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Effects of different tillage practices on the carbon footprint of wheat and maize production in the Loess Plateau of China

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A B S T R A C T

Appropriate tillage practices reduce a crop's carbon footprint (CF) and mitigate climate change. However, little is known about the CF of winter wheat and spring maize production under different tillage practices in the Loess Plateau of China. To quantify the tillage differences and crop type differences in CF, a field experiment was established in 2007 in which the following six tillage practices were evaluated: plow tillage (PT), no-tillage (NT), subsoil tillage (ST), PT/NT rotation, NT/ST rotation and ST/PT rotation. The results showed PT had the positive CF value (488 kg CO_2-eq ha^{-1}), indicating a carbon source. However, NT, ST, ST/PT, PT/NT and NT/ST significantly decreased the CF (−628, −1382, −2328, −3038 and −3545 kg CO_2-eq ha^{-1}), demonstrating these tillage practices served as carbon sinks. The functional unit-scaled CFs (yield-scaled CF, cost-scaled CF, production value-scaled CF and net income-scaled CF) were similar to the trend of CF, which exhibited the following order: NT/ST > PT/NT > ST/PT > ST > NT > PT. The CF and functional unit-scaled CFs of winter wheat production were significantly higher than those of spring maize production. The CF and functional unit-scaled CFs decreased as planting year increased. In addition, increasing SOC storage and grain yield were benefit for decreasing CF. The results of this study showed NT/ST rotation produced the highest grain yield and SOC storage with the lowest CF and functional unit-scaled CFs and was thus determined to be the best tillage practice for balancing sustainable production with the environment in the Loess Plateau.

1. Introduction

Climate change is a global issue. Greenhouse gases (GHGs) from human activities are continuously emitted into the atmosphere from industrialization, energy and agricultural activities (Linquist et al., 2012). Globally, agricultural activity-produced total non-CO_2 GHG emissions comprised 10–12% of the anthropogenic emissions recorded in 2010 (Edenhofer et al., 2014). In China, GHG emissions from agricultural activities were 0.94 Gt CO_2-eq·yr^{-1} in 2012 (NDRC, 2016). Therefore, promoting cleaner production technology with less GHG emissions is necessary to mitigate global climate change and realize sustainable agricultural development.

Carbon footprint (CF) is used to effectively evaluate the GHG emissions of a product (BSI, 2011) and have been used recently as a robust research approach to study climate change phenomena. Pishgar-Komleh et al. (2017) quantified the CF variability of tomato production in two farms in Iran. Ali et al. (2017) estimated the effect of 12 management practices on CF in Italy. Yang et al. (2014) compared the CF of five cropping systems in the North China Plain. These studies aimed to attain proper measures for reducing GHG emissions in the local crop production by comparing CF. In addition, different CF have been observed in major grain crops production. Previous studies have reported the CF of wheat production was higher than that of maize production (Huang et al., 2017; Yan et al., 2015).

Different tillage practices have resulted in significant impacts on soil organic carbon (SOC) (Lu and Liao, 2017). Extensive plow tillage (PT) in crop production accelerates SOC decomposition and increases CO_2 emissions by disrupting soil aggregates (Paustian et al., 1997). However, conservation tillage practices, such as no-tillage

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(NT) and subsoil tillage (ST), have been shown to reduce SOC loss (Follett, 2001) and GHG emissions because of their minimal disturbance (Zhang et al., 2013, 2017). Therefore, conservation tillage increased SOC, indicating that released less CO_2 emission and ultimately reduced CF (Lal, 2007). Furthermore, tillage practices resulted in different CO_2 emissions from diesel consumption produced by mechanical tilling. Generally, NT mitigated carbon emissions due to no mechanical tillage compared to PT and ST (zhang et al., 2016). In addition, tillage affected various soil physical, biological and chemical properties and thus influenced crop yield (Mu et al., 2016; Zhang et al., 2018a) and straw yield (Zhang et al., 2018b). Straws returned to the soil can enhance soil fertility and crop yield (Choudhury et al., 2014), also induce more N_2O emissions than straw removed (Langeroodi et al., 2019). Therefore, we suggested that tillage practices directly affected CF through SOC and machinery input, and indirectly affected CF through crop yield and straw yield.

The Weibei dryland is a typical major grain crop production region in the Loess Plateau of China. Winter wheat (*Triticum aestivum* L.) and spring maize (*Zea mays* L.) are the major grain crops in this region. The adoption of a reasonable farming and cropping system is critical because of the serious wind and water erosion in this area. PT is a conventional and principal farming practice applied in this region, while NT and ST have been applied in recent years. Quantitative changes in the SOC content, SOC stock and grain yield under different tillage practices have been reported at the both the national and regional scales (Barbera et al., 2012; Dikgwatlhe et al., 2014; Ghimire et al., 2017; Huang et al., 2017; Ji et al., 2015; Zhang et al., 2017). However, little is known about the CF of major crops production for different tillage practices in the Weibei dryland. Therefore, a nine-year experiment for assessing the CF and functional unit-scaled CFs under six tillage practices for winter wheat and spring maize production was conducted and is described herein. The objective of this study was to identify an appropriate tillage practice for mitigating GHG emissions and to provide guidance for achieving sustainable agricultural production.

2. Materials and methods

2.1. Site description

The experiment was initiated in 2007 and was implemented over a nine-year period (2007–2016) in Ganjing Town (106°04′E, 35°19′N; at an altitude of 877 m), which is located in the Shaanxi Province of China and in the Loess Plateau. This region has a mean annual temperature of 11.5 °C, a mean annual sunshine duration of 2528 h, a mean annual evaporation of 1833 mm and a mean annual frost-free period of 210 days. The mean annual rainfall of Ganjing Town is 526 mm: 60% of the rainfall occurs in the months of July to September. Prior to the experimental period, PT without crop residue retention was practiced continuously, and spring maize was planted continuously. Dark loessial soil in the region was classified as a middle loam soil according to FAO/UNESCO (FAO, 1993). The physical and chemical properties of the soil in 2007, prior to the experimental period, are presented in Table 1.

2.2. Experimental design

This experiment was performed using a split plot design with two food crops (winter wheat and spring maize) as the primary plots and six tillage practices as sub-plots. The following six tillage practices were studied: PT, NT, ST, PT rotated with NT year by year (PT/NT), NT rotated with ST year by year (NT/ST) and ST rotated with PT year by year (ST/PT). All tillage practices used the full amount of crop residue return after crop harvest. For PT, crop straws were cut into small pieces, which were then mixed with the soil with a moldboard plow at a depth of 20–25 cm. However, for NT and ST, crop straws were cut and deposited on the soil surface. For NT, no soil disturbance was practiced until crop sowing. For ST, the topsoil was not disturbed, but the subsoil was tilled at a depth of 30–35 cm using a subsoiler at intervals of 60 cm. The area of each tillage plot was 37.5 m^2, and each tillage practice had three replicates.

2.3. Crop management

Annual one cropping systems is generally used in this region. Winter wheat and spring maize were planted annually in two different continuous fields from 2007 to 2016; thus, nine complete cycles were studied for both crops. The recommended fertilizer rates were 150 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} according to the local soil nutrients and suitable nutrient ratios for crop production. In order to study the tillage differences and crop type differences in CF, the fertilizer rates of N, P_2O_5 and K_2O for winter wheat and spring maize were the same every year in terms of the urea, diammonium phosphate and potassium chloride contents. All fertilizers were manually and evenly applied to the soil once before winter wheat sowing. However, before spring maize sowing, N, P_2O_5 and K_2O were manually and evenly applied to the soil at the rates of 75 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1}, respectively; and 75 kg N ha^{-1} was top-dressed during the big trumpet period. Herbicides were applied once on fallow soil. Table 2 presents information on seed time, seed rate and varieties of winter wheat and spring maize. Other farming practices were similar to the local practices described in this experiment.

2.4. Soil sampling and analysis

2.4.1. Soil organic carbon storage

During the harvest stages of winter wheat and spring maize every year, three soil samples for each of the soil tillage practices were taken at depths of 0–10 cm, 10–20 cm, 20–35 cm and 35–50 cm using a soil auger (5-cm diameter). Subsequently, soil samples were dried and passed through a 0.25-mm sieve to determine the SOC content. The SOC content was determined using 0.8 mol L^{-1} potassium dichromate (1/6 $K_2Cr_2O_7$) and a sulfuric acid (H_2SO_4) oxidation and titration method (Bao, 2000). The soil bulk density was determined using the core method (Blake and Hartge, 1986). SOC storage was estimated from the product of SOC, bulk density and soil depth (Blanco-Canqui and Lal, 2009), as shown in Eq. (1). The annual change of SOC storage was calculated using Eq.

Table 1
Soil physical and chemical properties in 2007, prior to the experimental period.

Soil depth (cm)	Winter wheat field		Spring maize field	
	Soil organic carbon (g kg^{-1})	Bulk density (g cm^{-3})	Soil organic carbon (g kg^{-1})	Bulk density (g cm^{-3})
0–10	7.4	1.35	7.1	1.38
10–20	7.2	1.35	6.6	1.48
20–35	5.8	1.48	4.8	1.58
35–50	4.3	1.45	4.2	1.57

Table 2
Details concerning the planting of winter wheat and spring maize.

Seeding time		Seeding rate (kg ha^{-1})		Variety	
Winter wheat	Spring maize	Winter wheat	Spring maize	Winter wheat	Spring maize
Sept., 2007–June 2008	Apr., 2008–Sept., 2008	150	75	Jin mai 47	Yu yu 22
Sept., 2008–June 2009	Apr., 2009–Sept., 2009	150	75	Jin mai 47	Yu yu 22
Sept., 2009–June 2010	Apr., 2010–Sept., 2010	150	75	Jin mai 47	Yu yu 22
Sept., 2010–June 2011	Apr., 2011–Sept., 2011	150	75	Jin mai 47	Yu yu 22
Sept., 2011–June 2012	Apr., 2012–Sept., 2012	150	75	Jin mai 47	Yu yu 22
Sept., 2012–June 2013	Apr., 2013–Sept., 2013	150	75	Jin mai 47	Yu yu 22
Sept., 2013–June 2014	Apr., 2014–Sept., 2014	150	75	Jin mai 47	Yu yu 22
Sept., 2014–June 2015	Apr., 2015–Sept., 2015	150	75	Chang 6359	Zheng Dan 958
Sept., 2015–June 2016	Apr., 2016–Sept., 2016	150	75	Chang 6359	Zheng Dan 958

(2).

$$SOCstorage\left(Mgha^{-1}\right) = SOC \times BD \times H \times 0.1 \quad (1)$$

$$AnnualchangeofSOCstorage\left(Mgha^{-1}year^{-1}\right) = \frac{1}{9}\sum_{i=1}^{9}\left[SOCstorage_{(y+1)} - SOCstorage_{(y)}\right] \times \frac{44}{12} \quad (2)$$

where *SOC* (g kg^{-1}) represents the soil organic carbon content; *BD* (g cm^{-3}) represents the soil bulk density; *H* (cm) represents the soil depth; 0.1 is the value of the coefficient that converts kg cm^{-2} into Mg ha^{-1}; 9 is the number of planting years; *SOC* storage$_{(y)}$ is the SOC storage obtained in a specific planting year, beginning in 2007; *SOC* storage$_{(y+1)}$ is the SOC storage determined for the next planting year, beginning in 2008; and 44/12 is the value of the coefficient that converts C to CO_2.

2.4.2. Grain yield and crop residue

For each soil tillage practice, winter wheat was collected from three 3-m^2 areas, and spring maize was collected from three groups of 20 plants cut along the diagonal direction during the crop harvest stage. Aboveground plant samples were cut at the soil surface. The grain and straw biomass of crops were separated by manual threshing. Root samples were obtained in triplicate from soil cubes that were 25 cm in length, 60 cm in width and 50 cm in height for both crops. Collection was started near the sampling plants, and roots from the same harvested plants were obtained. Root samples were washed with water and filtered through a 2-mm sieve. Crop residue (straws and roots) was oven-dried at 60 °C for 48 h (Hirte et al., 2018), and the dry matter content was determined after drying.

2.4.3. Carbon footprint

A CF can be defined as the total GHG emissions directly and indirectly produced during a single life cycle of a crop and is expressed in carbon dioxide equivalents (CO_2-eq) using the actual global warming potential values (IPCC, 2013). Direct GHG emissions include CO_2, CH_4 and N_2O emissions from upland areas. In this study, direct CO_2, N_2O and CH_4 emissions were not determined, but N_2O emissions from N fertilizer and crop residue inputs were calculated using emission factors. N_2O emissions are a major contributor to CF because of their high global warming potential (Guo and Zhou, 2007), while CH_4 emissions produced by dryland crops are negligible (Li et al., 2017). Indirect GHG emissions include agricultural inputs (fertilizers, pesticides, seeds and human labor) for crop production and diesel fuel produced by mechanical tilling, planting and harvesting (Lal, 2004). Eq. (3) and Eq. (4) were used to calculate CF:

$$CF = \sum_{i}^{n} AI_i \times EF_i + GHG_{N_2O} + SOCstorage \quad (3)$$

$$GHG_{N_2O} = (N_2O_{direct} + N_2O_{indirect}) \times 298 \quad (4)$$

where AI_i represents the consumption of one input (Table S1), n represents the number of inputs, EF_i represents the emission coefficient of one input (Table 3), and GHG_{N2O} represents the total amount of N_2O emissions. The CO_2 and N_2O emissions were converted to CO_2-eq by multiplying the actual values by the 100-year time horizon of the global warming potential; the global warming potentials of CO_2 and N_2O are 1 and 298, respectively (IPCC, 2007).

Direct and indirect N_2O emissions were calculated using Eq. (5) and Eq. (6):

$$N_2O_{direct} = (F_{SN} + F_{CR}) \times \delta_{1N} \times \frac{44}{28} \quad (5)$$

$$N_2O_{Indirect} = \left[F_{SN} \times FRAC_{GASF} \times \delta_{2N} + (F_{SN} + F_{CR}) \times FRAC_{LEACH} \times \delta_{3N}\right] \times \frac{44}{28} \quad (6)$$

where F_{SN} represents N fertilizer inputs; F_{CR} represents the total amount of N present in crop straw and roots; δ_{1N} represents the direct emission coefficient of N inputs; $FRAC_{GASF}$ represents the fraction of N fertilizer volatilized as NH_3 and NO_X-N; δ_{2N} represents the emission coefficient of the volatilization of N fertilizer; $FRAC_{LEACH}$ represents the fraction of N leaching; δ_{3N} represents the emission coefficient of N leaching (Table 3); and 44/28 is the coefficient used to convert N_2 to N_2O.

The N content in crop straw and roots was calculated using Eq. (7):

$$F_{CR} = (Straw_i + Root_i) \times N_{C(i)} \quad (7)$$

where i represents different crop types and $N_{C(i)}$ represents the N

Table 3
Emission factors of agricultural inputs used in calculating carbon footprint.

Item	Abbreviation	Emission factor	Unit	Source
N	EF_N	1.53	kg CO_2-eq kg^{-1}	CLCD 0.7
P_2O_5	EF_P	1.63	kg CO_2-eq kg^{-1}	CLCD 0.7
K_2O	EF_K	0.66	kg CO_2-eq kg^{-1}	CLCD 0.7
Pesticide	EF_{2P}	12.44	kg CO_2-eq kg^{-1}	Ecoinvent 2.2
Diesel	EF_D	3.10	kg CO_2-eq kg^{-1}	NDRC (2011)
Winter wheat seed	EF_W	0.58	kg CO_2-eq kg^{-1}	Ecoinvent 2.2
Spring maize seed	EF_S	1.93	kg CO_2-eq kg^{-1}	Ecoinvent 2.2
Labor	EF_L	0.86	kg CO_2-eq (person per day)$^{-1}$	Liu et al. (2014)
N fertilizer volatilization fraction	$FRAC_{GASF}$	0.1	kg NH_3–N + NO_X-N volatilized kg^{-1} N input	IPCC (2006)
N leaching fraction	$FRAC_{LEACH}$	0.3	kg N kg^{-1} N input	IPCC (2006)
Direct N_2O emission from N fertilizer on upland crops	δ_{1N}	0.01	kg N_2O–N kg^{-1} N input	IPCC (2006)
Indirect N_2O emission from N fertilizer volatilization	δ_{2N}	0.01	kg N_2O–N kg^{-1} NH_3–N + NO_X-N volatilized	IPCC (2006)
Indirect N_2O emission from N fertilizer leaching	δ_{3N}	0.0075	kg N_2O–N kg^{-1} N leaching	IPCC (2006)
N content of winter wheat	N_{CW}	0.0052	kg N (kg dry matter)$^{-1}$	NDRC (2011)
N content of spring maize	N_{CS}	0.0058	kg N (kg dry matter)$^{-1}$	NDRC (2011)

Note: The emission factors presented in this table were obtained from the Chinese Core Life Cycle Database (CLCD), IPCC guidelines Tire 1, National Development and Reform Commission (NDRC) and Ecoinvent database (http://www.ecoinvent.ch).

content of crops (Table 3).

CF from multiple perspectives was estimated herein. The functional unit-scaled CFs comprised the yield-scaled CF, production value-scaled CF, cost-scaled CF and net income-scaled CF, which were calculated as follows:

$$Yield - scaledCF = \frac{CF}{TY} \tag{8}$$

$$Productionvalue - scaledCF = \frac{CF}{TV} \tag{9}$$

$$Cost - scaledCF = \frac{CF}{TC} \tag{10}$$

$$Netincome - scaledCF = \frac{CF}{TI} \tag{11}$$

where *TY* (kg ha^{-1}) represents the total yield, *TV* (kg yuan^{-1}) represents the total yield value, *TC* (kg yuan^{-1}) represents the total cost of crop production, and *TI* (kg yuan^{-1}) represents the total net income of crop production (Table S2).

2.5. Statistical analysis

IBM SPSS version 19.0 software was used to perform an analysis of variance (ANOVA). The means and interaction comparisons were analyzed using the least significant difference (LSD) test. Origin Pro 2016 (64-bit) and Adobe Illustrator were used to design figures.

3. Results

3.1. Grain yield, straw biomass, root biomass and crop residue

To estimate the CF accurately, grain yield and crop residue (straw and root biomass) were analyzed. Grain yield, straw biomass, root biomass and crop residue were largely influenced by tillage practices, crop type and planting year (Table 4). With regard to the tillage effect, NT, ST, PT/NT, NT/ST and ST/PT significantly enhanced grain yield by 5.9%, 7.9%, 10.4%, 17.6% and 14.4% ($p < 0.05$), respectively, upon comparison to PT. NT/ST resulted in the highest grain yield, which was 11.1%, 9.0%, 6.5% and 2.8% ($p < 0.05$) higher than that of NT, ST, PT/NT and ST/PT, respectively. Compared with PT, ST, PT/NT, NT/ST and ST/PT increased straw biomass by 5.5%, 6.2%, 12.1% and 9.2% ($p < 0.05$), respectively; root biomass by 3.8%, 5.3%, 8.6% and 7.6% ($p < 0.05$); and crop residue by 5.2%, 6.1%, 11.5% and 8.9% ($p < 0.05$). Moreover, NT/ST exhibited the highest straw biomass, root biomass and crop residue, which were significantly different ($p < 0.05$) than those exhibited by NT, ST, PT/NT and ST/PT. Therefore, NT/ST was considered the best tillage for increasing winter wheat and spring maize yield, straw biomass and root biomass.

With regard to crop effects, the grain yield, straw biomass, root biomass and crop residue of spring maize were significantly higher than those of winter wheat. In terms of the effects of planting year, the grain yield, straw biomass, root biomass and crop residue fluctuated throughout the nine planting years. The minimum

Table 4
Effects of tillage, crop and planting year on grain yield, straw biomass, root biomass and crop residue.

Treatment	Grain yield (kg ha^{-1})	Straw biomass (kg ha^{-1})	Root biomass (kg ha^{-1})	Crop residue (kg ha^{-1})
Tillage (T)				
PT	6174 e	8855 e	1806 d	10662 e
NT	6536 d	9115 d	1843 cd	10957 d
ST	6661 d	9343 c	1874 bc	11217 c
PT/NT	6816 c	9407 c	1902 b	11310 c
NT/ST	7261 a	9925 a	1961 a	11887 a
ST/PT	7061 b	9666 b	1943 a	11609 b
Crop (C)				
Winter wheat	4142 b	5705 b	1017 b	6721 b
Spring maize	9361 a	13066 a	2760 a	15825 a
Year (Y)				
2008	5870 f	7908 g	1581 h	9489 g
2009	6112 e	8595 f	1685 g	10280 f
2010	5682 g	8037 g	1622 h	9659 g
2011	7333 c	10337 c	2113 c	12450 c
2012	6611 d	9089 e	1831 e	10920 e
2013	6160 e	8646 f	1782 f	10427 f
2014	6687 d	9372 d	1888 d	11260 d
2015	7926 b	10845 b	2182 b	13027 b
2016	8382 a	11640 a	2306 a	13946 a
ANOVA	p values			
T	<0.001	<0.001	<0.001	<0.001
C	<0.001	<0.001	<0.001	<0.001
Y	<0.001	<0.001	<0.001	<0.001
T*C	<0.001	0.047	0.164	0.060
T*Y	<0.001	<0.001	<0.001	<0.001
C*Y	<0.001	<0.001	<0.001	<0.001
T*C*Y	0.002	0.001	<0.001	0.001

Note: PT, plow tillage; NT, no-tillage; ST, subsoil tillage; PT/NT, PT and NT rotation; NT/ST, NT and ST rotation; ST/PT, ST and PT rotation. Different letters in the same columns represent significant differences among tillage practices ($p < 0.05$).

values were observed in the third year of planting (2010), while the maximum values were observed in the last year of planting (2016).

3.2. Soil organic carbon storage

SOC storage is an important index that reflects the CF of crop production, varies with time and is significantly affected by tillage (Gan et al., 2012). In this study, all practices exhibited significant effects on SOC storage (Table 5). The vertical distribution of SOC storage gradually decreased as soil depth increased. In terms of the effects of tillage, conservation tillage practices exhibited higher SOC storage values than conventional tillage. Compared with PT, the SOC storage of NT increased by 18.8% ($p < 0.05$) at a depth of 0–10 cm; the SOC storage of ST increased by 11.5%, 1.4% and 4.1% ($p < 0.05$) at depths of 0–10 cm, 10–20 cm and 35–50 cm, respectively; the SOC storage of PT/NT increased by 12.0%, 7.1%, 5.7% and 11.5% ($p < 0.05$) at depths of 0–10 cm, 10–20 cm, 20–35 cm and 35–50 cm; the SOC storage of NT/ST increased by 16.8%, 6.3%, 5.9% and 11.3% ($p < 0.05$) at depths of 0–10 cm, 10–20 cm, 20–35 cm and 35–50 cm; and the SOC storage of ST/PT increased by 8.3%, 3.7%, 4.4% and 10.8% ($p < 0.05$) at depths of 0–10 cm, 10–20 cm, 20–35 cm and 35–50 cm. Both the total SOC storage and annual change of SOC storage exhibited the following order: NT/ST > PT/NT > ST/PT > ST > NT > PT. The total SOC storage values obtained using NT/ST were 9.9%, 5.4%, 5.4%, 0.9% and 3.0% ($p < 0.05$) higher than those obtained using PT, NT, ST, PT/NT and ST/PT, respectively. The annual change of SOC storage obtained after NT/ST was 3.2, 2.1, 1.6, 1.1 and 1.2 times ($p < 0.05$) higher than that obtained after PT, NT, ST, PT/NT and ST/PT. These results indicated rotation tillage resulted in a better and more even distribution of SOC storage than single tillage, especially NT/ST, which exhibited the largest SOC storage and annual change.

As for the effects of crops on SOC storage, the total SOC storage in the spring maize field was higher than that in the winter wheat field. The annual change of SOC storage was 2.1-fold higher than that in the winter wheat field. In terms of the effects of the planting year, the SOC storage in each soil depth increased upon comparison with the base year data obtained in 2007. The annual change of SOC storage showed an increasing tendency as the planting year increased.

3.3. Carbon footprint and functional unit-scaled carbon footprints

The CF and functional unit-scaled CFs (yield-scaled CF, production value-scaled CF, cost-scaled CF and net income-scaled CF) were significantly affected by tillage, crop and planting year (Table 6). With regard to the effects of tillage, the CF and functional unit-scaled CFs after PT were positive values, indicating PT was carbon source. However, the other tillage practices resulted in negative CF and functional unit-scaled CF values, indicating NT, ST, PT/NT, NT/ST and ST/PT were carbon sinks. The lowest CF, obtained after NT/ST, was 5.6-, 2.6- and 1.5-fold lower than that obtained after NT, ST and ST/PT, respectively. Because NT/ST resulted in the lowest CF while producing a relatively high yield, high production value, high net income and low cost (Table S2), the yield-scaled CF, production value-scaled CF, cost-scaled CF and net income-scaled CF were also the lowest values produced by the tillage practice tested herein. The functional unit-scaled CFs of NT/ST was significantly lower than that of other tillage practices, with the exception of ST/PT. These results showed NT/ST was the preferred tillage system for promoting cleaner crop production, as it exhibited the lowest CF and functional unit-scaled CFs.

Table 5
Effects of tillage, crop and planting year on soil organic carbon storage and annual change of soil organic carbon storage.

Treatment	0–10 cm SOC storage ($Mg\ ha^{-1}$)	10–20 cm SOC storage ($Mg\ ha^{-1}$)	20–35 cm SOC storage ($Mg\ ha^{-1}$)	35–50 cm SOC storage ($Mg\ ha^{-1}$)	Total SOC storage ($Mg\ ha^{-1}$)	Annual change of SOC storage ($Mg\ ha^{-1}\ yr^{-1}$)
Tillage (T)						
PT	10.38 e	10.40 d	12.53 c	10.11 c	43.42 e	0.49 e
NT	12.33 a	10.33 d	12.37 d	10.22 c	45.25 d	0.77 d
ST	11.57 c	10.55 c	12.61 c	10.52 b	45.25 d	1.00 c
PT/NT	11.63 c	11.14 a	13.25 a	11.27 a	47.29 b	1.44 a
NT/ST	12.12 b	11.06 a	13.27 a	11.25 a	47.70 a	1.58 a
ST/PT	11.24 d	10.79 b	13.08 b	11.20 a	46.31 c	1.27 b
Crop (C)						
Winter wheat	11.78 a	10.26 b	13.14 a	9.64 b	44.81 b	0.71 b
Spring maize	11.31 b	11.17 a	12.56 b	11.88 a	46.93 a	1.47 a
Year (Y)						
2007	9.90 i	9.75 g	12.13 f	9.62 i	41.39 j	—
2008	10.06 h	9.82 g	12.12 f	9.70 hi	41.71 i	0.32 e
2009	10.34 g	10.13 f	12.16 f	9.85 h	42.48 h	0.77 d
2010	10.86 f	10.23 f	12.25 f	10.08 g	43.42 g	0.95 cd
2011	11.13 e	10.60 e	12.48 e	10.25 f	44.47 f	1.04 c
2012	11.57 d	10.58 e	12.57 e	10.57 e	45.28 e	0.81 d
2013	11.96 c	10.80 d	12.89 d	10.97 d	46.62 d	1.34 b
2014	12.35 b	11.01 c	13.31 c	11.29 c	47.95 c	1.33 b
2015	12.78 a	11.35 b	13.73 b	11.84 b	49.70 b	1.75 a
2016	12.84 a	11.89 a	14.17 a	12.3 a	51.21 a	1.51 b
ANOVA	p values					
T	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
C	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Y	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
T*C	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
T*Y	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
C*Y	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
T*C*Y	<0.001	0.002	<0.001	<0.001	<0.001	<0.001

Note: PT, plow tillage; NT, no-tillage; ST, subsoil tillage; PT/NT, PT and NT rotation; NT/ST, NT and ST rotation; ST/PT, ST and PT rotation. Different letters in the same columns represent significant differences among tillage practices ($p < 0.05$).

Table 6
Carbon footprint and functional unit-scaled carbon footprints of winter wheat and spring maize production after different tillage practices.

Treatment	CF (kg CO_2-eq ha^{-1})	Yield-scaled CF (kg CO_2-eq kg^{-1})	Production value-scaled CF (kg CO_2-eq $yuan^{-1}$)	Cost-scaled CF (kg CO_2-eq $yuan^{-1}$)	Net income-scaled CF (kg CO_2-eq $yuan^{-1}$)
Tillage (T)					
PT	488 a	0.134 a	0.069 a	0.086 a	0.712 a
NT	−628 b	−0.084 b	−0.047 b	−0.124 b	−0.058 b
ST	−1382 c	−0.202 c	−0.108 c	−0.241 c	−0.285 c
PT/NT	−3038 e	−0.355 d	−0.201 d	−0.583 e	−0.315 cd
NT/ST	−3545 e	−0.434 d	−0.240 d	−0.657 e	−0.462 d
ST/PT	−2328 d	−0.222 c	−0.131 c	−0.417 d	−0.183 bc
Crop (C)					
Winter wheat	−559 a	−0.101 a	−0.050 a	−0.102 a	0.051 a
Spring maize	−2918 b	−0.287 b	−0.169 b	−0.543 b	−0.248 b
Year (Y)					
2008	1032 a	0.252 a	0.129 a	0.185 a	0.746 a
2009	−602 b	−0.045 b	−0.030 b	−0.112 b	0.323 b
2010	−1256 bc	−0.227 cd	−0.122 cd	−0.234 bc	−0.323 de
2011	−1521 c	−0.154 bc	−0.091 bc	−0.287 c	−0.129 cd
2012	−718 b	−0.089 b	−0.049 b	−0.139 b	−0.087 c
2013	−2681 d	−0.338 de	−0.193 e	−0.493 d	−0.423 e
2014	−2627 d	−0.276 cde	−0.159 de	−0.487 d	−0.141 cd
2015	−4097 e	−0.484 f	−0.265 f	−0.755 e	−0.470 e
2016	−3179 d	−0.383 ef	−0.207 ef	−0.581 d	−0.384 e
ANOVA	p values				
T	<0.001	<0.001	<0.001	<0.001	<0.001
C	<0.001	<0.001	<0.001	<0.001	<0.001
Y	<0.001	<0.001	<0.001	<0.001	<0.001
T*C	<0.001	<0.001	<0.001	<0.001	<0.001
T*Y	<0.001	<0.001	<0.001	<0.001	<0.001
C*Y	<0.001	<0.001	<0.001	<0.001	<0.001
T*C*Y	<0.001	<0.001	<0.001	<0.001	<0.001

Note: PT, plow tillage; NT, no-tillage; ST, subsoil tillage; PT/NT, PT and NT rotation; NT/ST, NT and ST rotation; ST/PT, ST and PT rotation. Different letters in the same columns represent significant differences among tillage practices ($p < 0.05$).

With regard to the effects of crops on the CF, the CF and the functional unit-scaled CFs of winter wheat production were significantly higher than those of spring maize production. In terms of the effects of planting year, the CF and functional unit-scaled CFs decreased as the planting year increased. The CF and functional unit-scaled CFs were significantly lower in the last four years (2013–2016) upon comparison with first five years (2008–2012).

3.4. Components of carbon footprint

The components of the CF from winter wheat production (Fig. 1a) and spring maize production (Fig. 1b) showed the annual change of SOC storage resulted in the most negative contribution to CF, the ratios were 39.5%–65.2% in winter wheat production and 47.2%–75.8% in spring maize production. N_2O emissions produced by the application of N fertilizer and the incorporation of crop residue were secondary contributor to CF, mainly contributed 19.5%–33.2% in winter wheat production and 14.3%–30.3% in spring maize production. The third contributor to CF was fertilizer production, accounted for 8.3%–14.4% in winter wheat production and 4.8%–10.3% in spring maize production. The fourth contributor to CF was diesel consumption from tillage, sowing and harvest, which resulted in 4.4%–8.7% in winter wheat production and 3.1–8.0% in spring maize production. For both winter wheat and

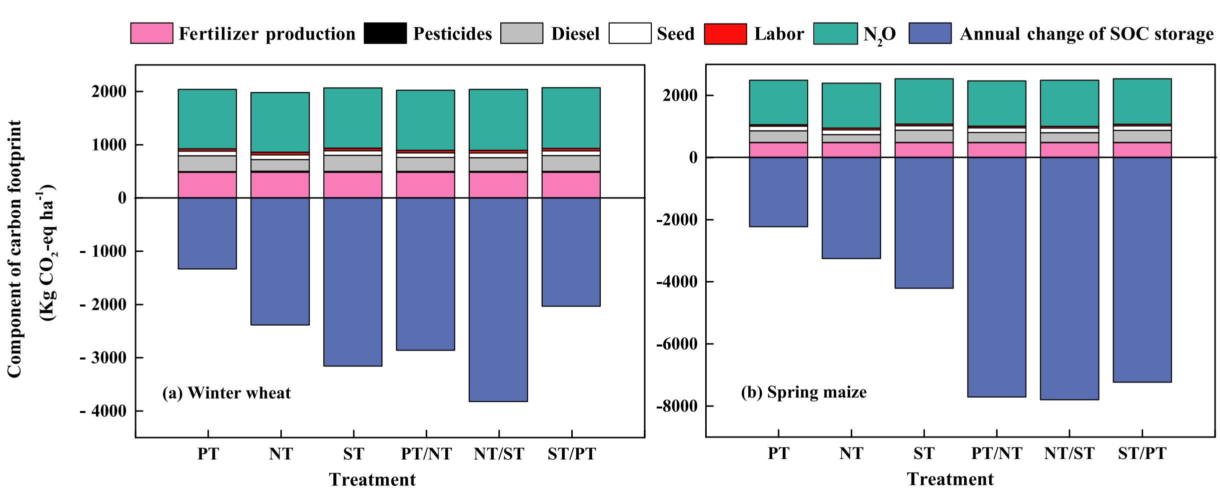

Fig. 1. Component of carbon footprint in winter wheat (a) and spring maize (b) production under different tillage treatments

spring maize production, seed (1.5%–2.6% and 1.4–3.1%, respectively), human labor (0.8%–1.3% and 0.5–1.1%, respectively) and pesticides (0.30–0.43% and 0.03–0.07%, respectively) made relatively smaller contributions to the CF.

3.5. Relationships among the carbon footprint, soil organic carbon storage, crop residue return and grain yield

The CF was significantly negatively correlated with SOC storage, crop residue return and grain yield (Table 7). The path analysis results showed the direct path coefficients (0.918 for winter wheat and 0.905 for spring maize production) between the CF and SOC storage were large. However, the indirect path coefficients (0.592 for winter wheat and 0.751 for spring maize production) between the CF and grain yield and the indirect path coefficients (0.564 for winter wheat and 0.709 for spring maize production) between the CF and residue return were larger than their direct path coefficients (0.457 and 0.374 between the CF and grain yield and 0.392 and 0.333 between the CF and residue return for winter wheat and spring maize production, respectively). Therefore, SOC storage exhibited a direct effect on the CF, grain yield and crop residue return exhibited indirect effects on the CF.

4. Discussion

4.1. Effects of tillage practices on soil organic carbon storage and grain yield

Tillage practices affected SOC storage was resulted by crop residue return amount and tillage depth. In this study, the crop residue obtained after NT, ST, PT/NT, NT/ST and ST/PT were significantly larger than those obtained after PT (Table 4). The larger amounts of crop residue returned to the soil during these tillage practices led to an increase in SOC storage. These results were consistent with those of Six et al. (2002), who demonstrated conservation tillage with residue return is an effective measure for improving the SOC pool. Furthermore, for different tillage practices, tillage depth affected the location of crop residue return, thus affecting the vertical distribution of SOC storage (Puget and Lal, 2005). Intensive soil disturbances after PT made the topsoil was uncovered, thus led to SOC decomposition loss. For NT and ST, crop residue was retained on the soil surface. NT primarily increased SOC storage at a depth of 0–10 cm because the soil was not disturbed. This SOC storage surface accumulation phenomenon was also reported in previous studies (Govaerts et al., 2009; Lenka and Lal, 2013; Tian et al., 2014; Yang et al., 2008). However, ST loosened the subsoil, promoted crop roots growth deeper and increased the amount of root biomass remaining in the deep soil after crop harvest, thus increasing SOC storage at the following depths: 0–10 cm, 10–20 cm and 35–50 cm. Similar trends were reported by Tian et al. (2016). PT/NT, NT/ST and ST/PT all increased SOC storage in each soil depth layer from 0 to 50 cm, with the highest SOC storage obtained after NT/ST. These findings were consistent with previous results reported by Wang et al. (2017), who indicated PT/NT, NT/ST and ST/PT rotations played a positive role in regulating SOC by reducing soil disturbances and avoiding SOC accumulation in the topsoil.

Grain yield, SOC storage and crop residue return were highly positively correlated with each other (Table 7). In general, a larger crop residue return to soil leads to an increase in SOC storage and, thus, an increase in grain yield. In this study, PT/NT, NT/ST and ST/PT rotations had higher crop residue return and better uniform distribution of SOC storage over a soil depth range of 0–50 cm, finally produced higher grain yield, and the highest grain yield obtained after NT/ST. In turn, higher crop production can lead to a higher C sequestration capacity because of high grain yield results in high straw residue return under a certain grain yield to straw mass ratio (She et al., 2017). This is a virtuous circle of crop residues return, SOC storage and crop yield.

4.2. Effects of tillage practices on carbon footprint

For both winter wheat and spring maize production, the highest CF was obtained after PT, followed by the CF obtained after NT, ST, ST/PT and PT/NT, and the lowest CF was after NT/ST. The primary factor resulting in significant differences in the CF among tillage practices was the difference in the annual change of SOC storage. NT/ST exhibited the highest annual change of SOC storage, suggesting that NT/ST largely mitigated C emissions and mostly reduced CF. Zhu et al. (2018) showed a similar finding that increased change of SOC storage contributed to reducing CF. N_2O emissions were a secondary contributor to the CF. Because the same fertilizer inputs were used for all the tillage practices studied herein, the differences in N_2O emissions were primarily caused by the amount of crop residue return. The N_2O emissions resulting from NT/ST were highest among all tillage, but the ratio of N_2O emissions to CF was far smaller than the ratio of the annual SOC storage change to CF, thus resulted in the lowest CF. Ali et al. (2017) reported similar results in which the crop residue remaining in the soil contributed only a small portion of N_2O to the CF. Fertilizer production was the third contributor; the portions (8.3%–14.4% in winter wheat production and 4.7%–10.3% in spring maize production) reported in this study were much lower than those reported in the studies of Zhang et al. (2013) (approximately 70%) and Huang et al. (2017) (68% in wheat production and 76% in maize production). One possible reason for this discrepancy could be different Fertilizer production and emission factors were applied. In this study, the rates of fertilizer (N and P) were only 50% of the traditional application rate in crop production, thus resulting in a

Table 7
Path analysis of carbon footprint, soil organic carbon storage, crop residue return and grain yield.

Factor	Winter wheat			Spring maize		
	SOC storage	Residue return	Grain yield	SOC storage	Residue return	Grain yield
Correlation coefficient						
CF	−0.864**	−0.504*	−0.523*	−0.954**	−0.743**	−0.797**
SOC storage		0.614**	0.645**		0.783**	0.830**
Residue return			0.988**			0.983**
Direct path coefficient						
CF	−0.918	−0.392	0.457	−0.905	0.333	−0.374
Indirect path coefficient						
SOC storage		−0.241	0.295		0.261	−0.310
Residue return	−0.564		0.452	−0.709		−0.368
Grain yield	−0.592	−0.387		−0.751	0.327	

Note: PT, plow tillage; NT, no-tillage; ST, subsoil tillage; PT/NT, PT and NT rotation; NT/ST, NT and ST rotation; ST/PT, ST and PT rotation. * means $P < 0.05$, ** means $p < 0.01$.

smaller contribution to the CF.

The CF of wheat winter production (−560 kg CO_2-eq ha^{-1}) was higher than that of spring maize production (−2918 kg CO_2-eq ha^{-1}) (Table 6). This trend was similar to that reported by Huang et al. (2017). However, the CF values were lower than those reported by Yan et al. (2015) (3000 kg CO_2-eq ha^{-1} and 2300 kg CO_2-eq ha^{-1} for wheat and maize, respectively) and Zhang et al. (2016) (4609 kg CO_2-eq ha^{-1} and 1914 kg CO_2-eq ha^{-1} for wheat and maize, respectively). These differences may be related to different planting patterns, management practices and whether SOC stock changes were considered when calculating the CF. In this study, winter wheat and spring maize were planted continuously each year and no irrigation was used during crop growth. Moreover, considering annual change of SOC storage in CF calculation can give a great CF reduction (Xu et al., 2019).

5. Conclusions

Tillage practices exhibited a significant impact on CF. The CF and functional unit-scaled CFs obtained after PT were the highest of the tillage practices studied herein, demonstrating PT showed as carbon source. However, the CF and functional unit-scaled CFs obtained after NT, ST, PT/NT, NT/ST and ST/PT were significantly decreased, showing these tillage practices functioned as carbon sinks. The CF and functional unit-scaled CFs were related to crop type and planting year; the CFs of winter wheat production were higher than those of spring maize production. The CF and functional unit-scaled CFs showed a decreasing trend as the planting year increased. The CF was directly and indirectly affected by SOC storage and grain yield; NT/ST had the highest SOC storage and grain yield with the lowest CF. In terms of sustainable production, NT/ST was the best tillage practice for promoting crop production and reducing the CF and the functional unit-scaled CFs in the Loess Plateau.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.161.

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