al. 2008a, 2008b). However, conservation tillage (e.g., no till, NT) results in less soil aggregate disruption at surface soil layer (0–10 cm depth), compared to CT. Furthermore, NT system promotes aggregate stability and carbon-rich formation of macro-aggregates (Sarker et al. 2018a, 2018b). In general, macro-aggregates are more stable and richer in SOC compared with micro-aggregates. Accordingly, more macro-aggregates indicated higher soil structure stability and mean weight diameter (MWD) values and less mineralization (Wang et al. 2019). Soil aggregate distributions are determined by the process of wet sieving to evaluate the influence of different tillage and farmland management practices (Bottinelli et al. 2017). The process of wet sieving can dissolve organic matter within an aggregate fraction, transfer microbial populations from macro-aggregates (> 2 mm and 2–0.25 mm) to micro-aggregates (0.25–0.053 mm and < 0.053 mm), and considerably disturb the microbial habitat (Gunina and Kuzyakov 2014), thereby disturbing mineralization mechanism (Kan et al. 2020a). However, dry sieving could be useful in low SOC concentration soil to better analyze the carbon cycling mechanism. Thus, it is necessary to understand the process and mechanism that strengthen scientific understanding regarding SOC mineralization, aggregate stability, and associated C contents under different tillage practices by adopting dry sieving technique.

Prior laboratory incubation studies have provided some useful insights of SOC mineralization under different tillage systems, even though with different results (Jacobs et al. 2010). For example, CT enhanced SOC (26–114%) mineralization in different aggregate fractions compared with NT in a Luvisol, however, had no effect in a Vertisol (Sarker et al. 2018b). In contrast, Fernández et al. (2010) reported that C mineralization was higher under NT compared with CT in all aggregate size classes for some soils in Argentina. Moreover, the magnitude of mineralization in aggregate fractions lacks a consensus. Typically, in comparison with micro-aggregates (0.25–0.053 mm and < 0.053 mm), macro-aggregates (> 2 mm and 2–0.25 mm) contain fresh labile C with greater microbial turnover and cumulative C mineralization rate (Fernández et al. 2010; Cai et al. 2016). In contrast, Rabbi et al. (2014) stated that there were no differences in C mineralization, when comparing macro-aggregates with micro-aggregates. Another recent study indicated that higher magnitude of cumulative C mineralization was in micro-aggregates compared with macro-aggregates (Xie et al. 2017). Such contradictory results are partly due to fact that SOC is heterogeneous in nature and partly because the grading or sieving size of aggregates was not homogenous in all conditions. Thus, in-depth understanding requires how aggregates protect, stabilize, and store SOC under particular soil type and climatic conditions in different macro- and micro-aggregate fractions to identify climate-smart tillage practice and to strengthen the soil aggregation hierarchy and SOC stability at regional scale.

Rice–wheat cropping system (RWCS) is the principal production system in the Indo-Gangetic Plains (IGP) and practiced on ~13.5 Mha area (Ladha et al. 2003). Historically, CT is usually followed by burning or removal of crop residues. However, long-term CT operation in the IGP continuously decreases soil structure and SOC stability due to residue burning (Mamta et al. 2022). Therefore, recommended soil conservation practices could stabilize soil aggregates and associated C contents and improve agricultural sustainability (Bhattacharyya et al. 2012). However, to date, research information is lacking on how different tillage practices directly influence the aggregate size distribution and associated C content in different sub-soil layers. Moreover, the mechanisms of soil structural stability, SOC protection, and mineralization in aggregates under various tillage systems for specific RWCS in the IGP have not been systematically addressed. Furthermore, the relationships between C input and soil aggregation under various tillage systems are still not well understood.

Hence, this study is aimed to assess the soil aggregate size distribution (using dry sieving technique), associated C contents, soil structural stability, and mineralization in different aggregate fractions and soil layers under different tillage systems and residue management practices. It is based on the hypothesis that no till with residue retention would (i) increase the macro-aggregates fraction, (ii) promote SOC contents in macro-aggregates, and (iii) decline cumulative C mineralization capacity because of C encapsulation in the macro-aggregates. Consequently, the specific aims of the study were to (i) evaluate the soil aggregate size distribution, structural stability, and associated SOC concentration under different tillage systems, (ii) investigate the cumulative C mineralization in various tillage systems, and (iii) identify the relationships between total C input and soil aggregation under different tillage and soil depths.

2 Materials and Methods

2.1 Field Experiment

The field experiment was initiated in June 2016 at Sukheki Farm, Hafizabad (longitude 73.46 E, latitude 31.88 N, and altitude 207 m ASL), Punjab, Pakistan (Fig. S1). The climatic zone of the study area is subtropical and semi-arid, with mean annual temperature of 25.3 °C and precipitation of 433.4 mm in the past 6 years. The soil type is clay loam and classified as Haplic Yermosols (FAO 2014). Before initiating the experiment in 2016, soil samples were taken by using core sampler (5 cm height, 5.05 cm diameter) at a depth of 0–20 cm. Initial soil had 1.37 g kg^{-1} SOC, 7.8 pH, 1.32 g cm^{-3} bulk density, 0.28 g kg^{-1} total nitrogen concentration, 1.35 dSm^{-1} electrical conductivity, 4.93 mg kg^{-1} available phosphorus, and 110 mg kg^{-1} exchangeable potassium. Rice–wheat is the predominant cropping system in this region.

This site-specific experiment was based on different tillage system that begun in rice season of 2016. The experiment was laid out in randomized compete block design, with three replications. There were 12 plots, and the individual plot size was 15 × 8 m (120 m^2). Two tillage and two residue retention methods investigated were CT0 (puddled rice, conventional wheat − residue); CTR (puddled rice, conventional wheat + residue); NT0 (direct rice seeding, zero-tilled wheat − residue); and NTR (direct rice seeding, zero-tilled wheat + residue). Additional details of the experimental treatments are presented in Table 1.

2.2 Soil Sampling and Analysis

Immediately after harvest of rice and wheat (in November 2020, April 2021, and correspondingly November 2021 and April 2022), samples of soil from 0–15, 15–30, and 30–45 cm depth were taken from five randomly chosen points. The soil samples were air-dried at room temperature (~20–25 °C room temperature) until the moisture from the surface of the clods completely evaporates. The visible parts of crop straw and debris were physically removed. Big clods (greater than 12 mm) were broken by visualizing natural breaks points by putting hand force. Thereafter, samples were sieved by hand using 10-mm sieve.

Sub-samples of 100 g soil were sieved on Motorized Vibratory Sieve Shaker (FRITSCH, Germany) for 3 min to obtain different aggregate fractions, i.e., > 2 mm (large macro-aggregate), 2–0.25 mm (small macro-aggregate), 0.25–0.053 mm (micro-aggregate), and < 0.053 mm (silt–clay particles) using dry sieving technique. A proper sieving duration (3 min) and amplitude (3 mm) were chosen to obtain appropriate aggregate fractions (Sarker et al. 2018b). Soil retained on different sieves were weighed and then determined associated SOC in these aggregates using $K_2Cr_2O_7$ oxidation method (Walkley and Black 1934). The mean weight diameter (MWD; mm) of the soil aggregates was estimated by using Eq. (1):

$$\mathrm{MWD} = \frac{\sum_{i=1}^{n} (Wi \times Xi)}{\sum_{i=1}^{n} Wi} \tag{1}$$

Table 1 Details of the experimental treatments under rice–wheat cropping system

Treatments	Tillage and residue management
CT0	In CT0, one disc harrowing and one cultivation followed by planking, and then the plots were flooded with irrigation water, and puddling was done with two wet plowing and then planking, followed by manual transplanting of rice seedlings in the soft-mud (puddled soil). After the rice harvesting, wheat was sown on 22.5 cm spaced rows using seed drill after conventional tillage (one disc harrowing, two plowing, and two planking) without residue addition
CTR	The plots under CTR were followed the similar practices as CT0 with 100% residue returning of the preceding crop by using disc harrowing and plow tillage
NT0	In NT0, no cultivation was done, direct rice sown (DSR) with multi-crop inclined plate seeding drill (Green Land Engineering Ltd Daska, Pakistan) in 22.5 cm spaced rows without residue addition. After DSR, wheat was sown without residue addition under no-till conditions using happy seeder (Sharif Engineering Ltd Faisalabad, Pakistan) at 22.5 cm spaced rows
NTR	In NTR, all the management practices kept similar to NT0 with 100 % residue retention of the preceding crop. The whole straw was chopped into 5–8-cm-long pieces by tractor driven mechanical chopper

CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. *NT0/NTR* represents direct seeded rice; zero-tilled wheat without/with residue retention where X_i indicated the mean aggregate diameter of particular aggregate fraction (mm) and W_i represented the weight percentage of each aggregate fraction (Pirmoradian et al. 2005).

The geometric mean diameter (GMD; mm) was determined according to Eq. (2):

$$GMD = \exp\left[\frac{\sum_{i=1}^{n} Wi \times \ln(Xi)}{\sum_{i=1}^{n} Wi}\right] \quad (2)$$

where W_i represents the weight percentage of the each aggregate fraction and X_i indicates the mean diameter of the particular aggregate fraction (Meng et al. 2014).

2.3 Incubation Experiment

Briefly, 30 g air-dried soil sample of the macro- (> 2 mm) and micro-aggregate (< 2 mm) fraction from 0–15 and 15–30 cm depths was incubated at 70% water holding capacity (WHC) in air-tight mason jars (350 ml) at 25 ± 1 °C over 60 days in the laboratory. All jars were pre-incubated for 7 days at 30 °C in the dark and then placed in incubator for 60 days, in triplicate. The WHC was assessed by soaking in wet and dry conditions (Shahbaz et al. 2017; Kan et al. 2020a). To trap the released CO_2, small beakers (20 ml) containing 10 ml of 1 M of NaOH were replaced at each measurement. The released CO_2 was trapped in NaOH, which was measured at 3, 5, 7, 15, 30, 45, and 60 days after incubation. Additional carbonates were removed by using $BaCl_2$ to convert Na_2CO_3 into $BaCO_3$. The remaining NaOH was back-titrated with 0.1 M HCl using phenolphthalein as indicator (Kumar et al. 2018). To determine the headspace CO_2, blank jars with NaOH solutions (for CO_2 trap) were also incubated. Cumulative amount of CO_2-C evolved during the 60-day incubation period was represented as C mineralization and expressed as mg CO_2 kg^{-1} soil. Moreover, first-order kinetic model was used for the estimation of the decomposition rate of soil C as affected by different tillage systems (Eq. (3)):

$$C_m = Co\left(1 - e^{-kt}\right) \quad (3)$$

where C_m indicated the cumulative mineralized CO_2-C emission (mg CO_2 kg^{-1} aggregate) after time t (days); Co indicated the initially mineralizable C; and k represents the rate constant.

Carbon mineralizability (labile C proportion) represented as g CO_2-C g^{-1} SOC and calculated according to Eq. (4) (Das et al. 2019):

$$C_{\text{mineralizability}} = \frac{Cm}{\text{SOC concentration}} \quad (4)$$

where C_m is the total cumulative SOC mineralization (mg CO_2 kg^{-1} soil/aggregate) after 60-day incubation. The SOC concentration (g kg^{-1}) indicates the average SOC contents in aggregate fractions.

Rice and wheat were manually harvested from 3 m^2 area from each plot, and the crop biomass was then oven dried at 60 °C until the constant weight to obtain the adjusted straw yield which was presented after subtracting the moisture content. The total C input considering the above-ground plant parts (C_s), below-ground (C_r), and rhizodeposition (C_{rhizo}) were estimated from using empirical method (Zhang et al. 2022). Moreover, the C input estimation by root biomass percentage distribution in the specific soil layer (0–15, 15–30, and 30–45 cm) under different tillage systems was calculated by using the findings of Alam et al. (2014). The root biomass distribution of rice and wheat crop under different tillage systems was estimated (Huang et al. 2011; Singh et al. 2014). Moreover, the CTR tillage incorporates 10% of their retained residue at 15–30 cm (Mairhofer et al. 2019); therefore, 10% C input of residue was included in 15–30 cm soil:

$$\text{Total } C \text{ inputs} = C_s + C_r + C_{\text{rhizo}} \quad (5)$$

The above-ground biomass straw's (C_s) C inputs were calculated as

$$C_s = B_{straw} \times 0.45 \quad (6)$$

Rice and wheat straw biomass is known as B_{straw} (Mg ha^{-1}). The crop biomass C input was determined using the above-ground plant parts' 45% C concentration (Johnson et al. 2006).

Below-ground root (C_r) contribution to the C input was calculated as

$$C_r = B_{straw} \times rs \times 0.45 \quad (7)$$

where the root-to-shoot ratio is denoted by rs. The root-to-shoot ratios for rice and wheat are approximately 0.13 (Chen et al. 2014) and 0.22, respectively (Kong et al. 2005).

The C addition from rhizodeposition (C_{rhizo}) was estimated using Eq. (7) as described by Maillard and McConkey (2018):

$$C_{rhizo} = C_r \times 0.65 \quad (8)$$

2.4 Statistical Analysis

Statistical analysis was carried by using the SPSS 20.0 software package (SPSS Inc., Chicago, IL 2004). The significant differences among treatments in soil aggregate size fractions, aggregate associate C, soil structural stability, and cumulative C mineralization were assessed by one-way ANNOVA with the least significant difference (LSD) test at $p < 0.05$.

3 Results

3.1 Soil Aggregate Size Distribution, Structural Stability, and Associated SOC Concentration

The soil aggregate size distribution varied significantly ($p < 0.05$) among different tillage systems, and the macro-aggregate fractions were the most abundant in rice and wheat seasons at 0–45 cm soil depths (Fig. 1), following the order NTR > CTR > NT0 > CT0. The higher macro-aggregate fractions were obtained under NTR, which were considerably greater than CTR, NT0, and CT0 in rice season by 7%, 7.9%, and 17.2% at 0–15 cm layer and by 3.5%, 3.8%, and 17.2% at 15–30 cm layer, and by 7.7%, 7.4%, and 16.9% at 30–45 cm layer (Fig. 1). A similar trend was observed during the wheat season at 0–45 cm layer (Fig. 2).

The increase in macro-aggregate proportion resulted in a significant increase in MWD and GMD at 0–45 cm soil depth (Table 2). Different tillage systems significantly affected the MWD and GMD at 0–45 cm layer ($p < 0.05$). Generally, NTR increased the soil structural stability in rice and wheat at all layers (0–45 cm) compared to other treatments. Specifically, the values of MWD and GMD averagely improved under CTR, NT0, and NTR in rice by 10.7%, 11%, 18.3%, and 41.1%, 42.5%, 72% and wheat by 14.4%, 12.5%, 19.6%, and 45.6%, 39.4%, and 66.6%, respectively, at 0–15 cm layer and 13.3%, 13.3%, 17.8%, and 49%, 48.5%, and 68.5% in rice and 11.9%, 11.4%, 17.7%, and 37%, 36.9%, and 61.1% in wheat at 15–30 cm layer compared with CT0. Similarly, at 30–45 cm layer, the MWD and GMD increased under CTR, NT0, and NTR by 10.5%, 9.6%, 16.8%, and 39.1%, 35.5%, and 64.2% in rice and wheat, compared to CT0 (Table 2).

At a depth of 0–30 cm, there were obvious differences across tillage practices, but after this depth, there were no significant changes in the SOC content for different treatments in the rice and wheat seasons (Table S3). Moreover, the aggregate-associated SOC concentration decreased with increase in soil depth, and the maximum concentration was in 0–15 cm layer (Fig. 3 and 4). In 0–15 cm layer, the aggregate-associated SOC concentration in rice and wheat seasons varied significantly in different tillage systems ($p < 0.05$), with the greatest value observed under NTR and the lowest under CT0. Compared with CT0, SOC concentration

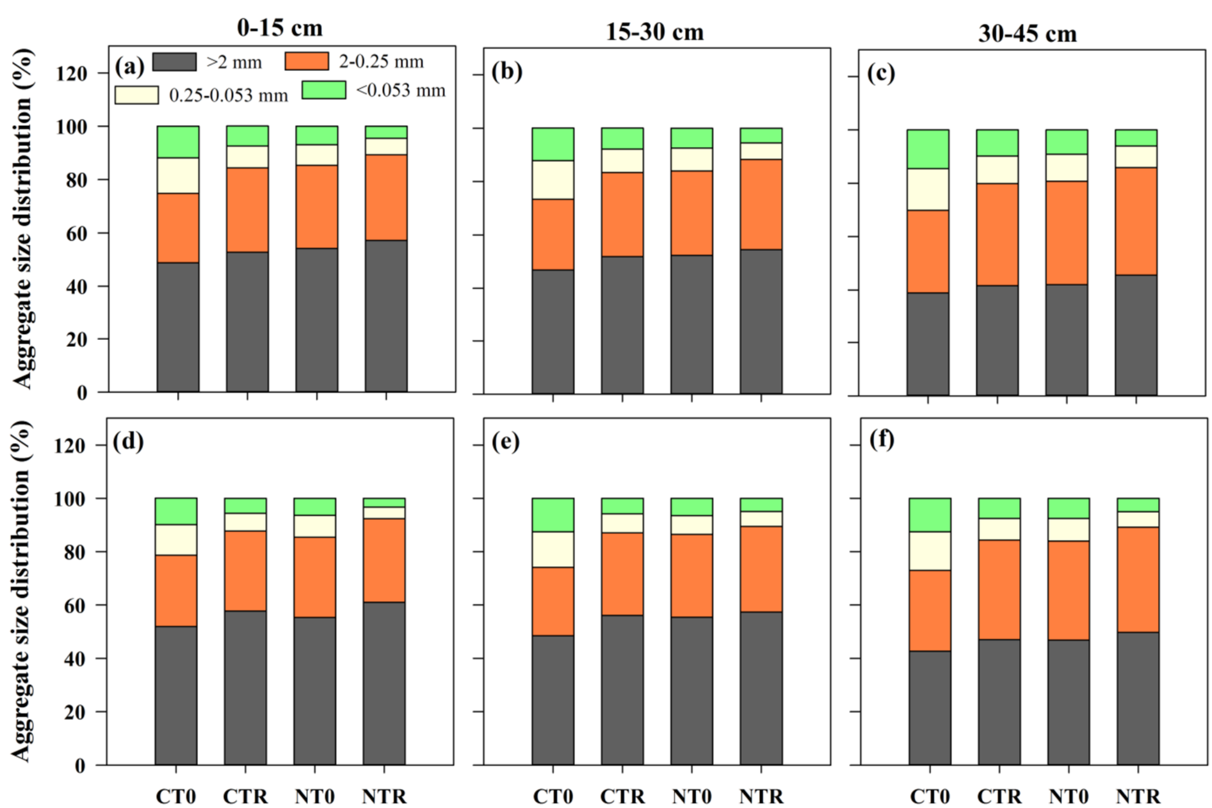

Fig. 1 Soil aggregate size distribution (%) of different aggregate fractions (> 2 mm, 2–0.25 mm, 0.25–0.053, mm and < 0.053 mm) in rice 2020 (**a**, **b**, **c**) and 2021 (**d**, **e**, **f**) from 0–15, 15–30, and 30–45 cm soil depths under different tillage systems. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR represents direct seeded rice; zero-tilled wheat without/with residue retention

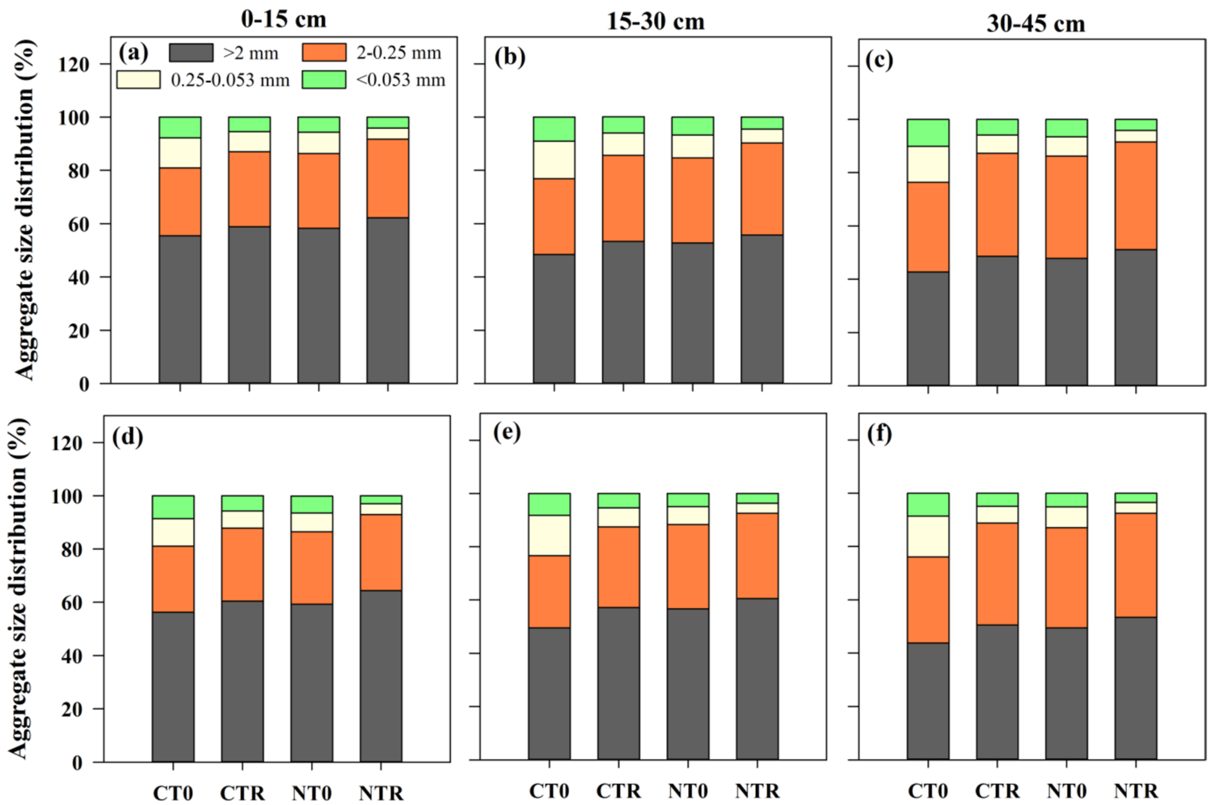

Fig. 2 Soil aggregate size distribution (%) of different aggregate fractions (> 2 mm, 2–0.25 mm, 0.25–0.053 mm and < 0.053 mm) in wheat 2020 (**a**, **b**, **c**) and 2021 (**d**, **e**, **f**) from 0–15, 15–30, and 30–45 cm soil depth under different tillage systems. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR represents direct seeded rice; zero-tilled wheat without/with residue retention

in > 2 mm, 2–0.25 mm, 0.25–0.053 mm, and < 0.053 mm increased by 31.1%, 38%, 33.9%, and 34.4% and by 29.1%, 36.2%, 30.6%, and 37.1% under NTR at 0–15 cm layer in rice 2020 and 2021 (Fig. 3a, d) and by 25.9%, 37.2%, 32.2%, and 37.1 % and by 24.1 %, 34.2 %, 31.8 %, and 36.5 % in wheat 2020 and 2021, respectively (Fig. 4a, d). Likewise, a significant increase was observed in aggregate-associated SOC in the > 2 mm, 2–0.25 mm, 0.25–0.053 mm, and < 0.053 mm which was 31.7%, 42.2%, 37.3%, 43.3%, and 33%, 36.7%, 34.2%, and 39.4% in rice 2020 and 2021 (Fig. 3b, e) and by 30.4 %, 40.9 %, 31 %, 37.5 %, and 22.9%, 36.2%, 34.1%, and 37.5% in wheat 2020–2021 at 15–30 cm layer, respectively, under CTR compared with CT0 (Fig. 4b, e). Different tillage systems did not significantly affect aggregate-associated SOC at 30–45 cm layer, except in rice 2020 (Figs. 3 and 4).

3.2 Cumulative SOC Mineralization in Aggregates Under Different Tillage System

During the first 2 weeks of incubation, pronounced CO_2 emissions were observed that became stable over time (15 to 60 days) (Fig. S2, S3, S4, and S5). Different tillage systems strongly affected the cumulative SOC mineralization in macro- and micro-aggregates over 60 day's incubation ($p < 0.05$). In general, CO_2-C emissions were greater at 0–15 cm than that in 15–30 cm layer (Fig. 5 and 6). Further, cumulative SOC mineralization rate was higher in macro-aggregates than micro-aggregates. Specifically, in rice seasons (2020–2021), NTR on average increased 36.2% and 45.5% C mineralization in macro- and micro-aggregates (Fig. 5), while 43.2% and 55.4% increase in wheat (2020–2021), respectively, at 0–15 cm layer compared with CT0 (Fig. 6). However, at 15–30 cm layer, CTR increased 16.9% and 24.3% SOC mineralization in macro- and micro-aggregates in rice and by 33.7% and 39% in wheat respectively, compared with CT0.

3.3 Carbon Mineralization Kinetics

The first-order kinetic equation/model was used to fit C mineralization data with correlation coefficient ($R^2 = 0.97–0.98$) (Table 3). The kinetics parameter estimated the C mineralization rate and the constant value for different tillage systems at 0–15 and 15–30 cm layer. Overall, higher mineralization rates were noted at 0–15 cm than 15–30 cm layer.

Table 2 MWD and GMD from 0 to 45 cm soil profile under different tillage system

Season	Treatment	0–15 cm		15–30 cm		30–45 cm	
		MWD	GMD	MWD	GMD	MWD	GMD
Rice 2020							
	CT0	1.74c	0.74c	1.96c	0.91c	2.02c	0.96d
	CTR	1.91b	1.03b	2.18b	1.27b	2.22b	1.32c
	NT0	1.93b	1.06b	2.20b	1.31b	2.26b	1.38b
	NTR	2.07a	1.29a	2.30a	1.51a	2.37a	1.60a
Rice 2021							
	CT0	1.86c	0.86c	2.01d	0.94c	2.14c	1.13c
	CTR	2.08b	1.23b	2.32b	1.49b	2.38ab	1.59b
	NT0	2.07b	1.22b	2.30c	1.44b	2.30b	1.44b
	NTR	2.19a	1.46a	2.38a	1.61a	2.49a	1.83a
Wheat 2020							
	CT0	1.89c	0.96c	2.04c	1.05c	2.25c	1.26c
	CTR	2.15b	1.38b	2.24b	1.39b	3.39b	1.55b
	NT0	2.12b	1.32b	2.22b	1.35b	2.37b	1.51b
	NTR	2.25a	1.58a	2.35a	1.62a	2.52a	1.81a
Wheat 2021							
	CT0	1.92c	0.99c	2.06c	1.08c	2.27c	1.27c
	CTR	2.21b	1.46b	2.35b	1.53b	2.44b	1.59b
	NT0	2.17b	1.40b	2.35b	1.57b	2.41b	1.55b
	NTR	2.31a	1.67a	2.48a	1.82a	2.58a	1.92a

CT0/*CTR* indicates puddled rice; conventional wheat without/with residue retention. *NT0*/*NTR* represents direct seeded rice; zero-tilled wheat without/with residue retention. Lowercase letters shows statistical significant difference ($p < 0.05$) among treatments

Notably, higher C mineralization rate were observed under NTR at 0–15 cm layer, while CTR had higher mineralization rate at 15–30 cm layer in rice and wheat seasons.

3.4 Total C Input and C Mineralizability

Figure S8 and S9 shows that total C input (considering straw, root, and rhizodeposition C) significantly ($p < 0.05$) affected by different tillage systems at 0–15, 15–30, and 30–45 cm soil layers in rice and wheat rotation. The treatments under residue return CTR and NTR significantly increased the total C input at 0–15 cm soil layer in both rice and wheat seasons, compared to other treatments (Fig. S8a, d and S9a, d). However, CTR significantly increased the total C input at 15–30 cm soil layer compared to the other treatments in rice and wheat by followed the trend as CTR > CT0 > NTR ≥ NT0 (Fig. S8b, e and S9b, e). Moreover, CTR and CT0 almost equally contributed to total C input at 30–45 cm layer, compared to other treatments (Fig. S8c, f and S9c, f).

Different tillage systems did not significantly affect the C mineralizability in rice and wheat season at 0–15 and 15–30 cm layer (Table S2). Generally, C mineralizability showed an increasing trend over the period of time. Overall, non-significant but higher values of C mineralizability were observed in micro-aggregates than in macro-aggregates at 0–15 and 15–30 cm depths. Non-significant differences were observed among different tillage systems.

4 Discussion

Soil aggregation could affect the SOC distribution in the soil profile, which could be driven by different tillage and residue inputs (Weidhuner et al. 2021). Results presented herein show that different tillage practices significantly affect the total C input at three soil layers (0–15, 15–30, and 30–45 cm). The residue input under different tillage systems can increase the supply of C required for the formation of aggregates (Verhulst et al. 2011). In general, NTR increased the macro-aggregate contents at the surface soil layer (0–15 cm); however, CTR increased at subsurface soil layer (15–30 cm). It is widely reported that conventional plowing (CTR) has a negative impact on the macro-aggregates at upper soil layer (0–15 cm); however, at subsurface soil (below 15 cm soil layer), CTR results in an increased incorporation of fresh organic material and residue due to tine cultivation depth and efficient litter translocation. These processes can induce microbial activity, produce binding agents, and function as a location for the nucleation of macro-aggregates in deeper soil layers (Luo et al. 2010). Moreover, soil aggregation

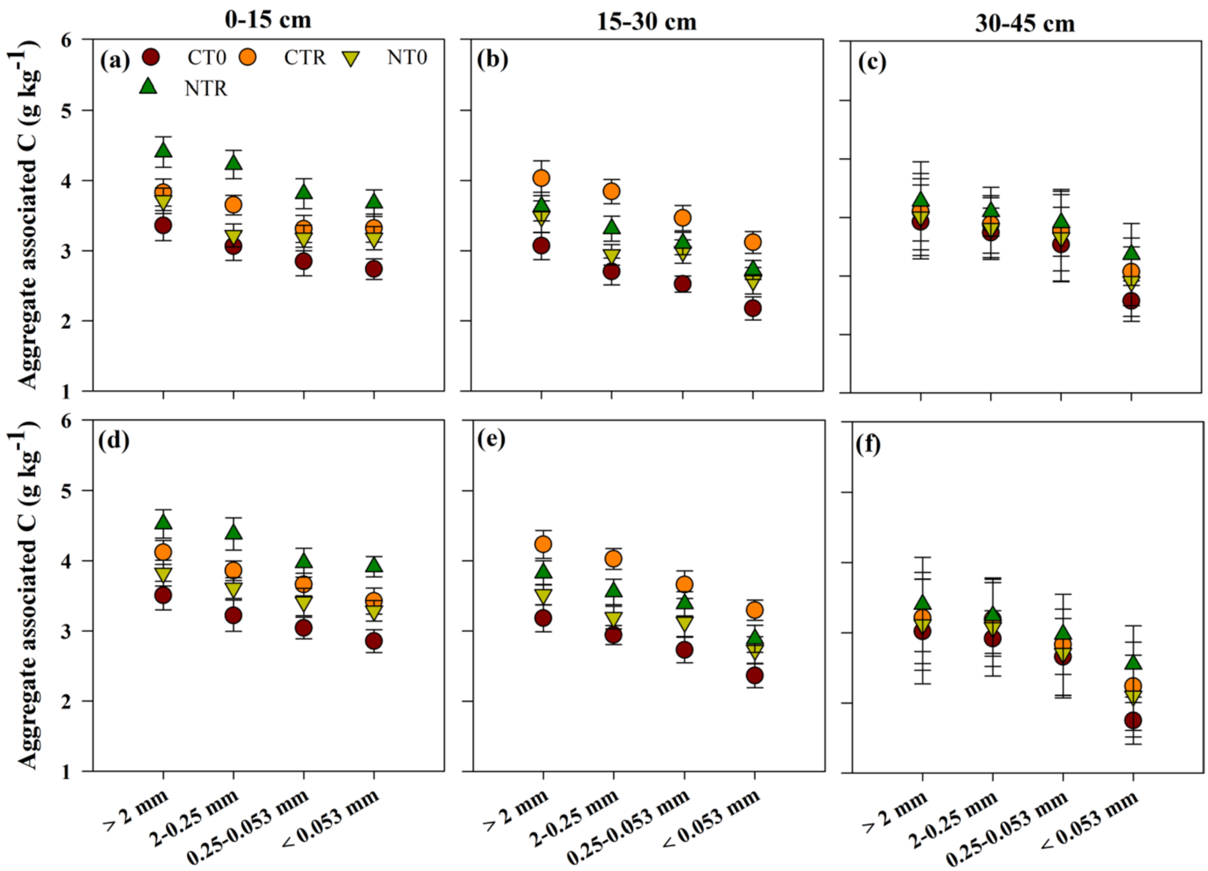

Fig. 3 SOC concentrations (g kg^{-1}) in soil aggregates (> 2 mm, 2–0.25 mm, 0.25–0.053 mm, < 0.053 mm) in rice 2020 (**a**, **b**, **c**) and 2021 (**d**, **e**, **f**) from 0 to 45 cm soil profile under different tillage systems. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR represents direct seeded rice; zero-tilled wheat without/with residue retention. Error bars indicate standard error

was not significantly affected by rice and wheat cropping system. However, the relationship among total C input and soil aggregation was significantly affected by different tillage and residue inputs at different soil depths. For example, residue addition in a paddy season decomposed quickly due to higher microbial activity under continuous water application and release several particle binding agents (particulate carbon) that might contribute in soil aggregation process (Wang et al. 2019). The relationship of total C input with > 2 mm soil aggregation found that C input of NT0, NTR, and CTR increased > 2 mm aggregates at 0–15 cm, while C input of CTR increased > 2 mm at 15–30 cm soil depth. The soil aggregation is mainly driven by particle binding agents and microbial growth such as fungal hyphal network (Hartmann 2022). In the same way, NTR might increase fungal hyphal network under residue retention. In contrast, CTR can break hyphal network due to repeated cultivation and thereby decrease aggregation (Roger-Estrade et al. 2010). Similarly, the higher amount of C derived from decomposed residue significantly promoted aggregate-associated SOC (Huang et al. 2018). Both wheat and rice crops had similar SOC concentration, i.e., higher SOC in macro-aggregates that decreased with decrease in aggregate class size. This trend may be attributed to the fact that macro-aggregate formation comes from particulate organic matter and other residue derived binding agents (Kravchenko et al. 2015; Xue et al. 2019). More importantly, this mechanism could be enhanced under wet field condition coupled with residue addition and minimum tillage (Xue et al. 2019; Zhang et al. 2023). Similar results were reported by Kan et al. (2020a) and Wang et al. (2019) for wheat and rice field of north China plains and southern China, respectively. Some studies have emphasized that long-term conventional tillage practices destroy soil structure mechanically as well as fungal hyphae structure, resulting in lower proportion of macro-aggregates in the field. In addition, results presented herein show that soil stability indicators such as MWD and GMD had higher values under residue return and conservation tillage treatments than those under conventional tillage. Similarly, conservation tillage practices are known to improve soil structure and stability not only in the surface layer, but also in sub-soil, probably due to greater microbial abundance and earthworm

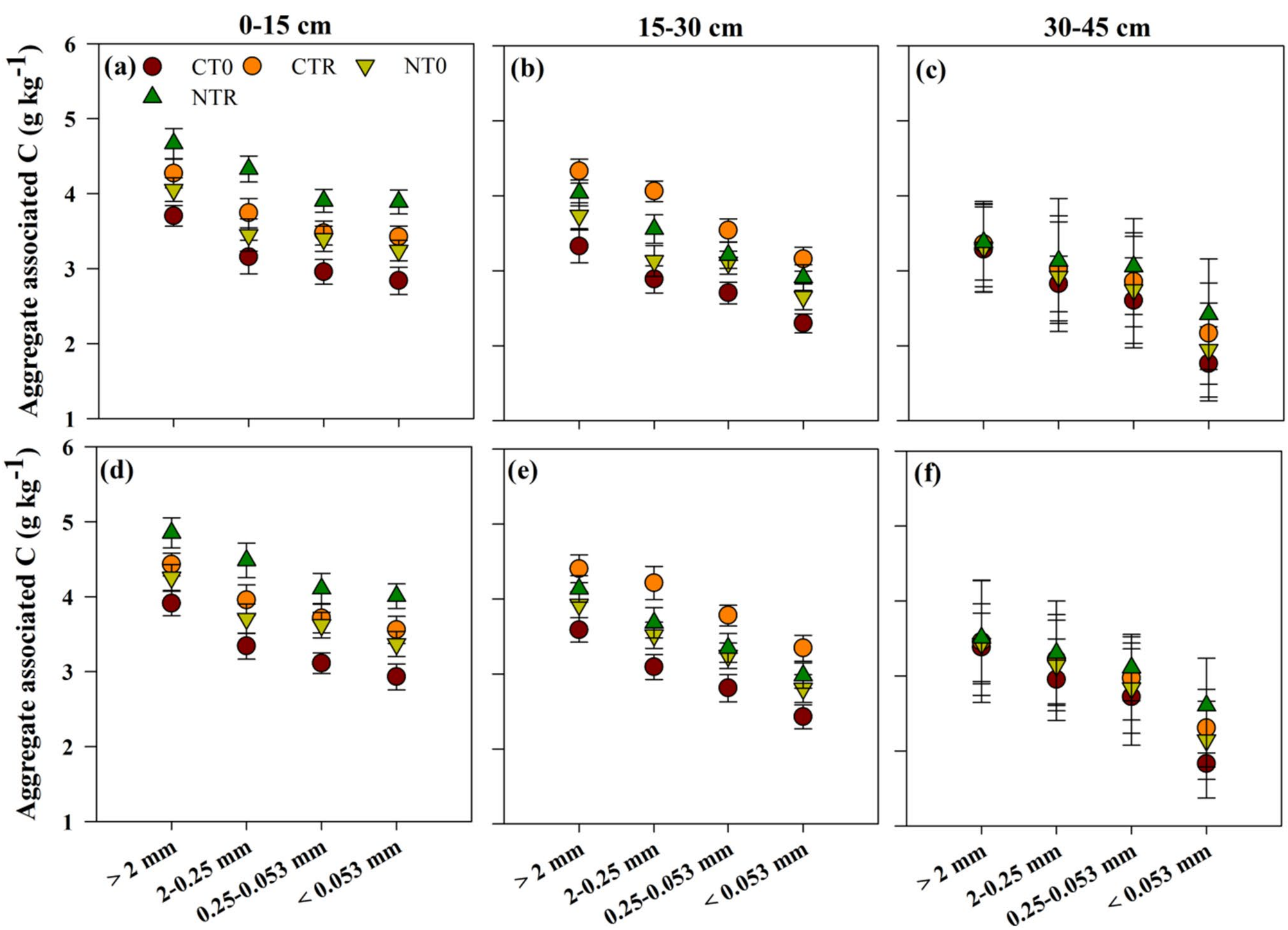

Fig. 4 SOC concentrations (g kg^{-1}) in soil aggregates (> 2 mm, 2–0.25 mm, 0.25–0.053 mm, < 0.053 mm) in wheat 2020 (**a**, **b**, **c**) and 2021 (**d**, **e**, **f**) from 0 to 45 cm soil profile under different tillage systems. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR represents direct seeded rice; zero-tilled wheat without/with residue retention. Error bars indicate standard error

biomass, which greatly contribute to stabilize soil structure (Table 4) (Bhattacharyya et al. 2021).

Soil C mineralization was higher in the aggregates from upper soil layer that decreased with increase in soil depth in both crops. In terms of tillage comparisons, NTR and CTR had higher C mineralization at 0–15 cm soil depth as compared to NT0 and CT0. These results depicted that conservation and conventional tillage systems without residue addition had lower SOC contents that might reduce C mineralization. In contrast, however, NTR and CTR had higher C input in the form of residue, resulting in higher SOC storage and C mineralization (Kan et al. 2020a; He et al. 2023). In fact, C input and loss are a major problem in most regions of the world. Such C sequestration and stabilization could be the main strategy to mitigate climate change (Lal 2004). The cumulative C mineralization was higher in > 2 mm aggregates, suggesting that higher macro-aggregates had relatively higher SOC concentration as compared to micro-aggregates (Kan et al. 2020a). Specifically, the rice season sampled aggregates had relatively higher C mineralization as compared to those obtained during the wheat season in both years. The plausible explanation of this phenomena is that rice crop has continuous or frequent water supply that could decompose crop residue and provide instant material to microbes for processing/oxidation (Qi et al. 2021). Several studies have elaborated that higher concentration of SOC along with organic acids could enhance microbial activities and C oxidation (Zhang et al. 2021). Soil structure is also a major indicator influencing C mineralization, and soil structure is affected by agronomic and tillage management practices (Raiesi and Kabiri 2017; Guo et al. 2019). In general, macro-aggregates had higher C mineralization at 0–15 cm soil depth as compared to 15–30 cm soil depth. This trend shows that macro-aggregates at upper soil depth had higher proportion of C input in the form of crop residue because surface residue application is effective in upper soil layer (Zhang et al. 2022). Another plausible explanation of this result is that the higher proportion of macro-aggregates was

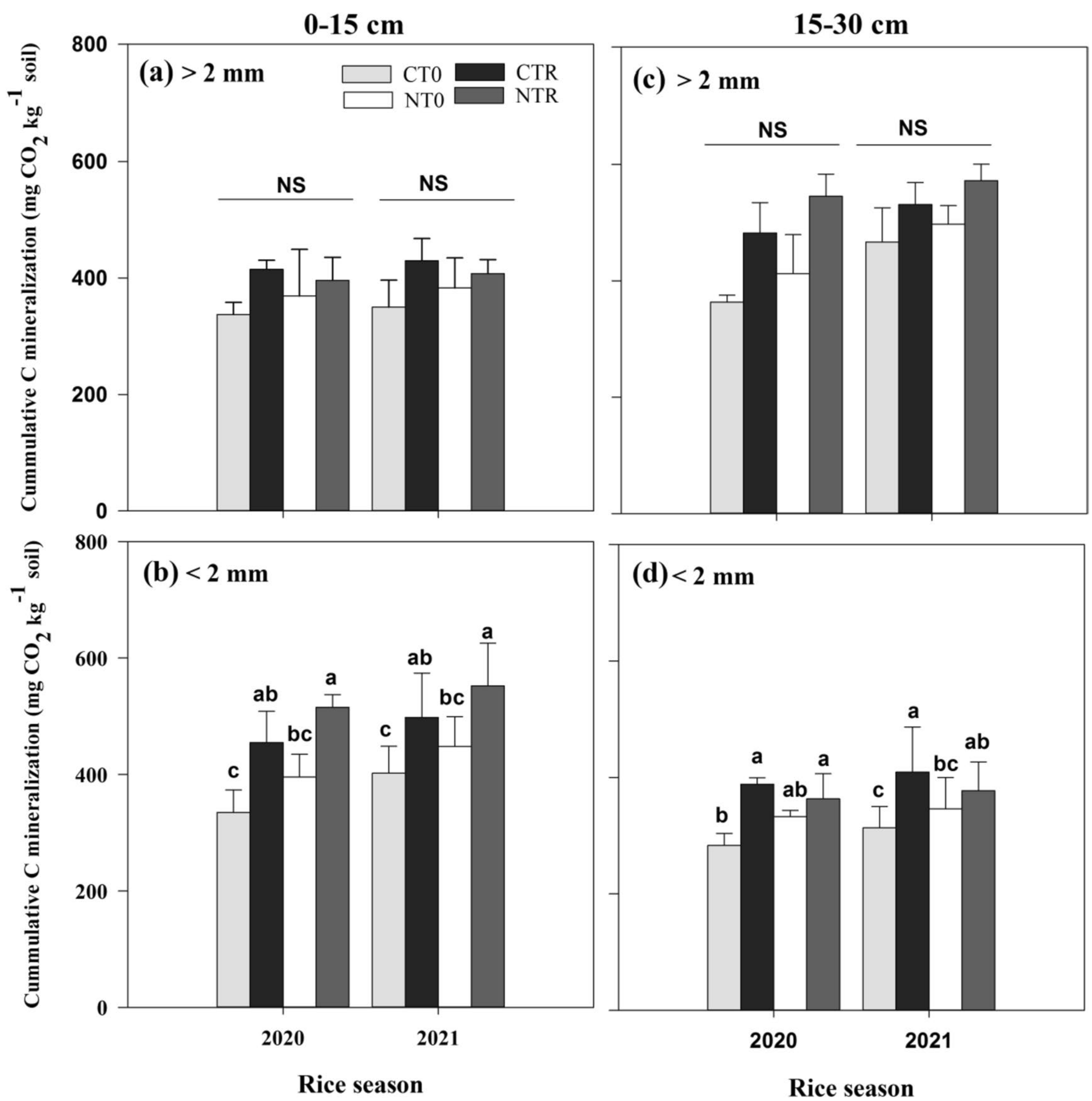

Fig. 5 Cumulative C mineralization rate (mg CO_2 kg^{-1} soil) in soil aggregates > 2 mm (**a**, **c**) (macro-aggregates) and < 2 mm (**b**, **d**) (micro-aggregates) under different tillage practices at 0–15 and 15–30 cm soil profile in rice seasons 2020–2021. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR shows direct seeded rice; zero-tilled wheat without/with residue retention. Different lowercase letters indicate statistical significant difference ($p < 0.05$) among treatments. Error bars indicate standard error. NS, non-significant

present at upper soil layer that decreased with increase in soil depth. Therefore, higher proportion of macro-aggregates contains higher amount of carbon as compared to lower proportion of macro-aggregates (Andruschkewitsch et al. 2014). In addition, residue-added tillage treatments had relatively higher cumulative C mineralization rate as compared to residue removal tillage treatments; this might be due to residue addition and tillage treatment differences (Kan et al. 2020c; Virk et al. 2021). Several studies have reported that plow tillage and no tillage may have higher cumulative C mineralization or oxidation process in the field conditions right after tillage implementation, because continuous application of tillage practices disrupt soil aggregation, exposing physically protected SOC and make it available to microbial oxidation (Kan et al. 2020b; Liu et al. 2022). Despite a higher C mineralization in residue-added tillage treatments, residue addition and conservation agricultural practices can decrease C mineralization potential when comparing with conventional tillage practices (Datta et al. 2019; Kan et al. 2020a). Moreover, conservation tillage practices mostly favor soil structural stability and aggregation, increasing SOC sequestration and stability as compared to conventional tillage practices (He et al. 2023). Kan et al. (2020a) and Qi et al. (2021) also reported that SOC mineralizability (mg of oxidize CO_2 per g of SOC) is another important indicator to evaluate the SOC stabilization in bulk soil or aggregates,

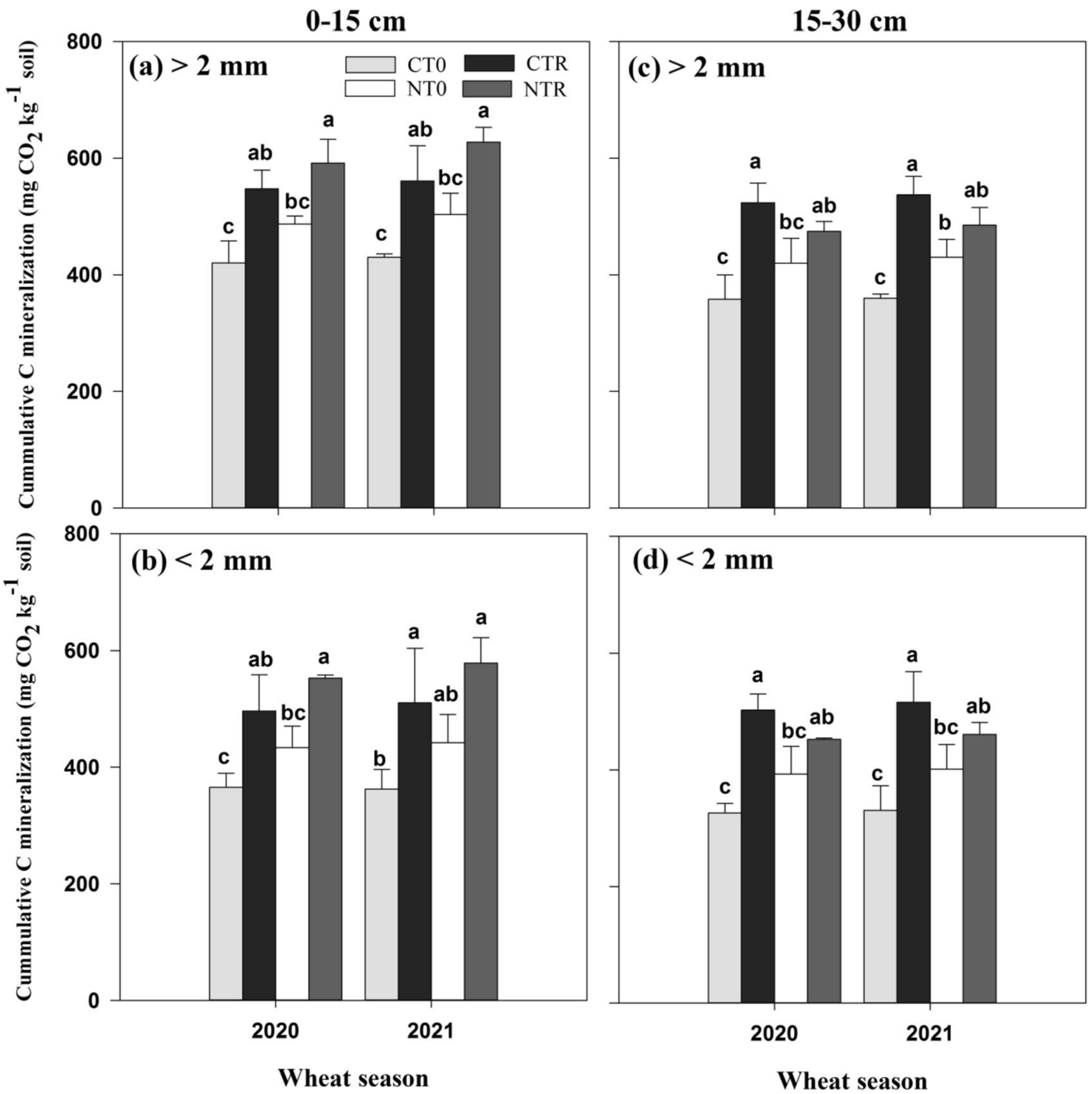

Fig. 6 Cumulative C mineralization (mg CO_2 kg^{-1} soil) in soil aggregates > 2 mm (**a**, **c**) (macro-aggregates) and < 2 mm (**b**, **d**) (micro-aggregates) under different tillage practices at 0–15 and 15–30 cm soil profile in wheat 2020–2021. CT0/CTR indicates puddled rice; conventional wheat without/with residue retention. NT0/NTR shows direct seeded rice; zero-tilled wheat without/with residue retention. Lowercase letters shows statistical significant difference ($p < 0.05$) among treatments. Error bars indicate standard error

which have been lower in conservation agricultural practices (Duan et al. 2022).

Globally, conservation tillage has been covered 122–215 M ha of the land area, due to its ability to store C (Lal 2004; Prestele et al. 2018). Conservation tillage significantly influences the aggregate size distribution and aggregate-associated SOC concentration, compared to conventional tillage. However, it is not well-known how SOC sequestered in various aggregates (Zhao et al. 2015). Our results signify that no tillage with residue retention increased the SOC accumulation while decreased the mineralization in macro-aggregates. Briefly, this study demonstrated the importance of macro-aggregates encapsulating SOC, thus improving soil quality under NTR. Nevertheless, the mineralization of SOC under field conditions cannot be evaluated; therefore, laboratory incubation is necessary to estimate the mineralization rate in different aggregates. In comparison to our results, others studies also reported higher macro-aggregate fraction and aggregate-associated C under conservation tillage compared to conventional tillage in the North China Plain (Zhang et al. 2017; Gao et al. 2019). Furthermore, the macro-aggregates and associated C were increased under conservation tillage in many parts of the world, e.g., Spain (Hontoria et al. 2016), France (Bottinelli et al. 2017), and India (Somasundaram et al. 2017, 2018). On contrary, conservation tillage did not enhance macro-aggregates and associated C stock compared to conventional tillage in Western Australia (Sarker et al. 2018a). Thus, it is suggested that conservation tillage would

Table 3 Parameters of first-order exponential equations describing the C mineralization rate (mg CO_2–C kg^{-1} day^{-1}) in macro- (> 2 mm) and micro-aggregates (< 2 mm) from 0 to 30 cm soil profile under different tillage system

Season	Treatment	0–15 cm			15–30 cm		
		Mineralization constant (K)	C mineralization rate (mg CO_2–C kg^{-1} day^{-1})	R^{2*}	Mineralization constant (K)	C mineralization rate (mg CO_2–C kg^{-1} day^{-1})	R^{2*}
Rice 2020 > 2 mm	CT0	0.0168	11.49 ± 0.39	0.978	0.0167	10.96 ± 0.38	0.977
	CTR	0.0163	16.40 ± 0.60	0.976	0.0166	13.50 ± 0.47	0.977
	NT0	0.0163	13.48 ± 0.47	0.977	0.0166	12.05 ± 0.42	0.977
	NTR	0.0161	18.99 ± 0.72	0.975	0.0167	12.97 ± 0.46	0.977
Rice 2020 < 2 mm	CT0	0.0171	10.43 ± 0.35	0.978	0.0167	9.19 ± 0.32	0.977
	CTR	0.0170	15.62 ± 0.58	0.974	0.0166	12.60 ± 0.44	0.977
	NT0	0.0169	13.06 ± 0.47	0.976	0.0167	10.88 ± 0.38	0.977
	NTR	0.0164	17.88 ± 0.67	0.975	0.0166	11.74 ± 0.41	0.977
Rice 2021 > 2 mm	CT0	0.0164	15.68 ± 0.57	0.98	0.0164	11.30 ± 0.39	0.977
	CTR	0.0162	18.12 ± 0.67	0.975	0.0165	14.10 ± 0.50	0.977
	NT0	0.0165	16.98 ± 0.63	0.975	0.0167	12.55 ± 0.44	0.977
	NTR	0.0159	20.47 ± 0.79	0.974	0.0168	13.35 ± 0.47	0.977
Rice 2021 < 2 mm	CT0	0.0167	13.86 ± 0.52	0.975	0.0168	10.25 ± 0.36	0.977
	CTR	0.0164	17.45 ± 0.66	0.974	0.0166	13.48 ± 0.48	0.976
	NT0	0.0167	15.59 ± 0.59	0.974	0.0166	11.30 ± 0.40	0.977
	NTR	0.0158	19.70 ± 0.76	0.974	0.0166	12.22 ± 0.43	0.977
Wheat 2020 > 2 mm	CT0	0.0169	13.02 ± 0.43	0.978	0.0165	10.77 ± 0.35	0.98
	CTR	0.0166	18.52 ± 0.68	0.975	0.0164	18.43 ± 0.71	0.974
	NT0	0.0167	15.87 ± 0.56	0.977	0.0167	13.71 ± 0.48	0.977
	NTR	0.0164	20.49 ± 0.77	0.975	0.0166	16.25 ± 0.60	0.975
Wheat 2020 < 2 mm	CT0	0.0161	11.16 ± 0.36	0.979	0.0166	9.78 ± 0.32	0.98
	CTR	0.0165	16.85 ± 0.62	0.975	0.0166	17.83 ± 0.69	0.974
	NT0	0.0167	14.13 ± 0.50	0.977	0.0167	12.83 ± 0.45	0.977
	NTR	0.0163	19.31 ± 0.73	0.975	0.0167	15.48 ± 0.57	0.975
Wheat 2021 > 2 mm	CT0	0.0165	12.98 ± 0.42	0.979	0.0167	10.95 ± 0.36	0.979
	CTR	0.0165	18.96 ± 0.69	0.976	0.1637	18.79 ± 0.71	0.975
	NT0	0.0167	16.49 ± 0.58	0.977	0.0167	14.07 ± 0.49	0.977
	NTR	0.0169	23.59 ± 0.97	0.971	0.0166	16.47 ± 0.61	0.975
Wheat 2021 < 2 mm	CT0	0.0171	10.96 ± 0.36	0.979	0.0168	9.99 ± 0.32	0.979
	CTR	0.0162	16.99 ± 0.61	0.976	0.0164	18.12 ± 0.69	0.974
	NT0	0.0167	14.44 ± 0.51	0.977	0.0166	12.96 ± 0.45	0.977
	NTR	0.0163	20.47 ± 0.78	0.974	0.0165	15.60 ± 0.57	0.976

CT0/*CTR* shows puddled rice; conventional wheat without/with residue returning. *NT0*/*NTR* shows direct seeded rice; zero-tilled wheat without/with residue returning

be a viable option to enhance macro-aggregation and associated C stock in most regions of the world.

A field experiment and laboratory-based incubation in various aggregates by using dry sieving were combined to reveal the mechanism of aggregate formation and C sequestration under different tillage systems. Prior studies also showed that C mineralization (from laboratory incubation) and C loss (from field based experiment) were correlated

Table 4 Correlation analysis between total C input and soil aggregate fractions under different tillage practices and soil layers in rice–wheat cropping system

	0–15 cm				15–30 cm				30–45 cm			
Rice	> 2	2–0.25	0.25–0.053	< 0.053	> 2	2–0.25	0.25–0.053	< 0.053	> 2	2–0.25	0.25–0.053	< 0.053
CT0	0.75	0.95*	0.79	0.80	0.88*	0.83*	0.84*	0.98*	0.74*	0.98*	0.91*	0.79
CTR	0.63	0.88*	0.83*	0.81*	0.76	0.94*	0.69	0.68	0.61	0.90*	0.70	0.70
NT0	0.94*	0.88*	0.94*	0.89*	0.26	0.92*	0.75	0.83*	0.60	0.78	0.77	0.71
NTR	0.81	−0.97*	0.65	0.84*	0.80	0.73	0.91*	0.93*	0.75	0.92*	0.49	0.79
Wheat												
CT0	0.81	0.90*	0.82*	0.96*	0.86*	0.84*	0.87*	0.79	0.87*	0.77	0.80	0.75
CTR	0.92*	0.92*	0.87*	1.00*	0.73	0.75	0.79	0.90*	0.84*	0.92*	0.89*	−0.018
NT0	0.83*	0.85*	0.96*	0.99*	0.60	0.95*	0.79	0.79	0.82*	0.90*	0.98*	0.78
NTR	0.86*	0.91*	0.93*	0.45	0.74	0.77	0.80	0.90*	0.75	0.80	0.93*	0.88*

CT0/*CTR* shows puddled rice; conventional wheat without/with residue returning. *NT0*/*NTR* shows direct seeded rice; zero-tilled wheat without/with residue returning. * indicates $p \leq 0.05$

(Sierra and Desfontaines 2018). However, the environmental variables (moisture and temperature) can considerably influence SOC accumulation and mineralization in aggregates (Qi et al. 2019). Moreover, this study exhibits certain drawbacks regarding dry sieving of soil. Unlike wet sieving, clods could not dispersed naturally during dry sieving, and we used external hand force to break the big clods by visualizing their natural breaks points. In this study, the laboratory incubation of SOC mineralization was performed under a constant moisture and temperature. Future studies are needed to examine how laboratory incubation of SOC mineralization responds to environmental elements (e.g., varying moisture and temperature conditions) under different tillage practices.

5 Conclusions

The study proved the hypothesis that the retention of crop residues under no tillage (NTR) increases the macro-aggregate fraction (> 2 mm) and soil organic carbon (SOC) content in macro-aggregates in a rice–wheat double cropping system. In specific, higher proportion of macro-aggregate fraction was obtained under NTR, which were considerably greater than CTR (conventional tillage with residue return), NT0 (no tillage without residues), and CT0 (conventional tillage without residues) in rice and wheat season, respectively by 7%, 7.9%, and 17.2% and by 5.8%, 6.9%, and 12.1% at 0–15 cm soil layer. Subsequently, higher aggregate-associated SOC was accumulated at 0–15 cm soil layer in macro-aggregates under NTR, compared to other treatments, which considerably improved the soil structural stability. The relationship of total carbon input with soil aggregation (mainly > 2 mm) followed the pattern of NT0 > NTR > CTR > CT0 at 15–30 cm soil depth. The macro-aggregates under NTR resulted in the highest cumulative carbon mineralization rate at 0–15 cm; however, CTR enhanced the cumulative carbon mineralization at 15–30 cm depth. Overall, it is concluded that NTR is an effective management practice to improve the macro-aggregation, soil structural stability, and SOC contents in a rice–wheat double cropping system. However, further research about microbial contribution in soil aggregation and SOC mineralization should be explored in conservation agricultural practices.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-023-01555-2.

Acknowledgements We are thankful to the Chinese Scholarship Funding Agency (CSC No. 2019SLJ018944) and the Northwest A&F University for granting study support. We are thankful to the management and staff of Sukheki Farm for research trial execution, sampling, and cooperation. We are grateful to the Dr. Abdul Qadeer Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan, for their kind guidance throughout the research.

Author Contributions N.A.: conceptualization, methodology, formal analysis, data curation, and writing, original draft. A.L.V.: methodology, formal analysis, data curation, review, and editing. M.B.H. and H.M.W.I.: methodology, data curation, and investigation. Z.R.K.: writing, review, and editing. Z.S.: writing, review, and editing. R.W.: writing, review, and editing. M.I.A.R.: conceptualization; supervision; writing, review and editing; and project administration. X.W.: conceptualization; supervision; writing, review and editing; and project administration. R.L.: substantial editing and reviewing. J.L.: conceptualization; supervision; writing, review and editing; and project administration.

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

Declarations

Competing Interests The authors declare no competing interests.

References

Alam K, Islam M, Salahin N, Hasanuzzaman M (2014) Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping. Sci World J 2014:1–15

Álvaro-Fuentes J, Arrúe JL, Cantero-Martínez C, López MV (2008a) Aggregate breakdown during tillage in a Mediterranean loamy soil. Soil Tillage Res 101:62–68. https://doi.org/10.1016/J.STILL.2008.06.004

Álvaro-Fuentes J, Arrúe JL, Gracia R, López MV (2008b) Tillage and cropping intensification effects on soil aggregation: temporal dynamics and controlling factors under semiarid conditions. Geoderma 145:390–396. https://doi.org/10.1016/J.GEODERMA.2008.04.005

Andruschkewitsch R, Koch HJ, Ludwig B (2014) Effect of long-term tillage treatments on the temporal dynamics of water-stable aggregates and on macro-aggregate turnover at three German sites. Geoderma 217–218:57–64. https://doi.org/10.1016/J.GEODERMA.2013.10.022

Bhattacharyya R, Rabbi SMF, Zhang Y, Young IM, Jones AR, Dennis PG, Menzies NW, Kopittke PM, Dalal RC (2021) Soil organic carbon is significantly associated with the pore geometry, microbial diversity and enzyme activity of the macro-aggregates under different land uses. Sci Total Environ 778:146286. https://doi.org/10.1016/J.SCITOTENV.2021.146286

Bhattacharyya R, Tuti MD, Kundu S, Bisht JK, Bhatt JC (2012) Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. Soil Sci Soc Am J 76:617–627. https://doi.org/10.2136/SSSAJ2011.0320

Bottinelli N, Angers DA, Hallaire V, Michot D, Le Guillou C, Cluzeau D, Heddadj D, Menasseri-Aubry S (2017) Tillage and fertilization practices affect soil aggregate stability in a Humic Cambisol of Northwest France. Soil Tillage Res 170:14–17. https://doi.org/10.1016/J.STILL.2017.02.008

Cai A, Xu H, Shao X, Zhu P, Zhang W, Xu M, Murphy DV (2016) Carbon and nitrogen mineralization in relation to soil particle-size fractions after 32 years of chemical and manure application in a continuous maize cropping system. PLoS One 11:e0152521. https://doi.org/10.1371/JOURNAL.PONE.0152521

Carlson KM, Gerber JS, Mueller ND, Herrero M, MacDonald GK, Brauman KA, Havlik P, O'Connell CS, Johnson JA, Saatchi S, West PC (2016) Greenhouse gas emissions intensity of global croplands. Nat Clim Chang 71(7):63–68. https://doi.org/10.1038/nclimate3158

Chen L, Shi XZ, Xu SX, Yu DS, Wang YH, Song ZS, Wang MY (2014) Rice root biomass forecasting model based on leaf area index. Soils 46:862–868

Das S, Richards BK, Hanley KL, Krounbi L, Walter MF, Walter MT, Steenhuis TS, Lehmann J (2019) Lower mineralizability of soil carbon with higher legacy soil moisture. Soil Biol Biochem 130:94–104. https://doi.org/10.1016/J.SOILBIO.2018.12.006

Datta A, Jat HS, Yadav AK, Choudhary M, Sharma PC, Rai M, Singh LK, Majumder SP, Choudhary V, Jat ML (2019) Carbon mineralization in soil as influenced by crop residue type and placement in an Alfisols of Northwest India. Carbon Manag 10:37–50. https://doi.org/10.1080/17583004.2018.1544830

Duan H, Cheng J, Han M, Zhang H (2022) Effect of tillage and residue-returning mode on soil carbon mineralizability and accumulation in a wheat–maize system. Agron 12(12):1442. https://doi.org/10.3390/AGRONOMY12061442

FAO (2014) World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. https://www.fao.org/3/i3794en/I3794en.pdf

Fernández R, Quiroga A, Zorati C, Noellemeyer E (2010) Carbon contents and respiration rates of aggregate size fractions under no-till and conventional tillage. Soil Tillage Res 109:103–109. https://doi.org/10.1016/J.STILL.2010.05.002

Gao L, Wang B, Li S, Wu H, Wu X, Liang G, Gong D, Zhang X, Cai D, Degré A (2019) Soil wet aggregate distribution and pore size distribution under different tillage systems after 16 years in the Loess Plateau of China. CATENA 173:38–47. https://doi.org/10.1016/J.CATENA.2018.09.043

Gelaw AM, Singh BR, Lal R (2015) Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. L Degrad Dev 26:690–700. https://doi.org/10.1002/LDR.2261

Gunina A, Kuzyakov Y (2014) Pathways of litter C by formation of aggregates and SOM density fractions: implications from 13C natural abundance. Soil Biol Biochem 71:95–104. https://doi.org/10.1016/J.SOILBIO.2014.01.011

Guo Y, Liang A, Zhang Y, Zhang S, Chen X, Jia S, Zhang X, Wu D (2019) Evaluating the contributions of earthworms to soil organic carbon decomposition under different tillage practices combined with straw additions. Ecol Indic 105:516–524. https://doi.org/10.1016/J.ECOLIND.2018.04.046

Hartmann M (2022) Six J (2022) Soil structure and microbiome functions in agroecosystems. Nat Rev Earth Environ 41(4):4–18. https://doi.org/10.1038/s43017-022-00366-w

He C, Chen Z, Qiu KY, Chen JS, Bohoussou YND, Dang YP, Zhang HL (2023) Effects of conservation agriculture on carbon mineralization: a global meta-analysis. Soil Tillage Res 229:105685. https://doi.org/10.1016/J.STILL.2023.105685

Hontoria C, Gómez-Paccard C, Mariscal-Sancho I, Benito M, Pérez J, Espejo R (2016) Aggregate size distribution and associated organic C and N under different tillage systems and Ca-amendment in a degraded Ultisol. Soil Tillage Res 160:42–52. https://doi.org/10.1016/J.STILL.2016.01.003

Huang M, Zou Y, Feng Y, Cheng Z, Mo Y, Ibrahim M, Xia B, Jiang P (2011) No-tillage and direct seeding for super hybrid rice production in rice-oilseed rape cropping system. Eur J Agron 34:278–286. https://doi.org/10.1016/j.eja.2011.02.005

Huang R, Tian D, Liu J, Lv S, He X, Gao M (2018) Responses of soil carbon pool and soil aggregates associated organic carbon to straw and straw-derived biochar addition in a dryland cropping mesocosm system. Agric Ecosyst Environ 265:576–586. https://doi.org/10.1016/J.AGEE.2018.07.013

IPCC (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, K.S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Cambridge University Press: Cambridge. https://www.cambridge.org/core/books/climate-change-2013-the-physical-science-basis/BE9453E500DEF3640B383BADDC332C3E

IPCC (2018) Global Warming of 1.5 °C. world meteorological organization, Geneva, Switzerland. Geneva. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf

Jacobs A, Helfrich M, Hanisch S, Quendt U, Rauber R, Ludwig B (2010) Effect of conventional and minimum tillage on physical and biochemical stabilization of soil organic matter. Biol Fertil

Soils 46:671–680. https://doi.org/10.1007/S00374-010-0472-X/FIGURES/4

Johnson JMF, Allmaras RR, Reicosky DC (2006) Estimating source carbon from crop residues, roots and rhizodeposits using the National Grain-Yield Database. Agron J 98:622–636. https://doi.org/10.2134/AGRONJ2005.0179

Kan ZR, Ma ST, Liu QY, Liu BY, Virk AL, Qi JY, Zhao X, Lal R, Zhang HL (2020a) Carbon sequestration and mineralization in soil aggregates under long-term conservation tillage in the North China Plain. CATENA 188:104428. https://doi.org/10.1016/J.CATENA.2019.104428

Kan ZR, Virk AL, He C, Liu QY, Qi JY, Dang YP, Zhao X, Zhang HL (2020b) Characteristics of carbon mineralization and accumulation under long-term conservation tillage. CATENA 193:104636. https://doi.org/10.1016/J.CATENA.2020.104636

Kan ZR, Virk AL, Wu G, Qi JY, Ma ST, Wang X, Zhao X, Lal R, Zhang HL (2020c) Priming effect intensity of soil organic carbon mineralization under no-till and residue retention. Appl Soil Ecol 147:103445. https://doi.org/10.1016/J.APSOIL.2019.103445

Kong AYY, Six J, Bryant DC, Denison RF, van Kessel C (2005) The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci Soc Am J 69:1078–1085. https://doi.org/10.2136/SSSAJ2004.0215

Kravchenko AN, Negassa WC, Guber AK, Rivers ML (2015) Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics. Sci Reports 51(5):1–10. https://doi.org/10.1038/srep16261

Kumar M, Kundu DK, Ghorai AK, Mitra S, Singh SR (2018) Carbon and nitrogen mineralization kinetics as influenced by diversified cropping systems and residue incorporation in Inceptisols of eastern Indo-Gangetic Plain. Soil Tillage Res 178:108–117. https://doi.org/10.1016/J.STILL.2017.12.025

Ladha JK, Dawe D, Pathak H et al (2003) How extensive are yield declines in long-term rice–wheat experiments in Asia? F Crop Res 81:159–180. https://doi.org/10.1016/S0378-4290(02)00219-8

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science (80-) 304:1623–1627. https://doi.org/10.1126/SCIENCE.1097396/SUPPL_FILE/LAL.SOM.PDF

Lal R (2016) Beyond COP 21: potential and challenges of the "4 per Thousand" initiative. J Soil Water Conserv 71:20A–25A. https://doi.org/10.2489/JSWC.71.1.20A

Liu X, Li Q, Tan S, Wu X, Song X, Gao H, Han Z, Jia A, Liang G, Li S (2022) Evaluation of carbon mineralization and its temperature sensitivity in different soil aggregates and moisture regimes: a 21-year tillage experiment. Sci Total Environ 837:155566. https://doi.org/10.1016/J.SCITOTENV.2022.155566

Luo Z, Wang E, Sun OJ (2010) Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric Ecosyst Environ 139:224–231. https://doi.org/10.1016/J.AGEE.2010.08.006

Maillard É, McConkey BG, St. Luce M, Angers DA, Fan J (2018) Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada. Soil Tillage Res 177:97–104. https://doi.org/10.1016/J.STILL.2017.12.001

Mairhofer F, Barta N, Euteneuer P, Schuster J, Bauer A, Gronauer A (2019) Influence of tillage depth of a cultivator on the incorporation of crop residues of winter barley in a chernozem soil. Die Bodenkultur J L Manag Food Environ 70:69–79. https://doi.org/10.2478/boku-2019-0006

Malhi SS, Moulin AP, Johnston AM, Kutcher HR (2011) Short-term and long-term effects of tillage and crop rotation on soil physical properties, organic C and N in a Black Chernozem in northeastern Saskatchewan. Can J Soil Sci 88:273–282. https://doi.org/10.4141/CJSS07062

Mamta SS, Kumar R, Bairwa R, Meena P, Meena MC (2022) Assessment of carbon pools and stability of soil aggregates in Inceptisols of Indo-Gangetic plains as influenced by seven-year continuous tillage practices under maize-based cropping system. Commun Soil Sci Plant Anal 54:544–558. https://doi.org/10.1080/00103624.2022.2118298

Meng Q, Sun Y, Zhao J, Zhou L, Ma X, Zhou M, Gao W, Wang G (2014) Distribution of carbon and nitrogen in water-stable aggregates and soil stability under long-term manure application in solonetzic soils of the Songnen plain, northeast China. J Soils Sediments 14:1041–1049. https://doi.org/10.1007/S11368-014-0859-7/TABLES/4

Pirmoradian N, Sepaskhah AR, Hajabbasi MA (2005) Application of fractal theory to quantify soil aggregate stability as influenced by tillage treatments. Biosyst Eng 90:227–234. https://doi.org/10.1016/J.BIOSYSTEMSENG.2004.11.002

Prestele R, Hirsch AL, Davin EL, Seneviratne SI, Verburg PH (2018) A spatially explicit representation of conservation agriculture for application in global change studies. Glob Chang Biol 24:4038–4053. https://doi.org/10.1111/GCB.14307

Qi JY, Jing ZH, He C, Liu QY, Wang X, Kan ZR, Zhao X, Xiao XP, Zhang HL (2021) Effects of tillage management on soil carbon decomposition and its relationship with soil chemistry properties in rice paddy fields. J Environ Manage 279:111595. https://doi.org/10.1016/J.JENVMAN.2020.111595

Qi JY, Wang X, Zhao X, Pu C, Kan ZR, Li C, Liu P, Xiao XP, Lal R, Zhang HL (2019) Temporal variability of soil organic carbon in paddies during 13-year conservation tillage. L Degrad Dev 30:1840–1850. https://doi.org/10.1002/LDR.3384

Rabbi SMF, Wilson BR, Lockwood PV, Daniel H, Young IM (2014) Soil organic carbon mineralization rates in aggregates under contrasting land uses. Geoderma 216:10–18. https://doi.org/10.1016/J.GEODERMA.2013.10.023

Raiesi F, Kabiri V (2017) Carbon and nitrogen mineralization kinetics as affected by tillage systems in a calcareous loam soil. Ecol Eng 106:24–34. https://doi.org/10.1016/J.ECOLENG.2017.05.023

Roger-Estrade J, Anger C, Bertrand M, Richard G (2010) Tillage and soil ecology: partners for sustainable agriculture. Soil Tillage Res 111:33–40. https://doi.org/10.1016/J.STILL.2010.08.010

Sarker JR, Singh BP, Cowie AL, Fang Y, Collins D, Badgery W, Dalal RC (2018a) Agricultural management practices impacted carbon and nutrient concentrations in soil aggregates, with minimal influence on aggregate stability and total carbon and nutrient stocks in contrasting soils. Soil Tillage Res 178:209–223. https://doi.org/10.1016/J.STILL.2017.12.019

Sarker JR, Singh BP, Cowie AL, Fang Y, Collins D, Dougherty WJ, Singh BK (2018b) Carbon and nutrient mineralisation dynamics in aggregate-size classes from different tillage systems after input of canola and wheat residues. Soil Biol Biochem 116:22–38. https://doi.org/10.1016/J.SOILBIO.2017.09.030

Shahbaz M, Kuzyakov Y, Heitkamp F (2017) Decrease of soil organic matter stabilization with increasing inputs: mechanisms and controls. Geoderma 304:76–82. https://doi.org/10.1016/J.GEODERMA.2016.05.019

Sierra J, Desfontaines L (2018) Predicting the in situ rate constant of soil carbon mineralisation from laboratory-based measurements in tropical soils under contrasting tillage management systems. Soil Tillage Res 180:175–181. https://doi.org/10.1016/J.STILL.2018.03.008

Singh A, Phogat VK, Dahiya R, Batra SD (2014) Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice-wheat cropping system. Soil Tillage Res 140:98–105. https://doi.org/10.1016/j.still.2014.03.002

Somasundaram J, Chaudhary RS, Awanish Kumar D, Biswas AK, Sinha NK, Mohanty M, Hati KM, Jha P, Sankar M, Patra AK, Dalal R, Chaudhari SK (2018) Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols. Eur J Soil Sci 69:879–891. https://doi.org/10.1111/EJSS.12692

Somasundaram J, Reeves S, Wang W, Heenan M, Dalal R (2017) Impact of 47 years of no tillage and stubble retention on soil aggregation and carbon distribution in a Vertisol. L Degrad Dev 28:1589–1602. https://doi.org/10.1002/LDR.2689

Spohn M, Giani L (2010) Water-stable aggregates, glomalin-related soil protein, and carbohydrates in a chronosequence of sandy hydromorphic soils. Soil Biol Biochem 42:1505–1511. https://doi.org/10.1016/J.SOILBIO.2010.05.015

Verhulst N, Kienle F, Sayre KD, Deckers J, Raes D, Limon-Ortega A, Tijerina-Chavez L, Govaerts B (2011) Soil quality as affected by tillage-residue management in a wheat-maize irrigated bed planting system. Plant Soil 340:453–466. https://doi.org/10.1007/S11104-010-0618-5/METRICS

Virk AL, Kan ZR, Liu BY, Qi JY, He C, Liu QY, Zhao X, Zhang HL (2021) Impact of biochar water extract addition on soil organic carbon mineralization and C fractions in different tillage systems. Environ Technol Innov 21:101193. https://doi.org/10.1016/J.ETI.2020.101193

Walkley A, Black I (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Wang X, Qi JY, Zhang XZ, Li SS, Latif Virk A, Zhao X, Xiao XP, Zhang HL (2019) Effects of tillage and residue management on soil aggregates and associated carbon storage in a double paddy cropping system. Soil Tillage Res 194:104339. https://doi.org/10.1016/J.STILL.2019.104339

Weidhuner A, Hanauer A, Krausz R, Crittenden SJ, Gage K, Sadeghpour A (2021) Tillage impacts on soil aggregation and aggregate-associated carbon and nitrogen after 49 years. Soil Tillage Res 208:104878. https://doi.org/10.1016/J.STILL.2020.104878

Xie J, Hou M, Zhou Y, Wang R, Zhang S, Yang X, Sun B (2017) Carbon sequestration and mineralization of aggregate-associated carbon in an intensively cultivated Anthrosol in north China as affected by long term fertilization. Geoderma 296:1–9. https://doi.org/10.1016/J.GEODERMA.2017.02.023

Xue B, Huang L, Huang Y, Yin Z, Li X, Lu J (2019) Effects of organic carbon and iron oxides on soil aggregate stability under different tillage systems in a rice–rape cropping system. CATENA 177:1–12. https://doi.org/10.1016/J.CATENA.2019.01.035

Yang H, Ciais P, Frappart F, Li X, Brandt M, Fensholt R, Fan L, Saatchi S, Besnard S, Deng Z, Bowring S, Wigneron JP (2023) Global increase in biomass carbon stock dominated by growth of northern young forests over past decade. Nat Geosci 16:886–892. https://doi.org/10.1038/s41561-023-01274-4

Zhang G, Zhao Z, Yin XA, Zhu Y (2021) Impacts of biochars on bacterial community shifts and biodegradation of antibiotics in an agricultural soil during short-term incubation. Sci Total Environ 771:144751. https://doi.org/10.1016/J.SCITOTENV.2020.144751

Zhang X, Wang M, Zhang D, Zhang Y, Wang X (2022) Increasing soil organic carbon pools and wheat yields by optimising tillage and fertilisation on the Loess Plateau in China. Eur J Soil Sci 73:e13197. https://doi.org/10.1111/EJSS.13197

Zhang X, Xin X, Zhu A, Zhang J, Yang W (2017) Effects of tillage and residue managements on organic C accumulation and soil aggregation in a sandy loam soil of the North China Plain. CATENA 156:176–183. https://doi.org/10.1016/J.CATENA.2017.04.012

Zhang X, Shen S, Xue S, Hu Y, Wang X (2023) Long-term tillage and cropping systems affect soil organic carbon components and mineralization in aggregates in semiarid regions. Soil Tillage Res 231:105742. https://doi.org/10.1016/J.STILL.2023.105742

Zhao X, Zhang R, Xue JF, Pu C, Zhang XQ, Liu SL, Chen F, Lal R, Zhang HL (2015) Management-induced changes to soil organic carbon in China: a meta-analysis. Adv Agron 134:1–50. https://doi.org/10.1016/BS.AGRON.2015.06.002

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.