agriculture

MDPI

*Article*

# Conservation Agricultural Practices Impact on Soil Organic Carbon, Soil Aggregation and Greenhouse Gas Emission in a Vertisol

**Somasundaram Jayaraman [1,*], Meenakshi Sahu [1,2], Nishant K. Sinha [1], Monoranjan Mohanty [1], Ranjeet S. Chaudhary [1], Brijesh Yadav [3], Lalit K. Srivastava [2], Kuntal M. Hati [1], Ashok K. Patra [1] and Ram C. Dalal [4]**

1 ICAR–Indian Institute of Soil Science, Berasia Road, Nabibagh, Bhopal 462038, India; meenakshisahu1822@gmail.com (M.S.); nishant.sinha@icar.gov.in (N.K.S.); manoranjan.mohanty@icar.gov.in (M.M.); ranjeet.chaudhary@icar.gov.in (R.S.C.); kuntal.hati@icar.gov.in (K.M.H.); ashok.patra@icar.gov.in (A.K.P.)
2 Department of Soil Science and Agricultural Chemistry, Indira Gandhi Krishi Vishwa Vidyalaya, Raipur 492012, India; srivastavalalit9@gmail.com
3 ICAR–Directorate of Mushroom Research, Chambaghat, Solan 173213, India; brijesh.yadav@icar.gov.in
4 School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Brisbane, QLD 4072, Australia; r.dalal@uq.edu.au
* Correspondence: somajayaraman@gmail.com or somasundaram.j@icar.gov.in



**Citation:** Jayaraman, S.; Sahu, M.; Sinha, N.K.; Mohanty, M.; Chaudhary, R.S.; Yadav, B.; Srivastava, L.K.; Hati, K.M.; Patra, A.K.; Dalal, R.C. Conservation Agricultural Practices Impact on Soil Organic Carbon, Soil Aggregation and Greenhouse Gas Emission in a Vertisol. *Agriculture* **2022**, *12*, 1004. https://doi.org/10.3390/agriculture12071004

Academic Editors: Xiaoliang Qin and Vito Armando Laudicina

Received: 18 April 2022
Accepted: 1 July 2022
Published: 11 July 2022



**Abstract:** Conservation agriculture (CA), comprising of minimum soil disturbance and crop residue retention (>30%), with a diversified cropping system, has become increasingly popular around the world. It is recognized as a sustainable practice to improve soil health by augmenting key soil properties. However, scanty information exists about the effect of CA practices on soil organic carbon (SOC), aggregation and greenhouse gas emissions (GHG) in a vertisol. Thus, this study investigated the effect of CA practices on SOC, soil aggregation and GHG emission under soybean-wheat and maize-chickpea cropping systems in a vertisol in Central India. Treatment consisted of three different tillage practices, being conventional tillage (CT), reduced tillage (RT), and no tillage (NT) under four cropping systems viz., Soybean–Wheat, Soybean + Pigeon pea (2:1), Maize–Chickpea and Maize + Pigeon pea (1:1). Regardless of cropping system, the soil under NT and RT exhibited better aggregation (20.77 to 25.97% increase), and SOC (12.9 to 19.4% increase) compared to the CT practice in surface layers. The aggregate-associated C concentration increased with aggregate size, and it was highest with large macroaggregates and lowest with silt and clay fractions across different tillage and cropping systems. Higher SOC stock was recorded under NT (4.22 ± 0.133 Mg C/ha) compared to RT (3.84 ± 0.123 Mg C/ha) and CT (3.65 ± 0.04 Mg C/ha) practices at 0 to 5 cm depth. Thus, the adoption of CA practices reduced $CO_2$ emissions, while also contributing to increases in SOC as well as improvement in soil structure.

**Keywords:** conservation tillage; no-tillage; reduced tillage; greenhouse gas emissions; soil organic carbon; carbon sequestration

## 1. Introduction

Soil is one of the most vital natural resources as it regulates hydrological, bio-geochemical, and sediment cycles [1,2]. Soil plays an important role in agricultural production, ecosystem services, climate change mitigation and human development [3,4]. As a consequence, the United Nations has emphasized the importance of soils in fulfilling the Sustainable Development Goals (SDGs) as it closely linked with 7 out of 17 SDGs [2].

Soil organic matter (SOM) is an important indicator of soil quality in tropical agricultural systems where fertility degraded/nutrient depleted and highly weathered soils are managed with little external input addition [5,6]. Various farm management practices, namely tillage, mulching, crop residue retention and the use of organic and synthetic fertilizers, have a significant impact on SOM dynamics [7–10]. Conservation agriculture (CA) based tillage practices such as no-tillage (NT) and minimum/reduced tillage (RT) significantly improve SOC as compared to conventional tillage practices [11–15]. CA farming has become increasingly popular around the world (approximately 180 million ha of cropland, or ~12.5% of total global agricultural area in 2015/16) [16–18]. The CA is a sustainable farming system that includes NT, RT, residue retention over soil surface (>30%) and crop rotations, including cover crops [19]. These practices together aimed to increase crop yields by increasing many regulating and supporting ecosystem services with a minimum cost [20]. The CA practices reduce environmental degradation, enhance soil quality [6,14], increase crop yields, and lower cost of cultivation [17,18].

The CA has the ability to reduce the loss of SOC from the soil profile by reducing the turnover rate of macro-aggregates, enhancing the physical protection of particulate organic matter, and minimizing microbial attack [21,22]. In coarse textured soils, under NT, macro-aggregates (particle size > 0.25 mm) and mean weight diameter (MWD) were found to be larger than under CT [23]. Many researchers reported that CA practices/tillage methods significantly influence on water retention, pore size distribution, aggregate size distribution, aggregate stability [24–27], aggregate associated C and SOC [17,28,29]. Moreover, increasing crop residue addition can potentially improve higher SOC storage in CA systems [9,10,30,31]. However, in the areas where crop residue production is minimal, such as due to low soil fertility or soil constraints, residue retention may be insufficient to positively influence SOC storage [20,32]. Soil fertility and crop management practices, such as reducing tillage operations, crop-residue retention/addition, manuring, increasing soil aggregation, and types of mulching, play a crucial role in sequestering C in soil [7,24].

Agricultural activities/ecosystems often play an important role in sink and source of greenhouse gas (GHG) emission, specifically $CO_2$ [24,33,34]. Agricultural soil is estimated to be one of the largest sources of global GHG emissions, accounting for ~24% of total anthropogenic GHGs on a global scale [15,35]. In the last few decades there were reports indicating higher emission of GHG gases viz., carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), due to intensive tillage and cropping practices, excessive fertilization, etc. [33,36]. The emission of GHG from soil is a complex and interactive process between physico-chemical and biological properties of soil, land use management and climatic parameters [37]. Soil properties including soil texture, aggregates and their distribution, porosity, hydro-thermal regimes, pH, EC, redox potential and SOC greatly influence on GHG emissions [38–40]. The rate of SOC decomposition and the resulting GHG emissions are also affected by its distribution in aggregates and their chemical properties [41]. Soil aggregation and pore size distribution can have a direct impact on GHG emissions, which can have global warming consequences [42,43].

Although plenty of information is available on the impact of land use management on GHG emission under irrigated and flooded ecosystems, a field study is considered to be the best way to answer the question of how tillage and cropping system affects soil aggregates distribution and associated carbon, carbon stock and GHG emission in a rainfed region. We hypothesized that the soil under NT practice will have higher SOC stock and better aggregation than that under CT practice. Further, GHG emissions will be lower under NT due to higher SOC sequestration than the CT practice. The main objective of this study was to investigate the effects of different tillage and cropping systems on SOC stocks, soil aggregation and GHG emissions under different tillage and cropping systems in a vertisol in Central India.

## 2. Materials and Methods

### *2.1. Study Site and Climatic Conditions*

The experiment was carried out in 2018 at the research farm of Indian Council of Agricultural Research (ICAR)-Indian Institute of Soil Science, Bhopal, India (23°18′ N, 77°24′ E, 485 m elevation) (Figure 1). The experimental site has a sub-humid tropical climate.

The study region receives on average of 1080 mm with a mean air temperature of 25 °C. The soil of the study site is classified as a deep clayey vertisol (vertisol, Isohyperthemic, Typic Haplustert). Initial soil characteristics of the study site during 2011 are given in Table 1. Soil of the study site was characterized with neutral to alkaline (pH 7.9) in soil reaction, low electrical conductivity 0.14 dS $m^{-1}$, and clay in texture. The soil was characterized as low, low to medium and high status in available nitrogen (N), phosphorus (P) and potassium (K), respectively, whereas SOC was characterized as low to medium status. It was observed that major available nutrients decreased with increasing soil depth.

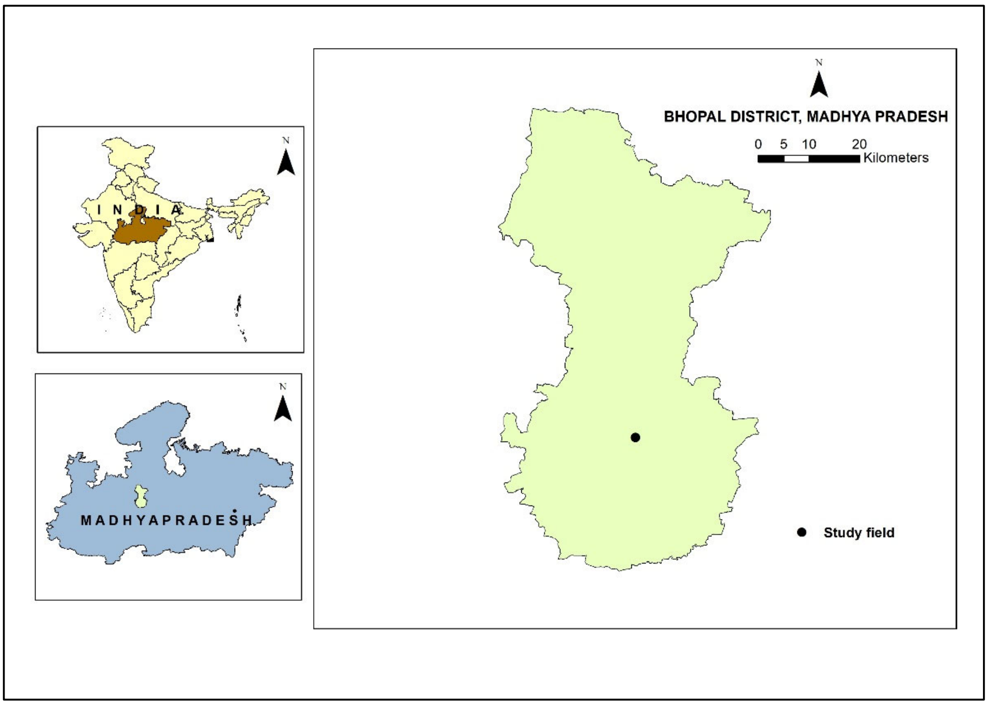


**Figure 1.** Location map of the study area.

**Table 1.** Physical and chemical properties of initial experimental soil sample.

| Soil Parameters | 0–5 cm | 5–15 cm | 15–30 cm | 30–45 cm |
|---|---|---|---|---|
| Soil texture | | | | |
| Sand (%) | 22 | | Clay soil | |
| Silt (%) | 20 | | | |
| Clay (%) | 58 | | | |
| pH | 7.94 | 7.77 | 8.00 | 7.94 |
| EC (dS$m^{-1}$) | 0.14 | 0.14 | 0.15 | 0.14 |
| OC (%) | 0.64 | 0.54 | 0.52 | 0.46 |
| N (kg $ha^{-1}$) | 256.8 | | 227.9 | |
| P (kg $ha^{-1}$) | 22.46 | 16.48 | 14.85 | 16.63 |
| K (kg $ha^{-1}$) | 582.28 | 569.46 | 519.06 | 492.92 |
| TC (%) | 1.05 | 0.94 | 0.88 | 0.80 |

## *2.2. Treatment Details*

The experiment was initiated in 2011 in a split plot design. The main plots (40 m long × 25 m wide) consisted of three tillage practices: no-tillage (NT), reduced tillage (RT) with retention of crop residue, and conventional tillage (CT), and the subplots (10 m long × 5 m wide) consisted of four cropping systems, Soybean (*Glycine max* L.)–Wheat (*Triticum aestivum* L.), Soybean + Pigeon pea (*Cajanus cajan* L.), Maize (*Zea mays* L.)–Chickpea or gram (*Cicer arietinum* L.), and Maize + Pigeon pea. Pigeon pea was a long duration crop which was intercropped with either soybean or maize. All the treatments were replicated thrice, and the experiment field has gentle slope of <1%. Before the start of this experiment, the study site was under an arable cropping system; soybean and pigeon pea during rainy season (*Kharif*), and wheat and chickpea was the winter (*Rabi*) crop. The nutrient requirement of the crop was fulfilled via an application of recommended doses of fertilizers (soybean 30:60:30; pigeon pea 30:60:60; wheat 120:60:40; maize 120:60:40 and chick pea 40:60:30 of N: $P_2O_5$: $K_2O$ kg ha$^{-1}$, respectively), which were applied during each cropping season.

### *2.3. Soil Sampling, Processing and Analysis*

Different soil properties were measured during the 7th year crop cycle. The bulk density at different depths (0–5, 5–10 and 10–15 cm) was measured by a core sampler. Soil samples were collected randomly from 2–3 locations of each plot after a harvest of the crops, and composited for each plot. After removing visibly seen large plant materials and stones, the samples were air-dried, crushed, and passed through a 2 mm sieve and stored for analysis. Before processing, sub-samples were also taken separately from the bulk soil and sieved through a 4 mm sieve. For analysis of aggregate stability and size distribution, soil retained on the sieve (4 mm) was used in the study. A wet sieving method was used to determine the water-stable aggregates in the soil [44] and the MWD was calculated using van Bavel's formula [45]. The percentage of water stable aggregates (WSA) greater than 250 µm of the total soil mass (after sand correction) was also calculated. In wet sieving, the soil retained in set of sieves of various diameters was divided into four categories: (i) large macroaggregates (LM) of > 2000 µm, (ii) small macroaggregates (SM) of > 250–2000 µm, (iii) microaggregates of (Mi) of > 53–250 µm) and (iv) silt + clay (S+C) of < 53 µm and soil and aggregate fractions were dried at 45 °C in the oven. The SOC concentration of the soil samples and the aggregates was determined following the wet digestion method by Walkley and Black [46]. A one gram sample was digested with 10 mL potassium dichromate ($K_2Cr_2O_7$) and 20 mL conc. $H_2SO_4$ in the dark condition for 30 min and titrated with 0.5 N ferrous ammonium sulphate using diphenylamine indicator. The SOC stock was calculated from the SOC concentration and the bulk density of the soil.

### *2.4. Gas Sampling and GHG Flux Measurement*

The protocol for gas sampling and analyses including gas chamber dimensions are given in Tirol-Padre et al. [35]. Briefly, gas samples were withdrawn at regular intervals throughout the chamber deployment. At a minimum, 4 time points were obtained for flux calculation: 0 min, 15 min, 30 min and 60 min. Sampling was conducted by means of inserting a syringe into the chamber septa, pumping up and down the syringe 2–3 times and the slowly taking the gas sample. Generally, 20 to 30 mL gas samples were collected and immediately transferred to a previously evacuated glass vial sealed with a septum.

The $CO_2$, $N_2O$ and $CH_4$ concentrations in the collected samples were determined by using gas chromatograph (model 7890A, Agilent Technology, Santa Clara, California, U.S.). The $CO_2$ concentration was determined with a thermal conductivity detector (TCD), $N_2O$ concentration was determined with an electron capture detector (ECD) and $CH_4$ concentration was determined with a flame ionization detector (FID). Since $CH_4$ concentrations were very low, only the $CO_2$ and $N_2O$ fluxes are reported. The $CO_2$-C/$N_2O$-N fluxes from fields were calculated using the following equations 1 and 2, respectively:

$$\text{The } CO_2\text{-C flux (mg m}^{-2}\text{ h}^{-1}) = (\Delta X \times EVB_{(STP)} \times 12 \times 10^3 \times 60)/(10^6 \times 22400 \times t \times A) \quad (1)$$

$$\text{The } N_2O\text{ -N lux (microg m}^{-2}\text{ h}^{-1}) = (\Delta X \times EVB_{(STP)} \times 14 \times 10^6 \times 60)/(10^6 \times 22400 \times t \times A) \quad (2)$$

where, ΔX= difference in flux value between 30 min and 0 min (converted to mg m$^{-2}$ h$^{-1}$ or microg m$^{-2}$ h$^{-1}$ based on the standard $CO_2$ or $N_2O$ values, respectively.

Box volume (V) = height of the box × length of the box × breadth of the box
Effective box volume (EVB) = V mL = V1 mL
Effective box volume at STP ($EVB_{STP}$) = $(V1 \times t_1)/t_2$

Where, $t_1$ 273 °K; $t_2$ = temperature at the time of 30 min flux taken
A = cross section area of the box = (length of the box × breadth of the box)
T = time difference of flux recorded = (30–0) min = 30 min

*2.5. Statistical Analysis*

Data obtained from all the measurements were statistically analysed by applying R software (Agricolae package) for the split-split plot design. The least significant difference values at $p < 0.05$ were obtained to test the significance of treatments difference.

## 3. Results

*3.1. Soil Bulk Density*

The soil bulk density (BD) values at 0–5, 5–10 and 10–15 cm depths during the 7th year crop cycle are shown in Table 2. The BD was significantly different among tillage and cropping systems at different soil depths. Irrespective of the tillage system, the top soil layer (0–5 cm depth) recorded lower BD values; as the soil depth increased BD values were also increased. Among different tillage systems, RT and NT recorded lower BD compared to the CT system after 7 crop cycles. Among different cropping systems, the lowest BD (1.13 Mg $m^{-3}$) was recorded in maize-chickpea cropping system under NT but it was similar to other cropping systems except the maize + pigeon pea system (1.19 Mg $m^{-3}$). However, the significantly higher BD (1.19 Mg $m^{-3}$) was recorded under the CT in maize-Chickpea than NT and RT and also in NT under maize + pigeon pea cropping system than CT and RT. At 5–10 cm depth, higher BD was observed under the NT into soybean + pigeon pea (2:1) cropping system (1.29 Mg $m^{-3}$) followed by CT and RT under similar cropping system (1.23 Mg $m^{-3}$ and 1.15 Mg $m^{-3}$, respectively). At 5–10 to 10–15 cm depth, a similar trend was observed, i.e., NT plot showed highest BD (1.30 Mg $m^{-3}$) under soybean + pigeon pea (2:1) cropping system whereas RT recorded lowest BD value (1.16 Mg $m^{-3}$) under the same cropping system. Further, we observed that there was an increase in soil BD with depth, regardless of all cropping systems and tillage. Moreover, the interaction effects of tillage system (TS) × cropping system (CS), tillage system × depth (D) and T × CS × D on BD values were significant. The soybean based cropping system under RT practice at both 0–5 cm and 5–10 cm depths had the lowest BD values (Table 2).

*3.2. Aggregate Size Distribution*

The effect of different tillage and cropping systems on aggregate size distribution (%) at 0–5 cm soil depth is presented in Supplementary Figure S1. The percentage of Mi was the highest, followed by SM; however, the LM and S+C, each comprised of ≤10% at 0–5 cm depth. The distribution of M under different tillage systems of CT, RT and NT were 45.94–49.49%; 45.56–48.76%; 42.65–47.26%, respectively, and the corresponding values for SM were 32.54–35.53%; 35.19–36.89%; 36.51–38.16%, respectively. The LM under different tillage of CT, RT and NT were 7.61–8.20%; 7.37–9.61%; 8.31–10.74% and the corresponding values for S+C were 8.85–10.82%; 7.49–9.31%; 8.34–10.16%, respectively. The LM was significantly affected by the tillage system at 0–5 cm depth, and recorded in the order: NT > RT > CT. The SM and M showed no significant differences among tillage systems. The tillage system had a significant effect on SM and M, whereas LM and S+C were not affected at 5–15 cm depth. At 15–30 cm depth, tillage had no significant effect on aggregate size distribution.

**Table 2.** Effect of different tillage and cropping systems on soil bulk density (Mg $m^{-3}$).

| Tillage System | Cropping System | 0–5 cm | 5–10 cm | 10–15 cm |
|---|---|---|---|---|
| CT | Soybean + P. Pea | 1.20 a | 1.23 bc | 1.24 bc |
| | Soybean − Wheat | 1.14 b | 1.22 b | 1.22 e |
| | Maize + P. Pea | 1.15 b | 1.18 d | 1.23 de |
| | Maize − Chickpea | 1.19 a | 1.22 b | 1.26 b |
| | Mean | 1.17 A | 1.21 A | 1.23 B |
| RT | Soybean + P. Pea | 1.12 c | 1.15 d | 1.16 f |
| | Soybean − Wheat | 1.13 bc | 1.17 d | 1.22 e |
| | Maize + P. Pea | 1.13 bc | 1.18 bc | 1.25 bc |
| | Maize − Chickpea | 1.17 b | 1.22 b | 1.24 de |
| | Mean | 1.13 C | 1.18 C | 1.21 C |
| NT | Soybean + P. Pea | 1.18 a | 1.29 a | 1.30 a |
| | Soybean − Wheat | 1.13 bc | 1.21 bc | 1.21 de |
| | Maize + P. Pea | 1.19 a | 1.23 bc | 1.29 a |
| | Maize − Chickpea | 1.17 b | 1.21 bc | 1.25 bc |
| | Mean | 1.16 B | 1.23 A | 1.26 A |
| | Grand Mean | 1.15 | 1.21 | 1.24 |
| Experimental Test | | | | |
| Tillage System (T) | *** | | | |
| Cropping system(CS) | *** | | | |
| Soil depth(D) | *** | | | |
| T × CS | *** | | | |
| T × D | *** | | | |
| CS × D | *** | | | |
| T × CS × D | *** | | | |
| $LSD_{tillage(0.05)}$ | 0.005 | | | |
| $LSD_{Cropping\ System(0.05)}$ | 0.012 | | | |
| $LSD_{Depth(0.05)}$ | 0.009 | | | |

*** Significant at 0.1% level. A different small letter a–f in a column indicates significant difference among the cropping treatments, however, a different capital letter A–C in a column indicates a significant difference among the tillage treatments.

### 3.3. Mean Weight Diameter

The mean weight diameter (MWD) under different tillage and cropping systems is shown in Supplementary Figure S2. The MWD value decreased with soil depth. Tillage, cropping system and soil depth had a significant interaction effect ($p < 0.05$) on MWD. Across the different tillage practices, NT had larger MWD (0.97 mm) followed by RT (0.93 mm) and CT (0.77 mm). The cropping system under RT and NT recorded higher MWD at 0–5 cm depth; the higher MWD was for maize-chickpea (1.04 mm) and the lowest for maize + p. pea (0.87 mm) under NT. Similarly, we observed the largest MWD for maize-chickpea (0.97 mm) and the smallest MWD for soybean + p. pea (0.85 mm) under RT at 0–5 cm depth. Under the CT practice, the largest MWD was recorded for maize + p. pea (0.83 mm) and smallest MWD for maize–chickpea (0.72 mm). At lower depths (5–15 cm and 15–30 cm), soil aggregation is decreased with depth. At 5–15 cm depth, the RT and NT recorded almost similar MWD value (0.91 mm) but higher than CT.

### 3.4. Water Stable Aggregates

The water stable aggregates (WSA, %) under different tillage and cropping systems at different soil depths are presented in Supplementary Figure S3. The percent WSA were significantly ($p < 0.05$) influenced by tillage and soil depth and their interaction. In the tillage system, results indicated that WSA (%) was recorded in the order of NT > RT > CT regardless of depths. We observed that the NT (71.26%) and RT (69.84%) had significantly larger WSA as compared to CT (60.88%) at the surface layer (0–5 cm depth). The WSA were decreased with increasing depth, irrespective of tillage and cropping system. The highest WSA was observed in maize-chickpea (72.71%) under NT, and the smallest was in soybean-wheat (60.34%) under CT at 0–5 cm depth. We observed that the interaction effect of tillage × cropping system and tillage × depth was significant ($p < 0.05$) at all soil depths.

### *3.5. Soil Organic Carbon (SOC)*

The SOC concentrations under different tillage and cropping systems during the 7th year of experimentation are shown in Table 3 and Supplementary Figure S4. In general, the concentration of SOC decreased with increasing depth. The SOC concentration was significantly affected by different tillage practices and cropping systems. The SOC concentration for the NT, RT and CT was 0.74, 0.70 and 0.62% at 0–5 cm depth, respectively; and the corresponding values for the 5–15 cm and 15–30 cm were 0.61, 0.62, 0.56%; and 0.56, 0.54 and 0.49%, respectively. The soil under NT recorded significantly higher SOC concentration (0.74%) than RT (0.70%) and CT (0.62%) at 0–5 cm depth, whereas at the lower depths (i.e., 15–30 cm) tillage systems did not have any significant effect.

**Table 3.** Effect of different tillage and cropping system on soil organic carbon (SOC) (%) at different soil depths.

| Tillage System | 0–5 cm | 5–15 cm | 15–30 cm | Mean |
|---|---|---|---|---|
| **CT** | | | | |
| Soybean + P. Pea | 0.63 e | 0.53 f | 0.52 c | 0.56 |
| Soybean − Wheat | 0.62 e | 0.54 ef | 0.47 de | 0.55 |
| Maize + P. Pea | 0.63 e | 0.61 c | 0.52 c | 0.59 |
| Maize − Gram | 0.62 e | 0.55 e | 0.46 e | 0.54 |
| Mean | 0.62 C | 0.56 C | 0.49 C | 0.56 |
| **RT** | | | | |
| Soybean + P. Pea | 0.70 c | 0.66 a | 0.56 b | 0.64 |
| Soybean − Wheat | 0.67 d | 0.62 ef | 0.55 b | 0.61 |
| Maize + P. Pea | 0.71 c | 0.53 f | 0.51 c | 0.58 |
| Maize − Gram | 0.71 c | 0.67 a | 0.55 b | 0.64 |
| Mean | 0.70 B | 0.62 B | 0.54 B | 0.62 |
| **NT** | | | | |
| Soybean + P. Pea | 0.74 ab | 0.60 c | 0.55 b | 0.63 |
| Soybean − Wheat | 0.73 b | 0.64 b | 0.64 a | 0.67 |
| Maize + P. Pea | 0.75 a | 0.57 d | 0.55 b | 0.62 |
| Maize − Gram | 0.73 b | 0.64 b | 0.48 d | 0.62 |
| Mean | 0.74 A | 0.61 A | 0.56 A | 0.64 |
| Tillage System(T) | | *** | | |
| Cropping system(CS) | | * | | |
| Soil depth(D) | | *** | | |
| T × CS | | *** | | |
| T × D | | *** | | |
| CS × D | | *** | | |
| T × CS × D | | *** | | |
| $LSD_{tillage(0.05)}$ | | 0.010 | | |
| $LSD_{Cropping\ System(0.05)}$ | | 0.006 | | |
| $LSD_{Depth(0.05)}$ | | 0.005 | | |

* Significant at 5% level. *** Significant at 0.1% level. A different small letter a–f in a column indicates significant difference among the cropping treatments, however, a different capital letter A–C in a column indicates a significant difference among the tillage treatments.

The cropping systems had a significant effect on SOC concentration. Among the cropping systems compared, the maize + p. pea recorded significantly higher SOC (0.75%) under NT than soybean–wheat and maize-chickpea (0.73%) at 0–5 cm depth; almost similar trends were observed under RT. Whereas, under CT, almost all the cropping systems recorded similar SOC concentrations (i.e., 0.62–0.63%). At 5–15 cm depth, the highest SOC was observed in NT soybean-wheat (0.64%) and the lowest in maize + p. pea (0.57%). At 15–30 cm depth, SOC concentrations in soybean-wheat (0.64%) and maize-chickpea (0.64%) were significantly higher under NT than CT. We observed a significant interactive effect between tillage × cropping system × soil depth.

### 3.6. Aggregate Associated Carbon

Aggregate associated C concentrations at different soil depths under different tillage and cropping systems are presented in Table 4. We observed that C concentration increased with aggregate size and it was in the order of LM > SM > M > S+C. Overall, LM had the highest aggregate C but S+C had the lowest aggregate associated C across different tillage and cropping systems. Tillage and cropping systems did not have significant effect on aggregate associated-C. However, soil depth was found to have a significant effect on all aggregate-associated C concentrations. Similarly, the interaction effect between the cropping system × depth was significant for LM-C. In the NT, we observed a higher C in LM aggregate under soybean + pigeon pea at 0–5 cm (0.61 %) and 5–15 cm depths (0.59%). A similar trend was observed for the SM aggregate C.

**Table 4.** Effect of different tillage and cropping systems on aggregate associated C concentration (%) at different soil depths.

| | | LM-C | | | SM-C | | | Mi-C | | | Si+C-C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tillage | Cropping System | Depth (cm) | | | Depth (cm) | | | Depth (cm) | | | Depth (cm) | | |
| | | 0–5 | 5–15 | 15–30 | 0–5 | 5–15 | 15–30 | 0–5 | 5–15 | 15–30 | 0–5 | 5–15 | 15–30 |
| CT | Soybean + P. Pea (2:1) | 0.51 ab | 0.51 abcd | 0.46 abc | 0.47 a | 0.39 a | 0.39 ab | 0.42 a | 0.35 a | 0.30 ab | 0.32 ab | 0.22 a | 0.21 a |
| | Soybean − Wheat | 0.50 ab | 0.41 cd | 0.34 bc | 0.40 a | 0.39 a | 0.41 ab | 0.37 a | 0.36 a | 0.36 ab | 0.29 abc | 0.23 a | 0.23 a |
| | Maize + P. Pea (1:1) | 0.44 ab | 0.35 d | 0.53 ab | 0.40 a | 0.43 a | 0.40 ab | 0.38 a | 0.37 a | 0.39 a | 0.33 ab | 0.28 a | 0.31 a |
| | Maize − Chickpea | 0.57 a | 0.52 abcd | 0.45 abc | 0.49 a | 0.46 a | 0.40 ab | 0.39 a | 0.36 a | 0.32 ab | 0.34 a | 0.20 a | 0.29 a |
| | Mean | 0.51 A | 0.45 A | 0.45 A | 0.44 A | 0.42 A | 0.40 A | 0.39 B | 0.36 A | 0.34 A | 0.32 A | 0.23 A | 0.26 A |
| RT | Soybean + P. Pea (2:1) | 0.50 ab | 0.43 bcd | 0.46 abc | 0.45 a | 0.40 a | 0.43 ab | 0.39 a | 0.35 a | 0.34 ab | 0.21 bc | 0.30 a | 0.28 a |
| | Soybean − Wheat | 0.52 a | 0.55 abc | 0.33 c | 0.43 a | 0.39 a | 0.43 a | 0.35 a | 0.35 a | 0.36 ab | 0.29 abc | 0.23 a | 0.22 a |
| | Maize + P. Pea (1:1) | 0.53 b | 0.53 abc | 0.53 ab | 0.40 a | 0.44 a | 0.45 a | 0.34 a | 0.35 a | 0.32 ab | 0.30 abc | 0.31 a | 0.20 a |
| | Maize − Chickpea | 0.55 a | 0.46 bcd | 0.45 abc | 0.49 a | 0.40 a | 0.34 b | 0.39 a | 0.34 a | 0.29 b | 0.38 a | 0.28 a | 0.20 a |
| | Mean | 0.53 A | 0.49 A | 0.44 A | 0.44 A | 0.41 A | 0.41 A | 0.37 C | 0.35 A | 0.33 A | 0.30 A | 0.28 A | 0.22 A |
| NT | Soybean + P. Pea (2:1) | 0.61 a | 0.59 ab | 0.50 abc | 0.48 a | 0.43 a | 0.41 ab | 0.43 a | 0.39 a | 0.33 ab | 0.37 a | 0.36 a | 0.28 a |
| | Soybean − Wheat | 0.58 a | 0.44 a | 0.55 a | 0.44 a | 0.47 a | 0.44 a | 0.42 a | 0.38 a | 0.38 ab | 0.31 abc | 0.23 a | 0.34 a |
| | Maize + P. Pea (1:1) | 0.55 a | 0.53 abc | 0.52 abc | 0.45 a | 0.47 a | 0.47 a | 0.38 a | 0.38 a | 0.36 ab | 0.32 abc | 0.24 a | 0.21 a |
| | Maize − Chickpea | 0.54 a | 0.49 bcd | 0.53 ab | 0.48 a | 0.40 a | 0.40 ab | 0.41 a | 0.36 a | 0.39 a | 0.20 c | 0.31 a | 0.23 a |
| | Mean | 0.57 A | 0.51 A | 0.53 A | 0.46 A | 0.44 A | 0.43 A | 0.41 A | 0.38 A | 0.36 A | 0.30 A | 0.28 A | 0.27 A |

CT, conventional tillage: RT, reduced tillage: NT, no tillage; LM-Large macroaggregate, SM-Small macroaggregate, Mi-Microaggregate, Si+C-Silt+Clay. A different small letter a–f in a column indicates significant difference among the cropping treatments, however, a different capital letter A–C in a column indicates a significant difference among the tillage treatments.

### 3.7. SOC Stocks

The amount of SOC stock was significantly affected by different tillage practices and cropping systems (Supplementary Figure S5). The values of SOC stock for CT, RT and NT varied from 3.54 to 3.76 Mg C/ha (3.65 ± 0.04 Mg C/ha), 3.58 to 4.14 Mg C/ha (3.84 ± 0.123 Mg C/ha) and 3.90 to 4.48 Mg C/ha (4.22 ± 0.133 Mg C/ha) at 0–5 cm depth, respectively; and the corresponding values at 5–15 cm depth were 9.69 to 10.87 Mg C/ha, 9.30 to 12.28 Mg C/ha; 10.47 to 11.68 Mg C/ha, respectively. Irrespective of soil depths, a higher SOC stock was recorded under NT compared to RT and CT practices. The NT recorded significantly higher SOC stock (11.35 ± 0.29 Mg C/ha) than RT (10.43 ± 0.67 mg C/ha) and CT (10.10 ± 0.26 Mg C/ha) at 5–15 cm depth, whereas at the lower depths (i.e., 15–30 cm) tillage systems did not have any significant effect on the SOC stock.

Among the various cropping systems evaluated, maize + p. pea (1:1) had a significantly higher SOC stock (4.48 Mg C/ha) under NT, however, maize–chickpea recorded lower

SOC stock (3.90 Mg C/ha) at 0–5 cm depth; similar trends were observed under RT. Whereas, under CT, all the cropping systems recorded a similar SOC stock (i.e., 3.54 to 3.76 Mg C/ha). At 5–15 cm depth, the highest SOC stock was recorded in RT maize-chickpea (12.28 Mg C/ha) and the lowest in maize + p. pea (9.30 Mg C/ha). At 15–30 cm depth, maize-chickpea (20.60 ± 0.25 Mg C/ha) recorded a significantly higher SOC stock under RT compared to the other cropping systems under RT. The SOC stock under RT was significantly higher than NT and CT. Results reveal that the SOC content was higher at the surface (0–5 cm) and decreased with depth. Results highlight that the interactive effect between tillage and cropping systems and soil depth was significant for SOC stock.

### *3.8. Greenhouse Gas Fluxes*

The temporal variation in mean greenhouse gases ($CO_2$ and $N_2O$) in flux under different tillage and cropping systems in a vertisol in central India is given in Supplementary Table S1. Mean data indicated that the soybean-wheat system recorded higher $CO_2$ (19.72–25.83 mg $m^{-2}$ $h^{-1}$) than the maize-chickpea system (14.46–21.83 mg $m^{-2}$ $h^{-1}$), regardless of tillage practice. In early July, the CT recorded higher $CO_2$ flux (9.17–25.83 mg $m^{-2}$ $h^{-1}$) compared to NT and RT. However, in the second sampling (29 July 2017), we did not observe such a trend. During the third sampling (24 August 2017), inconsistent results were observed irrespective of tillage and cropping systems. During October, the NT recorded a higher $CO_2$ flux (3.05–37.87 mg $m^{-2}$ $h^{-1}$) compared to RT (10.27–22.85 mg $m^{-2}$ $h^{-1}$) and CT (6.82–31.83 mg $m^{-2}$ $h{-1}$).

Perusal of $N_2O$-N fluxes across four sampling dates indicated that low fluxes of $N_2O$ were observed irrespective of cropping system and tillage practices. In this study, negative fluxes show the uptake by the soil, while positive fluxes demonstrate net emission from the soil. Barring maize-chickpea systems during the July sampling date, other cropping systems recorded net negative flux of $N_2O$. The NT during the second sampling and CT and RT during the third sampling (29 August 2017) recorded net positive emission. A similar trend was observed in the October sampling with little variations.

## 4. Discussion

The soil both under NT and RT at 0–5 cm depth had a slightly lower bulk density than the CT practice. Soil BD under the CT practice was higher due to repeated field operations while the soil under NT and RT practices possibly was repaired due to NT or RT (minimum soil disturbances) practices as well as the presence of crop residues on the soil surface, which contributed to the increase in organic matter, thus regained its structural stability and restored the pore space [47]. The lower BD of the CT treatment at the 5–10 cm depth reflects the loosening effect of this tillage treatment compared to the NT and RT practices. Blanco-Canqui and Ruis [1] analyzed meta data from 62 studies and found that NT can either increase or decrease soil BD, depending on the duration of field experiment. Our study results are in congruence with Sinha et al. [6], who have reported that a cropping system which incorporated more crop residues resulted in a lower BD compared to a cropping system which adds minimum crop residue to the soil surface.

Soil aggregation improved under the NT and RT practices, due to less soil disturbances and the addition/retention of crop residue compared with CT. In general, CA practices improve soil aggregation by reducing soil disturbance due to the avoidance/minimising of tillage as well as the residue retention [21,25,28,48]. Repeated soil disturbances through tillage operations favours a breakdown of aggregates coupled with less residue addition, which leads to lower MWD/soil aggregation under CT. Crop residue addition under NT and RT provides a C source for microbial activity, and also acts as nucleation centres for aggregation through increased microbial activity, and favours the gluing of residue and soil particles into macro-aggregates [17,18,28]. Sundermeier et al. [29] reported a higher aggregate stability under long-term adoption of NT practice of 23 (35%) and 44 years (45%) compared to CT. Similarly, Devine et al. [49] found that 30 years of continuous adoption of NT enhanced aggregate stability compared to CT at surface layer (0–5 cm depth).

High MWD and WSA were observed under the NT practice due to residue addition, higher SOC and minimal soil disturbances [50–53]. Chen et al. [23] also reported that crop residues retention helps in binding of soil particles and residue led to the formation of macro-aggregates. We reported that cereal-based cropping systems, namely maize-chickpea and soybean-wheat had a pronounced effect on soil aggregation (MWD). Moreover, in this study, the interaction effect of tillage and cropping system also favoured soil aggregation (MWD and WSA). Frequent soil disturbances through intensive tillage operations coupled with less or minimum crop residue addition under CT have led to poor soil aggregation (MWD) [21,51]. Our study results corroborated with several studies have reported a higher soil aggregation under NT compared with CT at 10 cm depth [28,29].

Tillage and cropping systems enhanced C in the LM and SM aggregates. Our results are in congruence with those of Bhattacharya et al. [52] who in their 6 year study of NT plots recorded significantly higher C in all aggregate sizes than under CT and CT-NT at 0–5 cm depth. Moreover, higher organic C concentration was observed with an increase in the size of aggregates [53,54]; the higher SOC concentration in the macro-aggregates was because the residue and microbial necromass (particulate organic C) provided the nuclei of aggregate formation to become the occluded C within macroaggregates, which was less accessible to microbial decomposition. Many researchers have reported that LM had higher aggregate-C and aggregate-N than other size fractions, regardless of tillage treatments [28,51]. In comparison to NT and RT, CT recorded less C in aggregate due to frequent soil disturbances through tillage which favours aggregate breakdown and decomposition of SOC. Pinheiro et al. [55] also reported that the continuous use of CT has led to a decreased aggregate size due to frequent disturbance of macro aggregates and potentially exposed SOM to microbial attack/decompostion. Under NT, soil aggregation improved as compared to RT and CT practices. Higher SOC contents in macro-aggregates were due to the addition of crop residues and root biomass favour microbial biomass, particularly fungal hyphae within macro-aggregates [10]. This process not only enhances C content but also promotes physical protection of aggregates [9,56]. Our results support that the occurrence of more C in large and small macro-aggregates with short-term adoption of conservation management improved soil microbial composition and community due to presence of crop residue [57,58].

The higher SOC in the surface soil was ascribed due to crop residue addition and relatively less soil disturbance under NT and RT [59]. Moreover, high SOC stocks under RT and NT were due to continuous residue addition as well as minimum soil disturbances under these treatments [28,29,55]. This indicates better soil quality under NT compared to CT practices as organic matter enrichment in the surface layer is necessary to water infiltration, conservation of nutrients and erosion control [6,21,52]. In addition, the organic matter underneath the surface layer was due to previous crops roots, which is undisturbed and prevents accelerated decomposition under CA treatments. These could be the possible reason for the increase in organic C in the upper layers of the soil. Our results are in agreement with the findings of Abid and Lal [60], Mando et al. [61] and Li et al. [62] who have reported a higher SOC concentration under NT than that under CT practice. Unlike conservation tillage (RT and NT), CT operation consists of intensive repeated tillage which exposes this protected organic matter and enhances its decomposition that leads to a reduction in soil C [63]. Chen et al. [23] reported that C input can be increased, and slowed down the decomposition process by appropriate residue management techniques under RT and/or NT practices. Several other researchers had also reported that higher SOC concentration in the soil surface following long term NT and RT practices as compared to CT [64,65]. The decomposition of soil organic matter such as residues and litters are the main cause for $CO_2$ emissions from soil [3]. In addition, microbial populations use reduced carbon (C) as an energy source, which accounts for a higher proportion of $CO_2$ emissions from the soil under agricultural systems. However, this $CO_2$ often has a neutral effect on atmospheric $CO_2$ levels, and often C is sequestered in the soil for longer period via appropriate management practices. Moreover, the soil is neither a source nor a sink of $CO_2$

when a soil is at equilibrium with respect to SOC concentrations. This was ascribed to CT facilitating/exposing more soil organic C for decomposition due to a greater mixing of soil and residue coupled with high soil temperatures. The NT or RT can maintain higher soil moisture levels and surface SOM compared to highly intensive CT practices. Mu et al. [66] reported that the joint application of mineral fertilizers and manure did not influence $CO_2$ emission ($p > 0.05$) compared with the application of mineral fertilizer only.

$N_2O$ is mostly formed via denitrification processes in the soil. In this process, denitrifying bacteria (facultative anaerobes) played a significant role, and can survive both under aerobic and anaerobic conditions. Some research has shown that NT results in higher emissions of $N_2O$ compared to conventional/intensive tillage systems [67]. However, some studies reported that NT produces less $N_2O$ than CT (i.e., moldboard plow or chisel tillage) [68]. We observed that $N_2O$ flux was very low under rainfed situations; this was probably due to low moisture content, which may limit the microbial denitrification activities. Our results were in accordance with Maag and Vinther, [69] and Mu et al. [66] who have reported that low $N_2O$ emissions were due to low moisture levels. Similarly, Linn and Doran [70] reported low soil moisture (water filled pores space (WFPS), 22 to 45%) may be possible reason for the low $N_2O$ fluxes. In contrast, Halvorson et al. [71] and Koga et al. [72] reported higher $N_2O$ emissions under NT compared to CT. This was ascribed to the residue left on the surface by NT and/or RT practice, which kept the soil wetter and provided energy to the denitrifying microorganisms [73]. Moreover, results of the study further highlight that continuous monitoring of gas emissions is necessary to draw a reasonable conclusion.

## 5. Conclusions

Study findings demonstrated that conservation agriculture practices i.e., no-tillage and reduced tillage with crop residue retention had a positive effect on SOC, soil aggregation and C in aggregates under soybean and maize based cropping systems in a vertisol in Central India. Cropping systems also played a significant role in CA management practices, viz. soybean-wheat, maize-chickpea, which had more residue incorporation than other cropping systems under RT and NT. Results revealed that a combination of tillage (i.e., NT and RT) and residue retention had higher emissions of $CO_2$ and $N_2O$ under CA practices compared to CT. From a SOC management perspective, CA-based system (NT, residue retained, rotation) should be scaled up to prevent soil degradation through the SOC build-up while increasing crop productivity to ensure farmers' long-term profitability and sustainability.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12071004/s1. Table S1: Temporal variation of mean greenhouse gas flux under different tillage and cropping systems in a Vertisol of central India; Figure S1: Effect of different tillage and cropping systems on aggregate size distribution at 0–5 cm soil depth; Figure S2: Effect of different tillage and cropping systems on mean weight diameter (mm) at different soil depths (d1: 0–5 cm, d2: 5–15 cm, d3: 15–30 cm); Figure S3: Effect of different tillage and cropping systems on water stable aggregates at different soil depths (d1: 0–5 cm, d2: 5–15 cm, d3: 15–30 cm); Figure S4: Effect of different tillage and cropping systems on soil organic carbon (SOC) at different soil depths; Figure S5: Effect of different tillage and cropping systems on soil organic carbon (SOC) stock (Mg C/ha) at different soil depths.

**Author Contributions:** Conceptualization, S.J.; methodology, S.J.; software, M.S.; validation, S.J. and M.S.; formal analysis, M.S., S.J., N.K.S. and B.Y.; investigation, M.S. and S.J.; resources, S.J. and A.K.P.; data curation, S.J., M.S., N.K.S. and B.Y.; writing—original draft preparation, S.J. and M.S.; writing—review and editing, S.J., R.C.D., R.S.C., M.M., B.Y., L.K.S., K.M.H. and A.K.P.; visualization, S.J. and R.C.D.; supervision, A.K.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data made available upon request after taking approval competent authority.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Blanco-Canqui, H.; Ruis, S.J. No-tillage and soil physical environment. *Geoderma* **2018**, *326*, 164–200. [CrossRef]
2. Keesstra, S.D.; Bouma, J.; Wallinga, J.; Tittonell, P.; Smith, P.; Cerdà, A.; Montanarella, L.; Quinton, J.N.; Pachepsky, Y.; Van Der Putten, W.H.; et al. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil* **2016**, *2*, 111–128. [CrossRef]
3. Lal, R. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by $CO_2$-enrichment. *Soil Tillage Res.* **1997**, *43*, 81–107. [CrossRef]
4. Rodrigo-Comino, J. Five decades of soil erosion research in "terroir". The State-of-the-Art. *Earth-Sci. Rev.* **2018**, *179*, 436–447. [CrossRef]
5. Rodrigo-Comino, J.; Keesstra, S.; Cerdà, A. Soil erosion as an environmental concern in vineyards: The case study of Celler del Roure, Eastern Spain, by means of rainfall simulation experiments. *Beverages* **2018**, *4*, 31. [CrossRef]
6. Sinha, N.K.; Chopra, U.K.; Singh, A.K.; Mohanty, M.; Somasundaram, J.; Chaudhary, R.S. Soil Physical Quality as Affected by Management Practices Under Maize—Wheat System. *Natl. Acad. Sci. Lett.* **2014**, *37*, 13–18. [CrossRef]
7. Bell, S.M.; Barriocanal, C.; Terrer, C.; Rosell-Melé, A. Management opportunities for soil carbon sequestration following agricultural land abandonment. *Environ. Sci. Policy* **2020**, *108*, 104–111. [CrossRef]
8. Ibrahim, M.; Khan, A.; Ali, W.; Akbar, H. Mulching techniques: An approach for offsetting soil moisture deficit and enhancing manure mineralization during maize cultivation. *Soil Tillage Res.* **2020**, *200*, 104631. [CrossRef]
9. Zhang, Y.; Li, X.; Gregorich, E.G.; McLaughlin, N.B.; Zhang, X.; Guo, Y.; Gao, Y.; Liang, A. Evaluating storage and pool size of soil organic carbon in degraded soils: Tillage effects when crop residue is returned. *Soil Tillage Res.* **2019**, *192*, 215–221. [CrossRef]
10. Zuber, S.M.; Behnke, G.D.; Nafziger, E.D.; Villamil, M.B. Carbon and nitrogen content of soil organic matter and microbial biomass under long-term crop rotation and tillage in Illinois, USA. *Agriculture* **2018**, *8*, 37. [CrossRef]
11. Das, T.K.; Saharawat, Y.S.; Bhattacharyya, R.; Sudhishri, S.; Bandyopadhyay, K.K.; Sharma, A.R.; Jat, M.L. Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crops Res.* **2018**, *215*, 222–231. [CrossRef]
12. Parihar, C.M.; Singh, A.K.; Jat, S.L.; Ghosh, A.; Dey, A.; Nayak, H.S.; Parihar, M.D.; Mahala, D.M.; Yadav, R.K.; Rai, V.; et al. Dependence of temperature sensitivity of soil organic carbon decomposition on nutrient management options under conservation agriculture in a sub-tropical Inceptisol. *Soil Tillage Res.* **2019**, *190*, 50–60. [CrossRef]
13. Purakayastha, T.J.; Rudrappa, L.; Singh, D.; Swarup, A.; Bhadraray, S. Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize-wheat-cowpea cropping system. *Geoderma* **2008**, *144*, 370–378. [CrossRef]
14. Teklu, E. Tillage effects on physical qualities of a vertisol in the central highlands of Ethiopia. *Afr. J. Environ. Sci. Technol.* **2011**, *5*, 1008–1016.
15. Tellez-Rio, A.; Vallejo, A.; Garcia-Marco, S.; Martin-Lammerding, D.; Tenorio, J.L.; Rees, R.M.; Guardia, G. Conservation Agriculture practices reduce the global warming potential of rainfed low N input semi-arid agriculture. *Eur. J. Agron.* **2017**, *84*, 95–104. [CrossRef]
16. Kassam, A.; Friedrich, T.; Derpsch, R. Global spread of conservation agriculture. *Int. J. Environ. Stud.* **2019**, *76*, 29–51. [CrossRef]
17. Somasundaram, J.; Dang, Y.P.; Naorem, A.; Page, K.L.; Dalal, R.C. Conservation Agriculture as a System to Enhance Ecosystem Services. *Agriculture* **2021**, *11*, 718.
18. Swanepoel, C.M.; Swanepoel, L.H.; Smith, H.J. A review of conservation agriculture research in South Africa. *S. Afr. J. Plant Soil* **2018**, *35*, 297–306. [CrossRef]
19. Gonzalez-Sanchez, E.J.; Veroz-Gonzalez, O.; Conway, G.; Moreno-Garcia, M.; Kassam, A.; Mkomwa, S.; Ordoñez-Fernandez, R.; Triviño-Tarradas, P.; Carbonell-Bojollo, R. Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. *Soil Tillage Res.* **2019**, *190*, 22–30. [CrossRef]
20. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]
21. Hati, K.M.; Jha, P.; Dalal, R.C.; Somasundaram, J.; Dang, Y.P.; Kopittke, P.M.; Kirchhof, G.; Menzies, N.W. 50 years of continuous no-tillage, stubble retention and nitrogen fertilization enhanced macro-aggregate formation and stabilisation in a Vertisol. *Soil Tillage Res.* **2021**, *214*, 105163. [CrossRef]
22. Page, K.L.; Dang, Y.P.; Dalal, R.C. The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. *Front. Sustain. Food Syst.* **2020**, *4*, 31. [CrossRef]
23. Chen, B.; Friedman, B.; Cheng, Q.; Tsai, P.; Schim, E.; Kleinfeld, D.; Lyden, P.D. Severe blood-brain barrier disruption and surrounding tissue injury. *Stroke* **2009**, *40*, 666–674. [CrossRef]
24. Ammann, C.; Neftel, A.; Jocher, M.; Fuhrer, J.; Leifeld, J. Effect of management and weather variations on the greenhouse gas budget of two grasslands during a 10-year experiment. *Agric. Ecosyst. Environ.* **2020**, *292*, 106814. [CrossRef]

25. Czyz, E.A.; Dexter, A.R. Soil physical properties as affected by traditional, reduced and no-tillage for winter wheat. *Int. Agrophys.* **2009**, *23*, 319–326.
26. Hill, R.L.; Curse, R.U. Tillage effects onsoil water retention and pore size distribution of two Mollisols. *Soil Sci. Soc. Am. J.* **1985**, *49*, 1264–1270. [CrossRef]
27. Pranagal, J.; Lipiec, J.; Dom, H. Changes in pore distribution and stability of two soils under long term tillage systems. *Int. Agrophys.* **2005**, *19*, 165–174.
28. Sheehy, J.; Regina, K.; Alakukku, L.; Six, J. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northen European agroecosystems. *Soil Tillage Res.* **2015**, *150*, 107–113. [CrossRef]
29. Sundermeier, A.P.; Islam, K.R.; Raut, Y.; Reeder, R.C.; Dick, W.A. Not-ill impacts of soil biophysical carbon sequestration. *Soil Sci. Soc. Am. J.* **2011**, *75*, 1779–1788. [CrossRef]
30. Haas, E.; Carozzi, M.; Massad, R.; Butterbach-Bahl, K.; Scheer, C. Long term impact of residue management on soil organic carbon stocks and nitrous oxide emissions from European croplands. *Sci. Total Environ.* **2022**, *836*, 154932. [CrossRef]
31. Martin-Gorriz, B.; Martínez-Alvarez, V.; Maestre-Valero, J.F.; Gallego-Elvira, B. Influence of the water source on the carbon footprint of irrigated agriculture: A regional study in South-Eastern Spain. *Agronomy* **2021**, *11*, 351. [CrossRef]
32. Dalal, R.C.; Allen, D.E.; Wang, W.J.; Reeves, S.; Gibson, I. Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil Tillage Res.* **2011**, *112*, 133–139. [CrossRef]
33. Nisar, S.; Benbi, D.K.; Toor, A.S. Energy budgeting and carbon footprints of three tillage systems in maize-wheat sequence of north-western Indo-Gangetic Plains. *Energy* **2021**, *229*, 120661. [CrossRef]
34. Wu, H.; Huang, H.; Tang, J.; Chen, W.; He, Y. Net greenhouse gas emissions from agriculture in China: Estimation, spatial correlation and convergence. *Sustainability* **2019**, *11*, 4817. [CrossRef]
35. Tirol-Padre, A.; Rai, M.; Gathala, M.; Sharma, S.; Kumar, V.; Sharma, P.C.; Sharma, D.K.; Wassmann, R.; Ladha, J. Assessing the performance of the photo-acoustic infrared gas monitor for measuring $CO_2$, $N_2O$, and $CH_4$ fluxes in two major cereal rotations. *Glob. Chang. Biol.* **2014**, *20*, 287–299. [CrossRef] [PubMed]
36. Haque, M.M.; Biswas, J.C.; Salahin, N.; Alam, M.K.; Akhter, S.; Akhtar, S.; Maniruzzaman, M.; Hossain, M.S. Tillage systems influence on greenhouse gas emission factor and global warming potential under rice-mustard-rice cropping system. *Arch. Agron. Soil Sci.* **2022**, 1–16. [CrossRef]
37. Oenema, O.; Velthof, G.; Kuikman, P. Technical and policy aspects of strategies to decrease greenhouse gas emissions from agriculture. *Nutr. Cycl. Agroecosyst.* **2001**, *60*, 301–315. [CrossRef]
38. Bajracharya, R.M.; Lal, R.; Kimble, J.M. Diurnal and seasonal CO2-C flux from soil as related to erosion phases in central Ohio. *Soil Sci. Soc. Am. J.* **2000**, *64*, 286–293. [CrossRef]
39. Pathak, H.; Prasad, S.; Bhatia, A.; Singh, S.; Kumar, S.; Singh, J.; Jain, M.C. Methane emission from rice-wheat cropping system in the Indo-Gangetic plain in relation to irrigation, farmyard manure and dicyandiamide application. *Agric. Ecosyst. Environ.* **2003**, *97*, 309–316. [CrossRef]
40. Ussiri, D.A.; Lal, R. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil Tillage Res.* **2009**, *104*, 39–47. [CrossRef]
41. Besnard, E.; Chenu, C.; Balesdent, J.; Puget, P.; Arrouays, D. Fate of particulate organic matter in soil aggregates during cultivation. *Eur. J. Soil Sci.* **1996**, *47*, 495–503. [CrossRef]
42. Bandyopadhyay, K.K.; Lal, R. Effect of land use management on greenhouse gas emissions from water stable aggregates. *Geoderma* **2014**, *232*, 363–372. [CrossRef]
43. Mangalassery, S.; Sjögersten, S.; Sparkes, D.L.; Sturrock, C.J.; Mooney, S.J. The effect of soil aggregate size on pore structure and its consequence on emission of greenhouse gases. *Soil Tillage Res.* **2013**, *132*, 39–46. [CrossRef]
44. Kemper, W.D.; Rosenau, R.C. Aggregate Stability and Size Distribution. In *Methods of Soil Analysis: Part I. Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; Agronomy Monographs; NWISRL Publications: Madison, WI, USA, 1986; Volume 9, pp. 425–442.
45. Van Bavel, H.M. Mean weight-diameter of soil aggregates as a statistical index of aggregation. *Soil Sci. Soc. Am. J.* **1950**, *14*, 20–23. [CrossRef]
46. Walkley, A.; Black, I.A. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–37. [CrossRef]
47. Kinsella, J. The effects of various tillage systems on soil compaction. In *Farming for a Better Environment*; Soil and Water Conservation Society: Ankeny, IA, USA, 1995; pp. 15–17.
48. Sithole, N.J.; Magwaza, L.S.; Mafongoya, P.L. Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. *Soil Tillage Res.* **2016**, *162*, 55–67. [CrossRef]
49. Devine, S.; Markewitz, D.; Hendrix, P.; Coleman, D. Soil aggregates and associated organic matter under conventional tillage, no-tillage, and forest succession after three decades. *PLoS ONE* **2014**, *9*, e84988. [CrossRef]
50. Arai, M.; Minamiya, Y.; Tsuzura, H.; Watanabe, Y.; Yagioka, A.; Kaneko, N. Changes in water stable aggregate and soil carbon accumulation in a no-tillage with weed mulch management site after conversion from conventional management practices. *Geoderma* **2014**, *221*, 50–60. [CrossRef]
51. Hati, K.M.; Chaudhary, R.S.; Mandal, K.G.; Bandyopadhyay, K.K.; Singh, R.K.; Sinha, N.K.; Mohanty, M.; Somasundaram, J.; Saha, R. Effects of tillage, residue and fertilizer nitrogen on crop yields, and soil physical properties under soybean-wheat rotation in vertisols of Central India. *Agric. Res.* **2015**, *4*, 48–56. [CrossRef]

52. Bhattacharya, R.; Tuti, M.D.; Kundu, S.; Bisht, J.K.; Bhatt, J.C. Conservation Tillage Impacts on Soil Aggregation and Carbon Pools in a Sandy Clay Loam Soil of the Indian Himalayas. *Soil Sci. Soc. Am. J.* **2012**, *76*, 617–627. [CrossRef]
53. Franzluebbers, A.J.; Arshad, M.A. Particulate organic carbon content and potential mineralization as affected by tillage and texture. *Soil Sci. Soc. Am. J.* **1997**, *61*, 1382–1386. [CrossRef]
54. Puget, P.; Chenu, C.; Balesdent, J. Total and young organic matter distribution in aggregates of silty cultivated soils. *Eur. J. Soil Sci.* **1995**, *46*, 449–459. [CrossRef]
55. Pinheiro, E.F.M.; Pereira, M.G.; Anjos, L.H.C. Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. *Soil Tillage Res.* **2004**, *77*, 79–84. [CrossRef]
56. Zhang, H.L.; Lal, R.; Zhao, X.; Xue, J.F.; Chen, F. Opportunities and challenges of soil carbon sequestration by conservation agriculture in China. *Adv. Agron.* **2014**, *124*, 1–36.
57. Guo, Y.; Fan, R.; Zhang, X.; Zhang, Y.; Wu, D.; McLaughlin, N.; Zhang, S.; Chen, X.; Jia, S.; Liang, A. Tillage-induced effects on SOC through changes in aggregate stability and soil pore structure. *Sci. Total Environ.* **2020**, *703*, 134617. [CrossRef]
58. Haynes, R.J. Labile organic matter fractions as central components of the quality of agricultural soils: An overview. *Adv. Agron.* **2005**, *5*, 221–268.
59. Swanepoel, C.M.; Rötter, R.P.; Van der Laan, M.; Annandale, J.G.; Beukes, D.J.; du Preez, C.C.; Swanepoel, L.H.; van der Merwe, A.; Hoffmann, M.P. The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. *Soil Tillage Res.* **2018**, *183*, 72–82. [CrossRef]
60. Abid, M.; Lal, R. Tillage and drainage impact on soil quality, aggregate stability, carbon and nitrogen pools. *Soil Tillage Res.* **2008**, *100*, 89–98. [CrossRef]
61. Mando, A.; Ouattara, B.; Sedogo, M.; Stroosnijder, L.; Ouattara, K.; Brussard, L.; Vanlauwe, B. Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-Sahelian conditions. *Soil Tillage Res.* **2005**, *80*, 95–101. [CrossRef]
62. Li, X.G.; Wang, Z.F.; Ma, Q.F.; Li, F.M. Crop cultivation and intensive grazing affect organic C pools and aggregate stability in arid grassland soil. *Soil Tillage Res.* **2007**, *95*, 172–181. [CrossRef]
63. Chung, H.; Ngo, K.J.; Plante, A.; Six, J. Evidence for carbon saturation in a highly structured and organic-matter-rich soil. *Soil Sci. Soc. Am. J.* **2009**, *74*, 130–138. [CrossRef]
64. Lopez-Fando, C.; Pardo, M.T. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. *Soil Tillage Res.* **2009**, *104*, 278–284. [CrossRef]
65. Thomas, G.A.; Dalal, R.C.; Standley, J. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. *Soil Tillage Res.* **2007**, *94*, 295–304. [CrossRef]
66. Mu, Z.J.; Huang, A.Y.; Ni, J.P.; Li, J.Q.; Liu, Y.Y.; Shi, S.; Xie, D.T.; Hatano, R. Soil greenhouse gas fluxes and net global warming potential from intensively cultivated vegetable fields in southwestern China. *J. Soil Sci. Plant Nutr.* **2013**, *13*, 566–578. [CrossRef]
67. Campbell, B.; Chen, L.; Dygert, C.; Dick, W. Tillage and crop rotation impacts on greenhouse gas fluxes from soil at two long-term agronomic experimental sites in Ohio. *J. Soil Water Conserv.* **2014**, *69*, 543–552. [CrossRef]
68. Omonode, R.A.; Smith, D.R.; Gál, A.; Vyn, T.J. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. *Soil Sci. Soc. Am. J.* **2011**, *75*, 152–163. [CrossRef]
69. Maag, M.; Vinther, F.P. Effect of temperature and water on gaseous emissions from soils treated with animal slurry. *Soil Sci. Soc. Am. J.* **1999**, *63*, 858–865. [CrossRef]
70. Linn, D.M.; Doran, J.W. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and no-tilled soils. *Soil Sci. Soc. Am. J.* **1984**, *48*, 1267–1272. [CrossRef]
71. Halvorson, A.D.; Mosier, A.R.; Reule, C.A.; Bausch, W.C. Nitrogen and tillage effects on irrigated continuous corn yields. *Agronomy* **2006**, *98*, 63–71. [CrossRef]
72. Koga, N.; Sawamoto, T.; Tsuruta, H. Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. *Soil Sci. Plant Nutr.* **2006**, *52*, 564–574. [CrossRef]
73. Sainju, U.M.; Stevens, W.B.; Caesar-TonThat, T.; Liebig, M.A. Soil greenhouse gas emissions affected by irrigation, tillage, crop rotation, and nitrogen fertilization. *J. Environ. Qual.* **2012**, *41*, 1774–1789. [CrossRef] [PubMed]