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Research article

No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system

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A R T I C L E I N F O

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A B S T R A C T

Soil organic carbon (SOC) storage and carbon dioxide (CO_2) emission under different tillage methods in a crop residue-returned farming system may not be consistent with result from studies of the usual tillage researches because crop residues are important carbon sources with significant effects on soil carbon input and output. Herein, we address a knowledge gap over the "hot spot" research on tillage practices on SOC storage and CO_2 emission in crop residue-returned farming systems. In this study, a long-term (2007–2019) field experiment was conducted, and the crop residues were returned to the soil after harvest; then, three tillage methods were conducted: no tillage (NT), subsoiling tillage (ST), and a moldboard plow tillage (CT). Our results showed that in the crop residue-returned farming system, NT and ST still showed advantages of lower CO_2 flux compared with CT, as well as a reduced average CO_2 flux of 14.5% and 8.5%, respectively, over a two-year average. The results of our long-term study suggest that the NT had advantages of SOC accumulation. In addition, as of June 2018, NT increased SOC stocks with 5.85 Mg hm^{-2} at a 0–60-cm soil depth compared with CT, whereas no significant difference was found between ST and CT. Overall, adopting NT in a crop residue-returned farming system improved SOC storage to 5.85 Mg hm^{-2} after 11 years as well as decreased CO_2 flux by 14.5% in comparison with CT, which is meaningful in improving soil carbon pool and decreasing soil CO_2 emission during agriculture production.

1. Introduction

Sustainable agricultural production requires farming to be ecologically responsible. This requires us to prioritize the impact of farming on soil quality and the environment rather than agronomic and economic factors (Robertson et al., 2000; Tilman et al., 2011). An increase in carbon sequestration is key to achieving sustainable agricultural and ecological development, as well as helping to alleviate the greenhouse effect. It can also increase soil organic carbon (SOC) storage and improve soil fertility (Dawson and Smith, 2007; Lal, 2004). Crop residues are rich in carbon, but their inappropriate use (e.g., incineration) can cause carbon to be directly converted into carbon dioxide (CO_2) that is released into the air and pollutes the environment (Smil, 1999). In recent years, in response to the government's directive and improvement in farmers' environmental awareness, the return of crop residues after harvest has been widely adopted. The advantages of crop residues returning to the soil have also been gradually discovered. For example, crop residue cover adds a protective layer to the surface that effectively reduces wind and water erosion of soil (Sharratt and Collins, 2018). In addition, crop residues returning to the field provides nutrients to the soil, thereby further improving soil fertility (Indoria et al., 2017; Ruis and Blanco-Canqui, 2017; Wegner et al., 2018). Furthermore, crop residues returning to the field prevents the air pollution that is caused by crop residue burning, thereby protecting the environment. Crop residues mulching or buried in the soil inevitably cause changes in the physical and chemical properties of the soil, thereby affecting soil biology characteristics, which in turn influences material circulation and energy exchange, as well as alters soil CO_2 emission flux (Hiel et al., 2018; Koga et al., 2016; Yamamoto et al., 2017).

Tillage can regulate the soil structure and is also a major factor affecting soil carbon storage and emissions (Abdalla et al., 2013). In dry land, CO_2 is the main form of soil carbon lost and it mainly comes from the mineralization of SOC. In agricultural production, the disturbance of soil by tillage is the primary method of increasing the soil CO_2 emission

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rate (Lu and Liao, 2017; Silva-Olaya et al., 2013). The traditional hoe-type plow turns over and loosens the shallow layer soils, which causes strong disturbances. The loose porous soil characteristics will fully combine with the air, causing SOC to mineralize and result in carbon loss (Abdalla et al., 2013). Conservation tillage, as a climate-smart agricultural practice, has been repeatedly reported to mitigate net greenhouse gas emissions by increasing SOC stocks (Stavi and Argaman, 2014). The adoption of no-till-based agriculture has the global potential to sequester 62–350 kg C·ha^{-1} per year (West and Post, 2002). Studies have shown that compared with conventional plow tillage methods, conservation tillage is more beneficial for SOC accumulation (Liu et al., 2015; Wang et al., 2018a). A study conducted in China has shown that adoption of conservation tillage could increase 0.16–0.99 Mg C·ha^{-1}·year^{-1} as well as decrease CO_2 flux by 55% compared with traditional plowing tillage (Dong et al., 2009).

However, in the crop residue-returned farming system, SOC storage and CO_2 emission under different tillage methods may not be concordant with data in studies wherein crop residues in plow tillage are removed. In the crop residue-returned farming system, after conducting plowing tillage methods, crop residues are buried into a relatively deep soil layer and covered by soil. Studies have previously shown that crop residues buried in soil are more beneficial in increasing soil carbon stocks than those on the soil surface because crop residues left on the surface are in direct contact with the air, and the decomposed portion is readily released via oxidation (Hu et al., 2016; Wang et al., 2015). With the crop residue-burying treatment, the soil particles covering the crop residues reduce the contact between the soil and the air; therefore, the decomposed crop residue carbon is more easily stored (Mulvaney et al., 2010), indicating that plowing tillage with crop residues buried is also an efficient method to store SOC. Additionally, conservation tillage is often considered as a method of increasing SOC storage. Studies comparing plowing tillage with crop residues buried and conservation tillage on SOC storage as well as CO_2 emission are limited. However, this information is essential because these practices are closely integrated with real agricultural production. With this knowledge, we could evaluate whether decreased soil disturbances with crop residues covered (e.g., NT and ST) still have advantages in a crop residue-returned farming system.

In view of this, we address a knowledge gap with compared SOC storage and CO_2 emission under no tillage, subsoiling, and plowing tillage methods under a crop residue-returned condition using a long-term *in situ* experiment (2007–2019) on the Loess Plateau, China. We aimed to evaluate the effects of tillage practices on SOC storage and CO_2 emission in the current agricultural production background and to achieve the goal of clean and sustainable agricultural production.

2. Materials and methods

2.1. Site description

This study established at the Heyang Dryland Agricultural Research Station in Heyang County, Shaanxi Province, China (35°19′54.45″N, 110°05′58.35″E; elevation 877 m), which is a typical semiarid area that belongs to a continental monsoon climate with a hot summer (maximum temperature: 30.3 °C) and cool winter temperature (minimum temperature: 7.5 °C). The precipitation is unevenly distributed during the year; large changes over time and the details of every month are shown in Fig. 1. The meteorological data were obtained from the nearest weather station, which was approximately 1 km away. The experimental fields were level, and the soils contain 27% clay, 39% silt, and 34% sand and are classified as Calcisol (WRB, 2014). Soil physical and chemical characteristics at the beginning of the experiment are shown in Table 1.

2.2. Tillage practices

The field experiment begun in 2007 and ongoing now which included three tillage treatments: no tillage (NT), minimum tillage with subsoiling (ST) and conventional tillage with a moldboard plowing (CT). Each plot was 5 m wide and 22.5 m long in a random block design with three repetitions. The crop system was a wheat and maize rotation. After the crop harvest, the full of crop residue was smashed into pieces with 10 cm or smaller using a crop residues pulverizer in a sunny day and the surface soil water content was less 18%. Then, we performed the different tillage practices. For the CT treatment, the soil was plowed at a depth of 18–25 cm using a tractor-mounted moldboard plow, with a rated power of 40.5 kW (Feng Yue 604 1LF-535 Machinery Co. Ltd., Shandong, China); this entire soil profile (0 to tilling depth) was disturbed and the crop residue was buried throughout the soil to a depth of approximately 20 cm. For the ST treatment, the soil was subsoiled to a

Table 1
The key properties of different soil layers (0–60 cm depth) at the beginning of the experiment.

Soil depth (cm)	SOC (g·kg^{-1})	TN (g·kg^{-1})	TP (g·kg^{-1})	TK (g·kg^{-1})	pH	Soil bulk density (g·cm^{-3})
0–20	7.65	0.75	0.59	5.91	8.22	1.31
20–40	5.96	0.68	0.18	5.53	7.91	1.45
40–60	5.34	0.62	0.11	5.72	7.93	1.46

SOC: soil organic carbon; TN: total nitrogen; TP: Total phosphorus; TK: Total potassium.

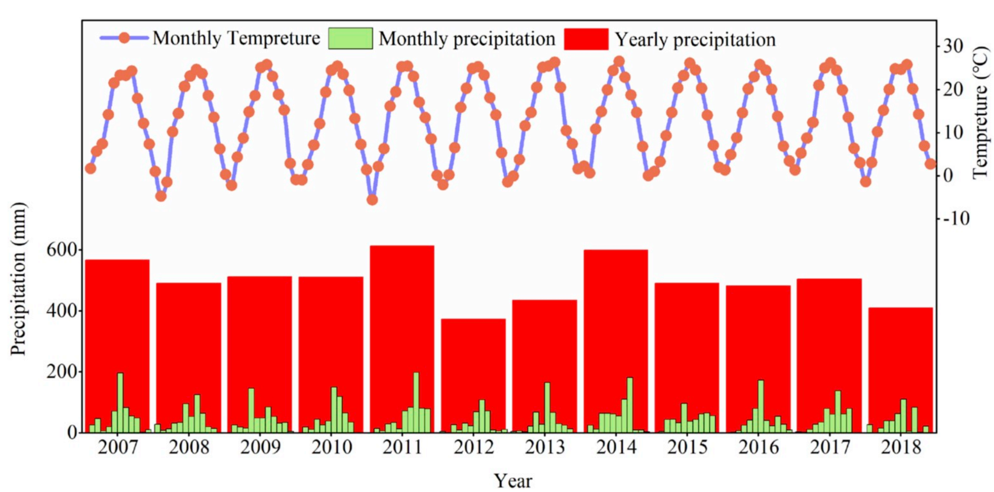

Fig. 1. Precipitation and temperature (2007–2018) at Heyang Dryland Agricultural Research Station in Heyang County, Shaanxi Province, China.

depth of 30–35 cm using a subsoiling chisel with adjustable wings set to 60-cm intervals between the terminal tines with slight surface soil disturbance. The draught power of the subsoiler was >88.2 KW, the working width was 250 cm by 4 rows. Soil disturbance was avoided in the NT treatment until sowing occurred. In NT and ST, the crop residues were retained and naturally mulched on the soil surface and the coverage ratio of crop residue was approximately 50–70%.

The crop pattern was one crop per year. Winter wheat and spring maize were rotation used and in the sequence of winter wheat one year and spring maize in the next year. Winter wheat variety of Chang 6359 were sown at early October and harvest at middle of June. Spring maize variety of Zhengdan 958 were sown at later April and harvest at middle of September. For the NT and ST treatments, the maize and wheat were drill seeded. However, in the CT treatment, sowing was carried out using a rotary tiller. The distances between the rows of wheat and maize were 20 cm and 60 cm, and were sown at densities of 3.3 million plants ha^{-1} and 60 thousand plants ha^{-1}, respectively. Whole fertilizer was applied once before sowing using 150 kg $N \cdot ha^{-1}$, 120 kg $P_2O_5 \cdot ha^{-1}$ and 90 kg $K_2O \cdot ha^{-1}$. The fertilizer types of N, P_2O_5 and K_2O were urea, ammonium phosphate and potassium sulfate, respectively. In the crop growth periods, weeds were removed by hand and often two times in the maize growth periods and one time in the wheat growth period.

2.3. Soil sampling, laboratory analysis and SOC stock calculation

Soil samples were collected from soil layers at a depth of 0–60 cm to measure the SOC, and three replicate samples were collected from each plot after crop harvest. Each soil sample was air-dried and finely ground. The samples were then used to determine SOC content using a potassium dichromate heating method, and we calculated standing stock values of SOC using the method described by Ellert and Bettany (1995).

2.4. Measurement of soil moisture content and temperature

Soil moisture, temperature, and CO_2 emissions measurements were performed simultaneously. The soil water content of all plots was measured at a 0–20 cm soil depth and determined by the gravimetric method (Wang et al., 2018b). Soil temperature was determined by an electronic thermometer (accuracy: 0.01; Shanghai, China), with a probe length of 20 cm; thus, the 0–20 cm soil temperature was determined.

2.5. Measurement of soil CO_2 emissions

Soil CO_2 emissions were measured using gas chamber gas chromatography, with a sampling box made of galvanized iron and with dimensions of 30 cm × 30 cm × 30 cm. Two small holes were drilled into the top of the box. One was connected to the three-way valve, and the other had a mercury thermometer inserted; then, the box was wrapped with sponge and aluminum foil to prevent extreme changes in temperature during sampling. The base was made of stainless steel with dimensions of 33 cm × 33 cm × 33 cm, and the upper part of the base had a sink with a width and height of 3 cm and 2 cm, respectively.

All experimental treatment plots were equipped with three sampling boxes and a base. After the seeds of corn or wheat were sown, the base was embedded in the soil. Before each sampling, we first injected water into the sink to a depth of approximately 1.5 cm to ensure airtightness when the static box was detained. Sample collection was conducted from 9:00 a.m. to 11:00 a.m. Before sampling, the fan in the box was opened to uniformly mix the gas. We simultaneously recorded the temperature and humidity inside the box as gas was being collected. The gas inside the chamber was sampled by a 25-mL plastic syringe at 0, 15, 30, and 45 min after the chamber was closed. The gas samples were stored in a 25-mL vacuum bag and then quantified in the laboratory using a gas chromatograph (Agilent 7890 A). The relevant measurement parameters were as described by Zhang et al. (2010). CO_2 flux was calculated using the equation of Zheng et al. (1998).

2.6. Statistical analysis

The data in the tables and figures are presented as the means of three replicates and the standard deviations in Fig. 2 and Fig. 4 were calculated using the three replication values. The statistical analysis software used in data analysis was Statistical Product and Service Solutions (SPSS, Inc., Chicago, IL, USA., version 19.0). Differences among tillage methods were determined by the least significant difference test (LSD). A linear model analysis was used to assess the relationship among water content, temperature, and CO_2 flux of soil (Fig. 5).

3. Results

3.1. SOC stocks

In this study, differences of SOC stocks using various tillage practices were observed (Fig. 2a). After 11 years of experimentation, the SOC stocks value in NT significantly increased by 5.85 Mg ha^{-1} in a 0–60-cm soil depth compared to CT, whereas no significant difference between ST and CT was observed. At a 0–20-cm soil depth, SOC stocks values decreased in the following order: NT > ST > CT and, compared to CT, NT and ST increased by 7.50 Mg ha^{-1} and 3.74 Mg ha^{-1}, respectively. At the 20–40-cm soil depth, CT showed a significantly increase in SOC compared to NT and ST by 1.39 Mg ha^{-1} and 2.67 Mg ha^{-1}, respectively. However, no significant differences in the 40–60-cm soil layer were observed among the three tillage practices.

3.2. Crop residues yield

This 11-year study measured whole crop biomass using three tillage methods (Fig. 2b). No differences were observed between NT and ST, whereas higher crop biomass was detected in NT and ST compared to CT, increasing by 6.1% and 7.3%, respectively. These results indicate a higher atmospheric CO_2 fixation in NT and ST, particularly ST.

3.3. CO_2 emissions

In this study, we measured CO_2 emissions from April 2017 to March 2019 to assess differences in CO_2 emissions flux using three tillage methods (Fig. 3a). Changes in soil CO_2 emission flux over time by NT, ST, and CT were basically synchronized, and the summer emission rate was higher than in winter. For all treatments during the observation period, the lowest value was observed in the CT treatment in winter (approximately 2.5 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$), and the highest value was observed in summer CT treatment (approximately 573 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$). In this study, two major differences of carbon flux with CT, NT, and ST were observed. NT and ST reduced CO_2 emission in October 2017 and June 2018 (calculated as 42.3%, 34.1% and 29.4%, 24.8%, respectively) compared with CT during the tillage conduction times. Outside of those times, the difference gradually became smaller.

We also calculated the average CO_2 flux to represent the overall difference of soil CO_2 emissions with different tillage methods (Fig. 4a). The results showed that CT had the highest average CO_2 flux, ST and NT had the lowest, and NT and ST exhibited a decrease in average CO_2 flux by 14.5% and 8.5%, respectively.

3.4. Soil water content and temperature

Soil temperature and soil moisture readily changed over time, and we recorded these from April 2017 to March 2019 (Fig. 3b and c). The soil temperature of NT was lower in most of the observation times (Fig. 4c), and the average soil temperature in NT was significantly lower than in CT, i.e., decreased by 0.7 °C, but no significant differences between ST and CT were observed. The average soil moisture content is shown in Fig. 4b. NT had, in most of the cases, higher moisture levels than CT and ST during the study period, and NT showed an increase in

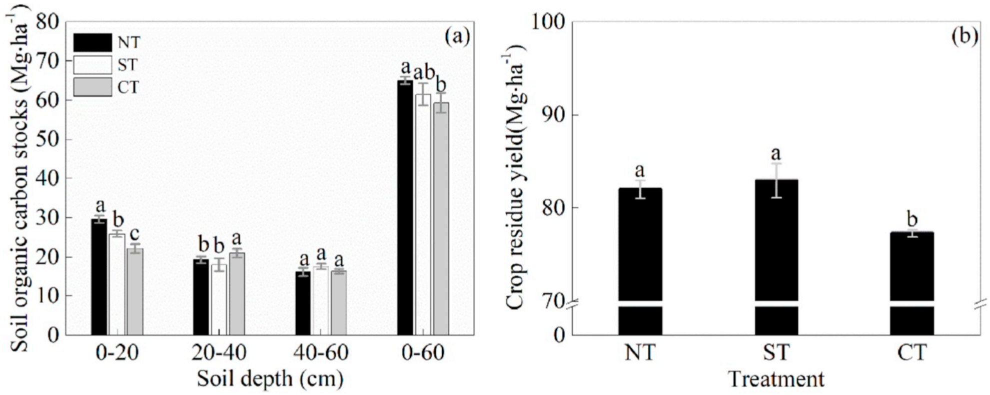

Fig. 2. Soil organic carbon stocks in 0–60-cm soil depth (a) and total crop residues yield (b) from 2007 to 2018 under tillage methods in crop residue-returned farming system. Error bars denote standard deviations (n = 3). The bars followed by different letters indicate significant differences between tillage methods ($LSD_{0.05}$). CT: conventional tillage with a moldboard plow; NT: no tillage; ST: minimum tillage with subsoiling.

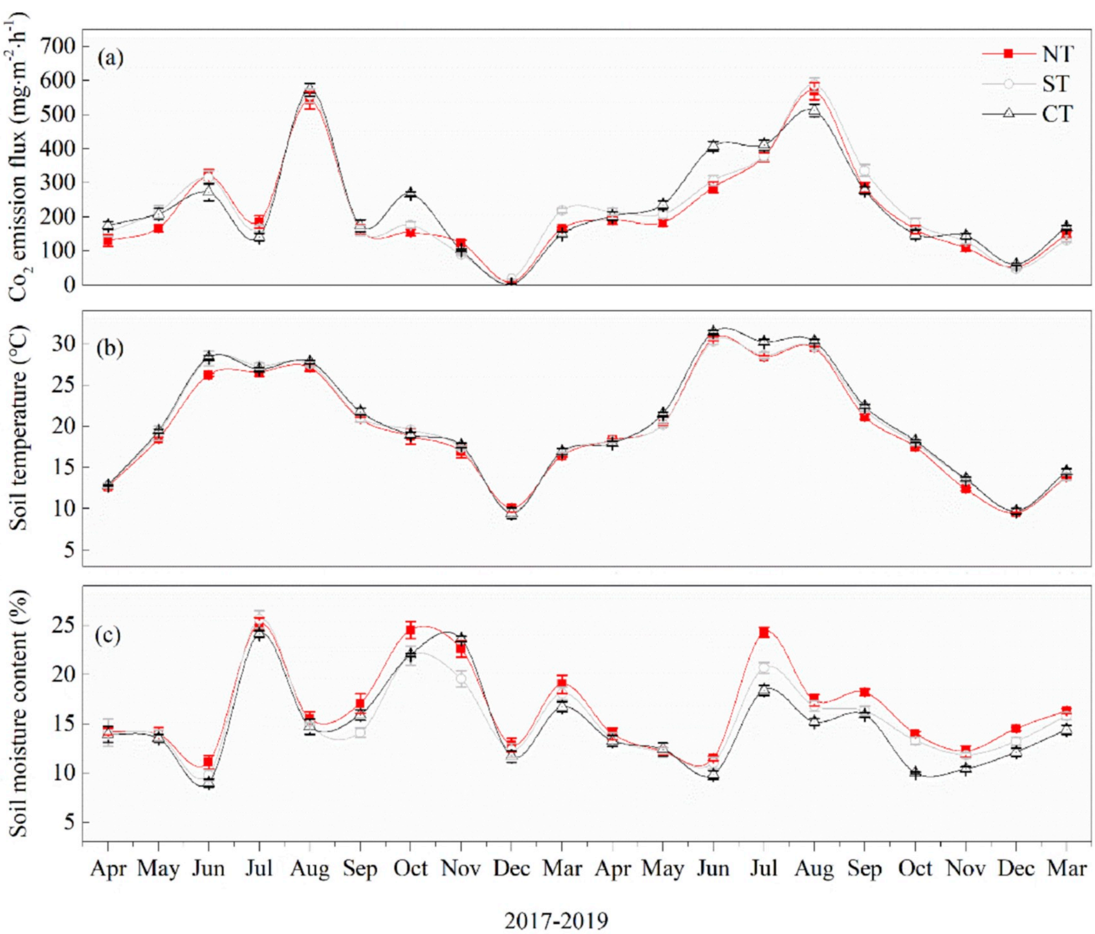

Fig. 3. CO_2 emission flux (a), soil temperature (b), and soil moisture content (c) under different tillage methods from 2017 to 2019 in crop residue-returned farming system. CT: conventional tillage with a moldboard plow; NT: no tillage; ST: minimum tillage with subsoiling.

the average annual soil moisture by 10.45% and 6.63% compared with CT and ST, respectively.

3.5. Relationships between soil water content, temperature and CO_2 emissions

A linear model was used to analyze the relationships among soil water content, temperature, and CO_2 emissions (Fig. 5). The results showed that the temperature had a close relationship with CO_2 flux ($R^2 = 0.6547$, $p < 0.01$). No significant correlation between soil temperature and soil water content was observed ($R^2 = 0.02$, $p = 0.50$). Additionally, the correlation between soil water content and CO_2 emission flux was depicted by quadratic equation, although no significant correlation between soil moisture content and CO_2 flux was detected ($R^2 = 0.02$, $p = 0.50$).

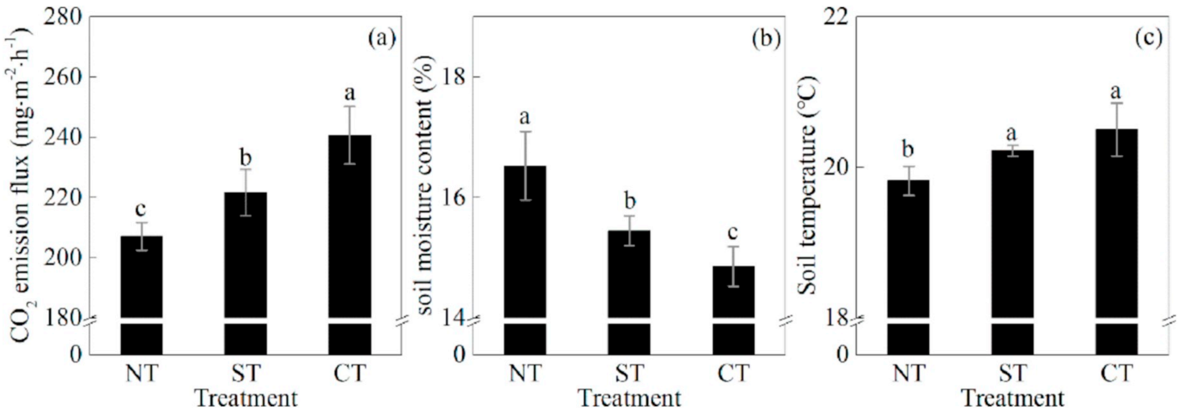

Fig. 4. Average CO_2 emission flux, soil moisture content, and soil temperature from Apr (2017) to Mar 2019 under tillage methods in crop residue-returned farming system. Error bars denote standard deviations (n = 3). The bars followed by different letters indicate significant differences between different tillage methods ($LSD_{0.05}$). CT: conventional tillage with a moldboard plow; NT: no tillage; ST: minimum tillage with subsoiling.

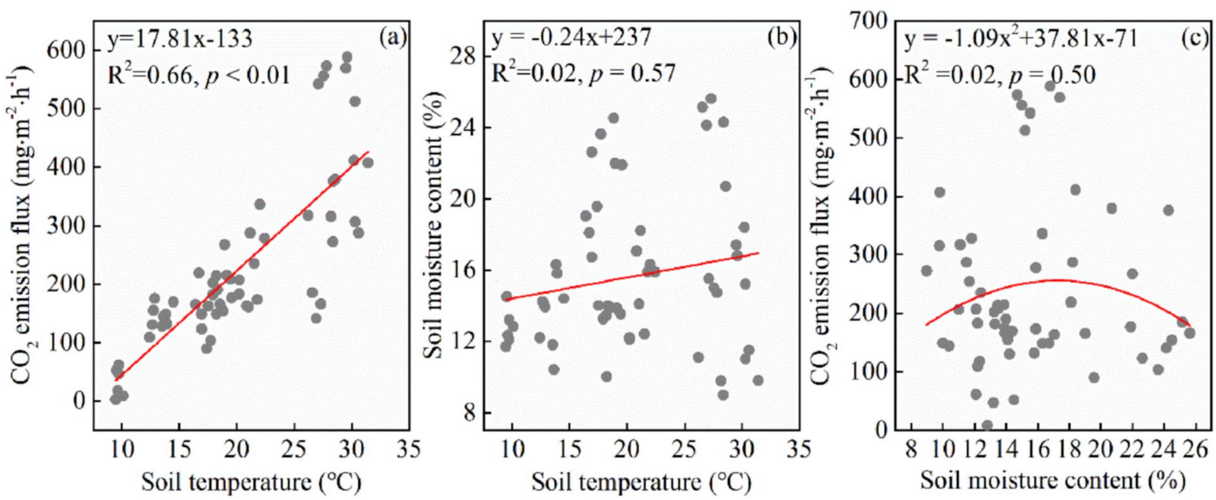

Fig. 5. Linear model analysis with soil temperature and CO_2 emission flux (a), soil temperature and soil moisture content (b), soil moisture content and CO_2 emission flux (c). n = 60.

4. Discussion

4.1. SOC stocks

An increase in SOC is expected because it represents an increase in soil fertility and a greater advantage in carbon storage, as well as a higher potential to sequestrate atmosphere carbon (Lal, 2004). In the crop residue-returned farming system, to our surprise, NT was the most efficient in SOC storage among the three tillage methods, i.e., our statistics showed it was 5.85 Mg ha^{-1} higher than CT. Our results may be discordant with the findings of other studies because in the crop residue-returned farming system, the crop residues in CT were buried in the soil, whereas previous studies have reported that buried crop residues are the most efficient way to convert carbon residues into organic carbon for storage in soil (Tang et al., 2019; Wu et al., 2017). This may be because of the advantages in SOC accumulation under NT treatments (Francaviglia et al., 2017). Perhaps the coverage of crop residues is not the most efficient way to use crop residues, but no tillage induces the accumulation of soil carbon compared with conventional plow tillage (Silva-Olaya et al., 2013), and our statistics have confirmed that no-tillage with covered crop residues compared with conventional tillage that buried these residues is still beneficial to the accumulation of SOC (Fig. 2a). Additionally, our study found that the improvement of SOC mainly occurred in the 0–20-cm soil layer with NT and ST compared with CT, and this result accords with the findings of other studies (Huang et al., 2006) because crop residues cover the surface soil layer and readily add a surface layer of SOC, and the downward movement of SOC is very slow. Additionally, a lower SOC value in NT and ST was found in the 20–40-cm soil layer, and CT significantly increased in SOC value compared with NT and ST by 1.39 and 2.67 Mg ha^{-1}, respectively. This finding may be because burying crop residues into a relatively deep soil layer under CT is conducive to deeper soil SOC accumulation (Ghimire et al., 2017).

4.2. Crop residues yield

Photosynthesis fixes carbon from the atmosphere, and it accumulates in crops as the primary method of atmosphere carbon fixation (Anonymous, 2016). We measured the entire crop residue yield from 2008 to 2018 under the crop residue under naturally returned conditions, as it could represent the difference in carbon input under different tillage methods. A higher crop residue yield was observed in NT and ST compared with CT soil with increases of 6.1% and 7.3%, respectively. This result means a higher carbon input in NT and ST, especially in ST. An improved atmospheric carbon fixation often indicates a better crop growth situation, and this is mainly related to the increase in soil water content in semiarid regions (Burgess et al., 2014; Ozpinar and Ozpinar, 2015). Many studies have also reported a positive correlation with crop biomass and SOC storage (Novelli et al., 2017); this means there was an increase in carbon input with NT and ST treatment compared with CT, which would benefit SOC accumulation.

4.3. CO_2 emission

The differences in soil carbon input, soil water, heat condition, and soil characteristics under different tillage practices in a crop residue-returned farming system can affect soil autotrophic and heterotrophic organism activity, which in turn can influence soil net carbon output (Reicosky, 1997). Under the comprehensive impact of tillage and crop residues, our study suggested that no tillage, crop residues covered, and subsoiling with crop residues covered all decreased soil CO_2 emission compared with conventional plow tillage with crop residues buried. This outcome means that under the crop residue naturally returned conditions, the adopted no tillage and subsoiling tillage had advantages of suppressing CO_2 emissions. It has been reported that no-tillage and subsoiling tillage can all decrease soil CO_2 emissions (Lu and Liao, 2017; Nath et al., 2017; Rutkowska et al., 2018). However, when referring to crop residues, the covering crops expose residual carbon into the air, and it is difficult to restore the residual carbon into the soil (Varela et al., 2017). In this study, for NT and ST, it is possible that the crop residue carbon did not have a higher utilization rate compared to plow tillage. However, the decrease in soil CO_2 emissions and increase in SOC stocks may be related to the cycling of carbon in soil (e.g., roots), perhaps because of the ability of microbial carbon sequestration (Schmidt et al., 2011; Six et al., 2002; Zachos et al., 2008). When referring to CT, the increase in CO_2 emission may be because of loosening of the soil, which increased the transfer of CO_2 between the interface of the soil profile and the air. Additionally, freshly decomposed crop residue is often unstable, and loose soil can increase its mineralization rate (Castanheira and Freire, 2013). Furthermore, a huge improve of increments with 42.3%, 34.1% and 29.4%, 24.8% compared with NT and ST in October 2017 and June 2018, respectively, was observed. These huge differences may due to the tillage conducted in these times. The plowing tillage would have stronger soil disturbance compared to NT and ST and also turning soil, which make the SOC in the 0–20 cm soil layer come directly in contact with air, which in turn accelerates the decomposition of SOC.

4.4. Relationships between soil water content, temperature and CO_2 emissions

Soil water content and soil temperature are two highly variable environmental factors that influence soil CO_2 emissions (Griscom et al., 2017). Soil temperature affects the metabolic intensity of soil microorganisms, and soil water content directly affects microbes by desiccation or resource limitations. These shifts could have influences on the soil material cycle and affect soil CO_2 emissions. In this study, we found a significant correlation between soil temperature and soil CO_2 flux, and these are supported by the results of other studies (Alvarez et al., 2001; Buragiene et al., 2015). However, no significant correlation was observed between soil water content and soil CO_2 flux, which is concordant with the results of Dong et al. (2017), but discordant with those of Zhang et al. (2011), who has showed that soil water content is closely related to CO_2 emission before and after tillage. Indeed, the close correlation between soil moisture content is often observed in certain conditions such as very high or very low soil moisture contents or a relative short period and with a low temperature change. This means that soil moisture influenced soil CO_2 emission, but the degree of influence is relatively lower than soil temperature, so in terms of the comprehensive effects of soil temperature and soil moisture content on soil CO_2 flux, the impact of soil moisture on soil CO_2 flux would not be significant.

Under crop residue naturally returned conditions, the use of no tillage still had advantages in increasing SOC storage (0–60 cm) compared with plow tillage and decreased CO_2 emission. This is undoubtedly useful to increasing soil fertility, thus making agricultural production more ecological and friendly to the environment, as well as solves the problem of finding a method of disposing crop residues.

5. Conclusions

Our study systematically evaluated SOC storage and CO_2 emissions under different tillage practices in crop residue-returned farming system. The results suggested that adopting NT still had advantages for SOC storage, which increased by 5.85 Mg ha^{-1} in 0–60-cm soil depth as well as decreased soil CO_2 emission flux by 14.5% compared with CT. However, in ST, a lower soil CO_2 flux was observed, whereas no significant differences in SOC storage compared with CT was detected in the 0–60-cm soil layer. These results indicate that the application of NT could improve SOC storage in a crop residue-returned farming system compared with plowing tillage with crop residues buried. Additionally, a decrease in soil temperature may contribute to lower rates of soil CO_2 emission under NT. Taken together, our results show that adopting no tillage methods in a crop residue-returned farming system helped decrease soil CO_2 emissions as well increase SOC storage, and this would benefit soil fertility improvement and help alleviate the greenhouse effect of agriculture. Simultaneously, our results could help us better manage soil and achieve sustainable agricultural and ecological agriculture development.

CRediT authorship contribution statement

Hao Wang: Methodology, Writing - original draft. **Shulan Wang:** Methodology, Writing - review & editing. **Qi Yu:** Writing - review & editing. **Yujiao Zhang:** Methodology. **Rui Wang:** Methodology. **Jun Li:** Writing - review & editing, Funding acquisition, Methodology, Writing - review & editing. **Xiaoli Wang:** Funding acquisition, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110261.

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