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Effects of Long-Term Straw-Return Modes on Soil Organic Carbon Content and Carbon Footprint in Wheat–Maize Rotation System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Straw return is widely applied in China to achieve sustainable grain production. However, inappropriate farm practices can increase greenhouse gas (GHG) emissions and reduce soil organic carbon (SOC) sequestration, thereby increasing the carbon footprint (CFP) and affecting

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soil fertility and climate change. A 10-year experiment was conducted to evaluate and quantify the effects of straw management on SOC, crop yield, and CFP under a winter wheat–summer maize rotation in the Guanzhong Plain. The experiment involved seven straw-return modes, namely high wheat stubble retention and chopped maize straw return (WH-MC), high wheat stubble retention and chopped maize straw return with sub-soiling every two years (WH-MM), high wheat stubble retention and no maize straw return (WH-MN), both chopped wheat and maize straw return (WC-MC), chopped wheat and maize straw return with sub-soiling every two years (WC-MM), chopped wheat straw return and no maize straw return (WC-MN), and a control with no return of either wheat or maize straw (WN-MN). The results indicate that SOC change, crop yield, and CFP were significantly influenced by the straw-return mode in the annual wheat–maize season. SOC sequestration rate was positively correlated with cumulative plant-derived C input, which ranged from 29.4 Mg C ha^{-1} in WN-MN to 100.7 Mg C ha^{-1} in WH-MC. Of all the studied treatments, WH-MC produced the highest grain yield and lowest CFP, which were 26% higher and 20.5% lower than those of the control, respectively. Grain yield and CFP in the individual seasons; WC-MN (by 31.8 and 25%) in the wheat season and WH-MC (by 24.6 and 21.1%), WH-MM (by 23.5 and 21%), respectively and WC-MN (by 20% only grain) in the maize season at ($P<0.05$) produced a significantly higher compared to the no straw return treatment. Annual GHG emissions were highest in the WC-MM treatment and lowest in WH-MN. Therefore, WH-MC found to be the most suitable straw-return for lowering CFP and enhancing crop yield and SOC sequestration. However, from perspective of the coordinated development of agriculture and the livestock industry, it is necessary to remove some straw for animal feed and fuel; so WH-MN produced optimum yield and maintained SOC stock with low GHG emissions. This study can help to improve sustainable agricultural productivity and addressing climate change by lowering atmospheric concentration of GHGs in the future.

Keywords: Soil organic carbon sequestration; straw-return mode; crop yield; carbon footprint; greenhouse gas emission; diesel.

1. INTRODUCTION

Global warming has become a pressing issue due to its potential impacts on natural and human systems. Increased atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) such as nitrous oxide (N_2O) and methane (CH_4) due to anthropogenic activities are of great concern due to the associated risk of global climate change. Substantial GHG emissions have been released as a result of the rapid development of industry and agriculture [1]. Agricultural production is one of the largest emitters of GHGs globally, accounting for 22% of total anthropogenic GHG emissions [2]. Agricultural inputs which are applied to maintain crop yield represent direct and indirect contributions to GHG emissions from agrochemical production, distribution, and on-farm operations [3]. However, appropriate management practices can reduce the GHG emissions from agriculture.

Agriculture must be environmentally sustainable while producing sufficient food for the growing world [4]. Feeding 22% of the global population with less than 9% of the world’s cultivated land, China must produce grain with a high efficiency while minimizing the negative impact of intensive agriculture on the environment [5]. China has more than 20% of the world's population and has among the largest agricultural outputs of any country, contributing 18 and 21% of the global production of wheat and maize, respectively [6]. Additionally, in order to increase crop production, China has become the largest consumer of inorganic fertilizer in the world, accounting for 90% of the global increase in use since the year 1981 [7]. Moreover, China is one of the world's largest anthropogenic GHG emitters, contributing 12% of global agricultural GHG emissions [8]. Previously, farmers in China burned crop residues in fields, thereby causing environmental pollution. Therefore, to reduce this negative consequence, a government policy was implemented to compel farmers to return crop residues to fields. Consequently, over the past two decades, straw return to crop fields has rapidly been popularized in China. According to the US–China Joint Announcement on Climate Change [9], China is committed to reaching a peak in anthropogenic GHG emissions by 2030 and to increasing the share of non-fossil fuels in its primary energy consumption to around 20% by the same year.

The North China Plain (NCP) is one of the most important agricultural regions in China. For example, between 1996 and 2007, crop production in this region accounted for 35.3 and 69.2% of China's total maize and winter wheat yields, respectively [10]. In the NCP, intensive agricultural practices are used and the rate of chemical fertilizer use is increasing rapidly. Intensive farming increases GHG emissions [11] and agricultural management costs, and additionally requires more resources and leads to environmental problems [12]. In addition to chemical fertilizers, tillage practices, pesticide application, crop harvesting, and residue management all contribute to GHG emissions [13].

Great attention has been paid to carbon sequestration as a way to reduce atmospheric CO_2 concentration in order to mitigate global climate change [14]. The global soil organic carbon (SOC) pool is about two times larger than the atmospheric C pool and three times larger than the biotic C pool, and thus C sequestration in soil has been widely considered as a promising measure for mitigating the atmospheric CO_2 concentration [15,16]. Among all management practices, straw return has been suggested as the best method to increase SOC sequestration in croplands [17]. In China, straw return is commonly applied as part of sustainable agriculture. The in situ retention of crop straw plays important roles in maintaining the soil nutrient balance and supplying organic matter to the soil; therefore, it improves soil fertility and is beneficial to sustainable crop production [18]. Several long- and short-term studies have investigated various forms of agricultural management involving SOC sequestration and/or the reduction of GHG emissions, including tillage, fertilization, crop rotation, and straw return [19,18,20,21,22,23,24]. Furthermore, numerous studies have shown that straw input effectively increases the SOC content [25,26,27,12]. However, these studies were focused either on the GHG emissions from agricultural inputs only, on only one effect of crop straw return, or on rice–wheat rotation and/or wheat–maize rotation with only one method of straw return. Straw can be incorporated into the soil in different ways (e.g., leaving stubble on the field surface, mulching on the surface, chopping and incorporating into soil), each of which require different amounts of fuel for machine operation and require different tillage methods (e.g., no tillage, rotary tillage, deep sub-soiling) and have different effects on the soil community, which can affect the SOC accumulation. However, there is a large research gap regarding the effects of different straw incorporation modes on net global warming potential considering together GHG emissions, SOC accumulation, and crop production.

The concept of carbon footprint (CFP) has been widely employed for calculating the impact of production sectors or human activities on climate change. Generally, CFP has been assessed using the full life stages of GHG emissions which are directly and indirectly caused by an activity or a product using the life cycle assessment (LCA) methodology [28]. The CFP of crop production can be assessed using the LCA method up to the farm gate boundary by quantifying the total GHG emissions associated with the production of agrochemical inputs such as fertilizers and pesticides and with energy consumption from farm mechanical operations [29,30]. Thus, it is critical to explore and develop C-responsive sustainable straw-return methods with low agricultural GHG emissions, high SOC sequestration potential, and optimum crop yield in upland wheat–maize double cropping systems. In this paper, we propose different long-term straw-return modes for a wheat–maize cropping system and the CFP of each straw-return mode was estimated based on the total GHG emissions from the manufacture, storage, and transportation of off-farm agricultural inputs, their on-farm application, and the direct emission of N_2O from the application of mineral N fertilizer in different straw-return modes.

Our objectives were to (**i**) evaluate the SOC change and SOC sequestration rate over10 years using different straw-return management methods, (**ii**) quantify the grain yield and CFP of different straw-return modes, and (iii) provide information for researchers, policy makers, and farmers to reduce the GHG emissions from China's agricultural sector help growers to decide which straw-return approach they should adopt. The CFP was estimated with the LCA method using long-term farm experimental data in a winter wheat–summer maize cropping system in the Guanzhong, North China Plain. The contributions of all individual inputs involved in different straw-return management methods and the tillage type and frequency of straw incorporation to the overall CFP were considered.

2. MATERIALS AND METHODS

2.1 Study Site

The field experiment was conducted at the Experimental Station of Northwest A&F

University in Yangling, Shaanxi Province, (34°36′ N, 108°52′ E, 427.4 m above sea level). The study site has a warm-temperate, sub-humid, continental monsoon climate and is prone to drought, with a dry and cold winter and a hot summer [31]. The average annual temperature and sunshine hours are 12.9°C and 2096 h, respectively. The annual precipitation (~527 mm) is unevenly distributed, with more than 75% falling from July to September over the last 30 years. The soil of the site is classified as a Eum-OrthicAnthrosol (Cumulic Haplustalf in the USDA system) with a silty loam texture. At the beginning of the experiment the physical and chemical properties of the topsoil (0–20 cm depth) were recorded as follows: pH of 8.2 (1:1 soil: water), SOC concentration of 11.32 g kg^{-1}, total N of 0.68 g kg^{-1}, total P of 0.61 g kg^{-1}, Olsen P of 52.6 mg kg^{-1}, total K of 21.53 g kg^{-1}, available K of 122.8 mg kg^{-1}, and bulk density of 1.20 g cm^{-3}.

2.2 Experimental Design

The field experiment was conducted between 2008 and 2018, and involved the continuous rotation of winter wheat and summer maize with a total of seven straw-return mode treatments every season, namely (1) high wheat stubble retention and chopped maize straw return (WH-MC), (2) high wheat stubble retention and chopped maize straw return with sub-soiling every two years (WH-MM), (3) high wheat stubble retention and no maize straw return (WH-MN), (4) both chopped wheat and chopped maize straw return (WC-MC), (5) chopped wheat and chopped maize straw return with sub-soiling every two years (WC-MM), (6) chopped wheat straw return and no maize straw return (WC-MN), and (7) a control with no return of either wheat or maize straw (WN-MN). For the WH mode, the aboveground straw was kept in the field in the form of 25- to 30-cm high stubble, and maize was precisely sown among the stubble without rotary tillage. For WC, wheat straw was chopped into 5- to 10-cm pieces by machine, distributed over the soil surface, and incorporated by rotary tillage prior to maize sowing. For WN, wheat straw was cut by machine and manually removed from the field, and then no-tillage sowing was employed for the summer maize crop. For MC, after the maize crop was harvested with combine harvesters, the aboveground straw was chopped into pieces with a length of 5–10 cm, distributed over the soil surface with a residue chopper, and then incorporated into the upper 0–5cm of soil by rotary tillage before winter wheat was sown. For the MM straw-return mode in the wheat seasons from 2008–2010, diesel use for farm operation was 112.5 L/ha and straw was mulched over the soil surface, however in subsequent years the design of this treatment was modified to straw chopping and sub-soiling every two years. Accordingly, every two years, 217.5 L/ha of diesel was used with straw chopping and deep sub-soiling, while in the years between, 157.5 L/ha of diesel was used with straw chopping and incorporation into soil, as for MC. Therefore, the average diesel consumption in MM return mode is162 L/ha for the whole 10 years, however for the GHG emission calculation the diesel consumption amount for each individual year was used. For MN, after the crop was harvested with combine harvesters, the aboveground part of the crop (straw) was chopped using a similar process to that employed in MC, and then the straw was removed from the field by machine and plowed by rotary tillage, prior to wheat sowing. Therefore, all the farm operations in MC and MN consumed the same amount of diesel for farm machine.

All field management operations during the experiment were mechanized, and different management was used for each treatment. During the maize season, all of the treatments were fertilized with 187.5 kg ha^{-1} N and 22.5 kg ha^{-1} P_2O_5, while during the wheat season all of the treatments were treated with 120 kg ha^{-1} N and 102 kg ha^{-1} P_2O_5.The nitrogen and phosphate fertilizers were urea and diammonium phosphate, respectively.

The maize cultivar (Nonghua-50) was sown with a row spacing of 50 cm at a density of ~63,000 plants ha^{-1}in early June each year and harvested in early October of the same year. The wheat cultivar (Mianyang-26) was planted with a row spacing of 15 cm at a seeding rate of 210 to 225 kg ha^{-1} at the beginning of October each year and harvested at the beginning of June of the following year. The plot size of each treatment was 12.5 × 56 m and replicated four times. Wheat and maize plants were supported by border strip irrigation during different stages in addition to rainfall. Pesticides were applied, 5.6 L/ha and 7.34 L/ha for each treatment plot, respectively during the maize and wheat growing seasons to control pests and weeds following recommended practices. Pesticide input quantity is the sum of herbicide, insecticide, and fungicide.

2.3 Data Collection

The SOC contents in the topsoil (0–20 cm) were determined before seeding maize in June 2008 and after wheat harvest in June 2018 using the $K_2Cr_2O_7$–H_2SO_4 digestion method after soil collection [31]. Additionally, soil bulk density was also determined at the same time to allow the calculation of SOC storage. Sampling of maize and wheat plants in each plot were manually collected for straw yield estimation and grain yields were measured every year from 2008 to 2018. GHG emissions and CFP was calculated for each year of the treatments in winter wheat and summer maize and then average result was taken for each treatment.

2.4 Measurement of Crop Biomass and Yield and Estimation of Cumulative Plant-Derived Carbon Input

Agronomic data were collected at crop maturity for both winter wheat and summer maize every year from 2008–2018. Maize grain and straw were manually harvested from two areas of 10 m^2 in each plot. After air drying, the grain and straw were oven-dried at 60°C to allow the determination of dry weight. Similarly, wheat grain and straw were collected from two separate areas of 2 m^2 from the center of each plot, and the dry weights of the grain and straw were air dried and determined after oven drying the collected sample at 60°C. The amount of aboveground stubble remaining in the field after straw harvest was estimated for each crop and each treatment using ratios of stubble to straw biomass of approximately 10% and 20% for maize and wheat, respectively [32,33]. The amount of root in the field was estimated based on root to straw biomass proportions of 23% and 22% for maize and wheat, respectively [34]. The average carbon concentrations of both maize and wheat were taken as 0.4 kg C kg^{-1} [35]. The rhizodeposition-derived C of maize and wheat was assumed to be equal to the root-derived C [36]. In general, cumulative plant-derived C input levels for each treatment were quantified by summing the total C returned from crop residues (straw, stubble, roots, and rhizodeposition) over the 10 years.

2.5 Soil Organic Carbon Storage and Sequestration Rate

In our study, SOC stock and sequestration rate was calculated for each treatment to determine the long-term effect of different straw-return modes on SOC change during the 10-year field experiment.

The following equation was used to convert the SOC concentration in the top 20 cm of soil to the SOC stock [37]:

$$\mathrm{SOC_S} = \mathrm{SOC_C} \times \mathrm{BD} \times \mathrm{D} \times 10^{-1} \qquad (1)$$

Where SOC_S is the SOC stock (Mg C ha^{-1}), SOC_C is the SOC concentration (g Ckg^{-1}), BD is the soil bulk density (g cm^{-3}), and D is the measured soil depth (cm).

The changes in SOC caused by different straw-return modes during the long-term investigation relative to the initial levels were calculated using the initial and final SOC stock (Mg C ha^{-1}) via Equation 2. Additionally, the percentage change in SOC relative to the initial SOC stock was calculated using Equation 3; positive changes indicate an increase in SOC stock, while negative changes indicate a decrease.

$$\Delta\mathrm{SOC\ stock} = \mathrm{SOC_f} - \mathrm{SOC_i} \qquad (2)$$

$$\%\Delta\mathrm{SOC\ stock} = \left(\frac{\Delta\mathrm{SOC}_{stock}}{\mathrm{SOC_i}}\right) \times 100 \qquad (3)$$

Where SOC_f and SOC_i are the SOC storages in the final year and initial year of a specific treatment, respectively, as calculated using Equation 1.

The carbon sequestration rate (CSR, Mg C ha^{-1} yr^{-1}) was calculated using the following equation:

$$\mathrm{CSR} = (\mathrm{SOC_f} - \mathrm{SOC_i})/\mathrm{t} \qquad (4)$$

Where t is the duration of the experiment (yr).

2.6 Calculation of CFP and the System Boundary

The CFP was estimated using the LCA method for each individual input used under each treatment for both wheat and maize. The system boundary was set from the seeding to harvesting of a crop, as shown schematically in Fig. 1. Indirect CO_2 emissions from agricultural inputs and direct N_2O emissions from N fertilizer application were estimated, and the results were expressed in carbon dioxide equivalent (CO_2-eq) using their relative global warming potential [1]. Emissions of CH_4were neglected in this study since they contribute little to GWP in upland areas [38,23]. Therefore, the CFP calculations included (1) the manufacture, storage, and transportation of inorganic N and P fertilizers, herbicides, and pesticides to the farm gate and their application, (2) the manufacture, storage, and transportation of diesel fuel for agricultural machinery used for planting, harvesting, and tilling, and (3) direct emissions of N_2O from N fertilizer application.

The carbon emission from agricultural inputs (CE_{inputs}) including fertilizers, pesticides, and energy consumption for farm mechanical operation were estimated using the following equation [39,40]

$$\mathrm{CE_{inputs}} = \sum_{i=1}^{n} \mathrm{AI_i \times EF_i} \tag{5}$$

Where AI_i is the amount of an individual agricultural input applied in the cropping system, including fertilizers and pesticides (kg/ha) and diesel fuel (L/ha) used for farm activities; EF_i is the specific GHG emission factor of an individual agricultural input, including manufacture, storage, and transportation; and n is the number of agricultural inputs.

The direct emission of N_2O from N fertilizer application was estimated using the following equation:

$$E_{N_2O} = Q_N \times EF_{N_2O} \times \frac{44}{28} \times 298 \tag{6}$$

Where E_{N2O} represents the direct N_2O emissions from the application of N fertilizer (kg CO_2-eq), Q_N is the quantity of N fertilizer applied in a single treatment (t), and EF_{N2O} is the default N_2O emission factor of applied N fertilizer (kg N_2O-N kg^{-1} N fertilizer). The emission factors of synthetic N fertilizer use in dry crops were adopted from [41]; 44/28 was taken as the molecular conversion factor of N_2 to N_2O, and 298 was taken as the global warming potential of N_2O in a 100-year horizon [1]. All of the emission factors (EFs) used in this analysis for different inputs or sources are listed in Table 1.

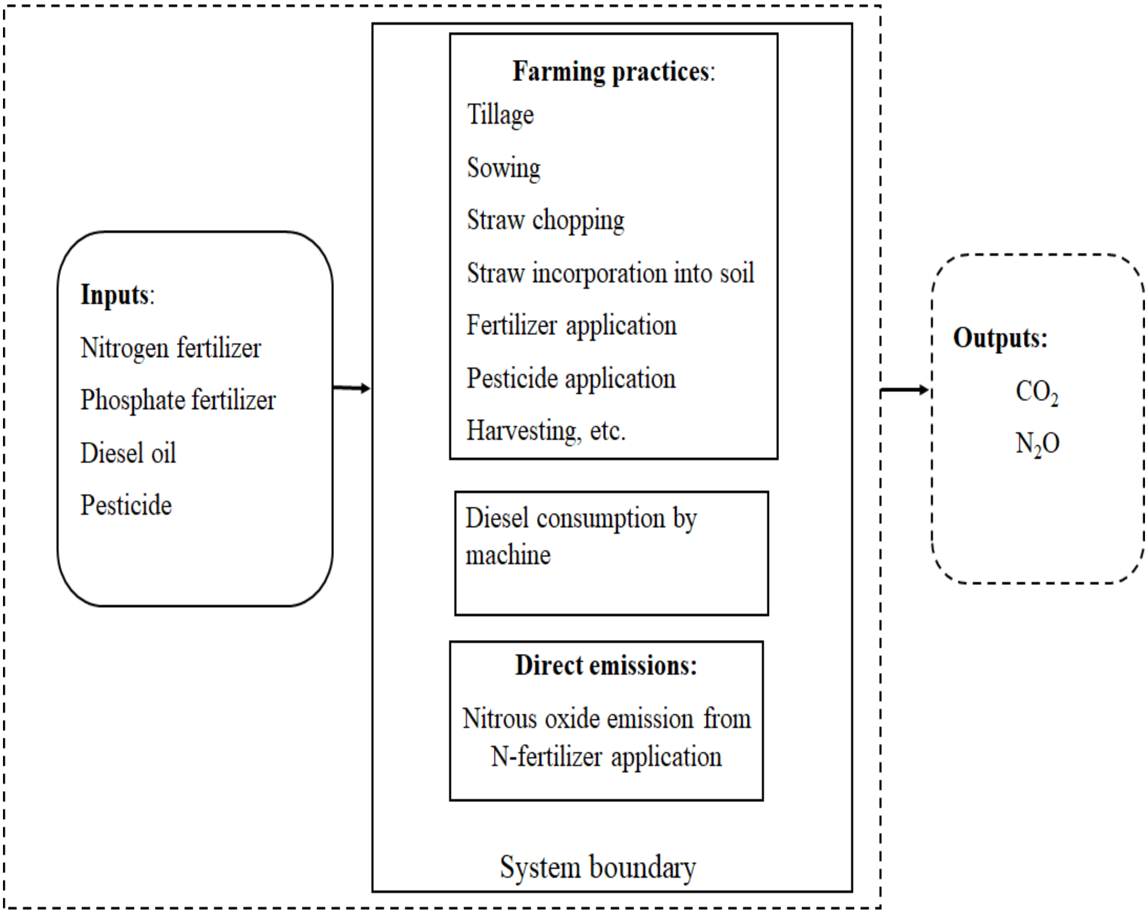

Fig. 1. System boundary used for the estimation of greenhouse gas (GHG) emissions in the winter wheat–summer maize cropping system.

Table 1. Agricultural inputs considered in the estimation of GHG emissions and their emission factors (EFs)

Agricultural input (AI)	EF	Source
N	4.96 kg CO_2-eq/kg	[22]
P_2O_5	1.14 kg CO_2-eq/kg	[22]
Diesel	3.32 kg CO_2-eq/L	[22]
Pesticide	12.44 kg CO_2-eq/kg	[23]
Direct N_2O emission from N fertilizer	0.01 kg N_2O-N/kg fertilizer N	[41]

Note: CO_2-eq: carbon dioxide equivalent. Values of EF for N, P_2O_5, diesel, and pesticide were obtained from studies of other long-term upland crops similar to those used in our study and planted in the same region, and the EF for direct N_2O emission from N fertilizer was adopted from a past study of dry croplands. The EF of pesticide is the mean value of the active ingredients of herbicide, insecticide, and fungicide.

The total GHG emissions from the agricultural inputs and the direct N_2O emission (E_{N2O}) from N fertilizer application for each treatment were calculated using the following equation:

$$\text{GHG Emissions} = \text{CE}_{\text{inputs}} + E_{N_2O} \tag{7}$$

Finally, the CFPs of the direct and indirect GHG emissions were estimated as follows:

$$\text{CFP} = \text{GHG Emissions}/\text{Grain yield} \tag{8}$$

2.7 Statistical Analysis

Data processing was performed using Microsoft Office Excel 2010, and statistical analyses were performed used SPSS 22.0 for Windows (SPSS Inc., Chicago, IL, USA). ANOVA was used to analyze the effects of straw return modes on SOC change, crop yield, and CFP and to compare SOC stock in the 0–20 cm soil layer between treatments. SigmaPlot version 12.5 (Systat Software, Inc., San Jose, CA, USA) was used to plot figures. Differences between treatments were determined by comparing their means using the least significant difference (LSD), and the level of significance was defined as $P<0.05$.

3. RESULTS

3.1 Plant-Derived C Input, ΔSOC, and SOC Sequestration Rate

It was found that the implementation of different straw-return modes resulted in different amounts of crop biomass, plant-derived C-input (consisting of crop straw, stubble, root biomass, and rhizodeposition), and SOC storage (Table 2 and Fig. 2). The cumulative plant-derived C input was significantly higher in the treatments in which straw was returned from both wheat and maize crops (WH-MC, WC-MC, WH-MM, and WC-MM) than those in which straw was returned from only one crop (WH-MN and WC-MN), while the control treatment without straw return (WN-MN) had significantly lower C input than all other treatments ($P<0.05$). The total C input ranged from 29.4 Mg C ha^{-1} in WN-MN up to 100.7 Mg C ha^{-1} in WH-MC. However, there was no significant difference between the treatments in which straw was returned from two seasons (Table 2), with the exception of WC-MM, which resulted in a lower C input compared to single-crop straw return (WH-MN).

Fig. 2 illustrates the SOC change and SOC sequestration potential of each treatment. The WH-MC and WC-MC straw-return modes showed the highest SOC change (37.5 and 37.67%, respectively) relative to the initial SOC content and the highest sequestration rates (1.02 and 1.03 Mg $ha^{-1}yr^{-1}$, respectively) ($P<0.05$), followed by WH-MM, which had a SOC change of 22.78% and a sequestration rate of 0.62 Mg $ha^{-1}yr^{-1}$ ($P<0.05$). The SOC changes and sequestration rates of WH-MC, WC-MC, WH-MM, and WH-MN were significantly higher than the control with no straw return (WN-MN), with the SOC changes being higher by 31.1, 31.3, 17, and 13%, respectively. Meanwhile, the SOC change and sequestration rate in WC-MM and WC-MN were slightly higher than those in the control (WN-MN) treatment (Fig. 2), although their plant-derived C input was higher (Table 2). The results indicate that both the amount and method of straw return affect SOC sequestration. No decline in sequestration or negative sequestration was observed in any of the treatments.

3.2 GHG Emissions from different Agricultural Inputs

In this study, differences in GHG emissions between treatments in each crop season were only due to differences in diesel use for the farm activity related to straw chopping, leaving stubble unmoved and/or removing stubble from the field. Meanwhile, tillage frequency depended on the straw-return mode, and all the diesel used for harvesting and sowing was considered for each treatments and season. The supplement of irrigation for each treatment was the same and not considered in the GHG estimation, since the source is from surface water without electricity usage. The other agricultural inputs were the same for each treatment for each crop type. The cumulative emission of GHGs in the summer maize season was higher than that in the winter wheat season, which can be attributed to high mineral N fertilizer use and the associated high direct emission of N_2O in the summer maize season. On average, during the wheat season, the treatments involving MC or MN (WH-MC, WH-MN, WC-MC, WC-MN, and WN-MN) showed slightly lower GHG emissions (1866.0 kg CO_2-eq ha^{-1}) than treatments involving MM (WH-MM and WC-MM) (1880.9 kg CO_2-eq ha^{-1}) (Table 3). During all the experimental periods from 2008–2018, treatments involving MC or MN consumed the same amount of diesel for machine use to manage the maize straw and field preparation for wheat sowing, since although MC used extra rotary tillage to incorporate straw into soil, MN used the same machine-based maize-straw chopping process that was used in MC in order to easily remove straw from the field, and thus both treatments used the same amount of diesel for machine operation.

During the maize season, the total GHG emissions from treatments involving the wheat return modes WH (2175.3 kg CO_2-eq ha^{-1}) and WN (2207.2 kg CO_2-eq ha^{-1}) were lower than those from treatments involving WC (2271.9 kg CO_2-eq ha^{-1}), and similarly the GHG emissions from diesel were significantly lower in WH (250 kg CO_2-eq ha^{-1}) and WN (282.2 kg CO_2-eq ha^{-1}) than in WC (346.9 kg CO_2-eq ha^{-1}) ($P<0.05$). The highest total GHG emissions for the entire season (annual emission from both wheat and maize) were observed for WC-MM, and the emissions from diesel for this treatment were significantly higher ($P<0.05$) than those for WH-MC, WH-MM, WH-MN, and WN-MN (however, no significant difference was observed between this treatment and WC-MC or WC-MN). Additionally, compared to WC-MM, the emissions from diesel in WH-MC and WH-MN were both lower by 6.73% over all the double seasons.

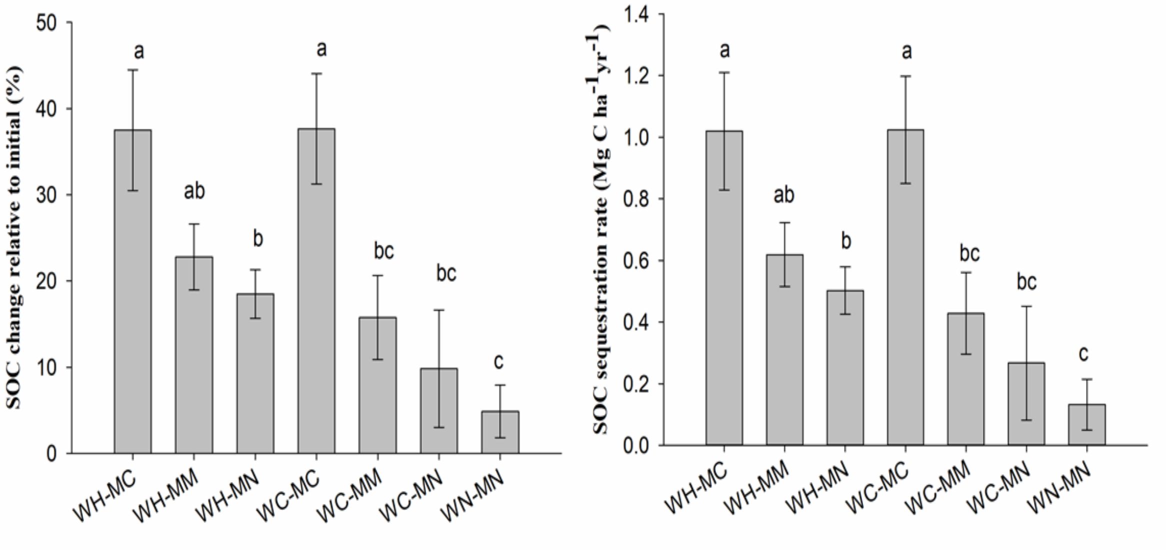

Fig. 2. Changes in soil organic carbon (SOC) between 2008 and 2018 (a) and average annual SOC sequestration rates (b) of different straw-return mode treatments

WH-MC: high wheat stubble retention and chopped maize straw return; WH-MM: high wheat stubble retention and chopped maize straw return and sub-soiling every two years; WH-MN: high wheat stubble retention and no maize straw return; WC-MC: both chopped wheat and chopped maize straw return; WC-MM: chopped wheat and chopped maize straw return and sub-soiling every two years; WC-MN: chopped wheat return and no maize straw return; WN-MN: control with no return of either wheat or maize straw. Different letters indicate significant difference at P<0.05.

Table 2. Estimated cumulative plant-derived biomass and C input during the 10-year experiment for different straw-return treatments (Mg C ha^{-1})

Treatment	**Straw**		**Stubble**[a]		**Root**[b]		**Rhizodeposition**[c]		**Total**[e]
	Wheat	**Maize**	**Wheat**	**Maize**	**Wheat**	**Maize**	**Wheat**	**Maize**	
Biomass input (Mg ha^{-1})									
WH-MC	65.825	92.200	13.175	9.225	14.475	21.200	0	0	216.10
WH-MM	60.575	92.800	12.125	9.275	13.325	21.350	0	0	209.45
WH-MN	53.700	0	10.750	8.350	11.800	19.200	0	0	103.80
WC-MC	61.550	93.275	12.300	9.325	13.550	21.450	0	0	211.45
WC-MM	60.250	88.375	12.050	8.850	13.250	20.325	0	0	203.10
WC-MN	59.750	0	11.950	8.275	13.150	19.000	0	0	112.13
WN-MN	0	0	9.875	7.475	10.875	17.175	0	0	45.40
C inputs[d] (Mg ha^{-1})									
WH-MC	26.330	36.880	5.270	3.690	5.790	8.480	5.79	8.48	100.70a
WH-MM	24.230	37.120	4.850	3.710	5.330	8.540	5.33	8.54	97.60ab
WH-MN	21.480	0	4.300	3.340	4.720	7.680	4.72	7.68	53.90c
WC-MC	24.620	37.310	4.920	3.730	5.420	8.580	5.42	8.58	98.60a
WC-MM	24.100	35.350	4.820	3.540	5.300	8.130	5.30	8.13	94.70b
WC-MN	23.90	0	4.780	3.310	5.260	7.600	5.26	7.60	57.70c
WN-MN	0	0	3.950	2.990	4.350	6.870	4.35	6.87	29.40d

[a] *Maize and wheat roots represented 23% and 22% of straw biomass, respectively [34].*

[b] *Maize and wheat stubble represented 10% and 20% of maize and wheat straw yield, respectively.*

[c] *Carbon content from rhizodeposition was assumed to be equal to root biomass C at harvest [36].*

[d] *Carbon content was assumed to be 40% for both maize and wheat [35].*

[e] *Different letters indicate significant difference at P<0.05.*

Table 3. Greenhouse gas emissions from the winter wheat–summer maize cropping system for different straw-return modes (kg CO_2-eq ha^{-1})

Crop type	Treatments	Emissions from agricultural inputs (Indirect emissions)				Direct emissions	Total GHG emissions
		N	P_2O_5	Diesel	Pesticides	N_2O	
Wheat	WH-MC	595.2	116.3	522.9a	69.7	561.9	1866.0
	WH-MM	595.2	116.3	537.0a	69.7	561.9	1880.9
	WH-MN	595.2	116.3	522.9a	69.7	561.9	1866.0
	WC-MC	595.2	116.3	522.9a	69.7	561.9	1866.0
	WC-MM	595.2	116.3	537.0a	69.7	561.9	1880.9
	WC-MN	595.2	116.3	522.9a	69.7	561.9	1866.0
	WN-MN	595.2	116.3	522.9a	69.7	561.9	1866.0
Maize	WH-MC	930.0	25.7	250.3c	91.3	878.0	2175.3
	WH-MM	930.0	25.7	250.3c	91.3	878.0	2175.3
	WH-MN	930.0	25.7	250.3c	91.3	878.0	2175.3
	WC-MC	930.0	25.7	346.9a	91.3	878.0	2271.9
	WC-MM	930.0	25.7	346.9a	91.3	878.0	2271.9
	WC-MN	930.0	25.7	346.9a	91.3	878.0	2271.9
	WN-MN	930.0	25.7	282.2b	91.3	878.0	2207.2
Wheat–Maize	WH-MC	1525.2	141.9	773.2c	161.0	1440.0	4041.3
	WH-MM	1525.2	141.9	788.2c	161.0	1440.0	4056.3
	WH-MN	1525.2	141.9	773.2c	161.0	1440.0	4041.3
	WC-MC	1525.2	141.9	869.8ab	161.0	1440.0	4137.9
	WC-MM	1525.2	141.9	884.8a	161.0	1440.0	4152.9
	WC-MN	1525.2	141.9	869.8ab	161.0	1440.0	4137.9
	WN-MN	1525.2	141.9	805.1bc	161.0	1440.0	4073.0

Note: Different lowercase letters indicate significant differences between treatments (P<0.05).

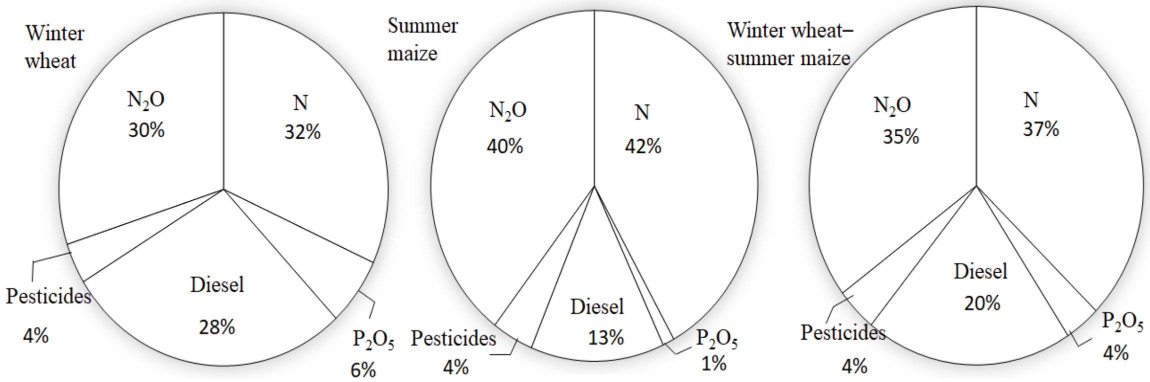

Fig. 3. Mean contributions of various sources to total GHG emissions for wheat, maize, and wheat–maize

The relative contributions of individual inputs to the total GHG emissions are shown in Fig. 3. The mean input of mineral N fertilizer, direct N_2O emission from N fertilizer application, and diesel for mechanical operation accounted for 32, 30, and 28% of the total GHG emissions for wheat, respectively, 42, 40, and 13% for maize, respectively, and 37, 35, and 20% for the annual wheat and maize crop, respectively. Meanwhile, phosphorus fertilizer (P_2O_5) and pesticides contributed only 4 and 6% of the total emissions for wheat, respectively, 4 and 1% for maize, respectively, and 4 and 4% for the annual wheat and maize crop, respectively.

3.3 Effects of different Long-Term Straw-Return Modes on Grain Yield and CFP

Over the whole 10-year study period, the average grain yield and carbon footprint was found to be slightly influenced by straw-return in individual wheat and maize season relative to the control, while annually during both the wheat and maize season the same parameters were found to be affected by both straw-return and straw-return mode (Fig. 4). In general, the control (WN-MN) had lower yield and higher CFP compared to the treatments which received wheat and maize straw for two seasons (WH-MC, WH-MM, WC-MC, and WC-MM) and a single season (WH-MN and WC-MN) annually. During the wheat season, WC-MN had the highest yield and lowest CFP, which were significantly higher by 31.8% and significantly lower by 25% compared to no straw return (WN-MN) (*P*<0.05), respectively; however, no significant difference was observed between WC-MN and any other treatment. In the wheat season, WH-MC had the next highest yield and next lowest CFP, which were significantly higher by 29.3% and significantly lower by 22.7% compared to WN-MN, respectively.

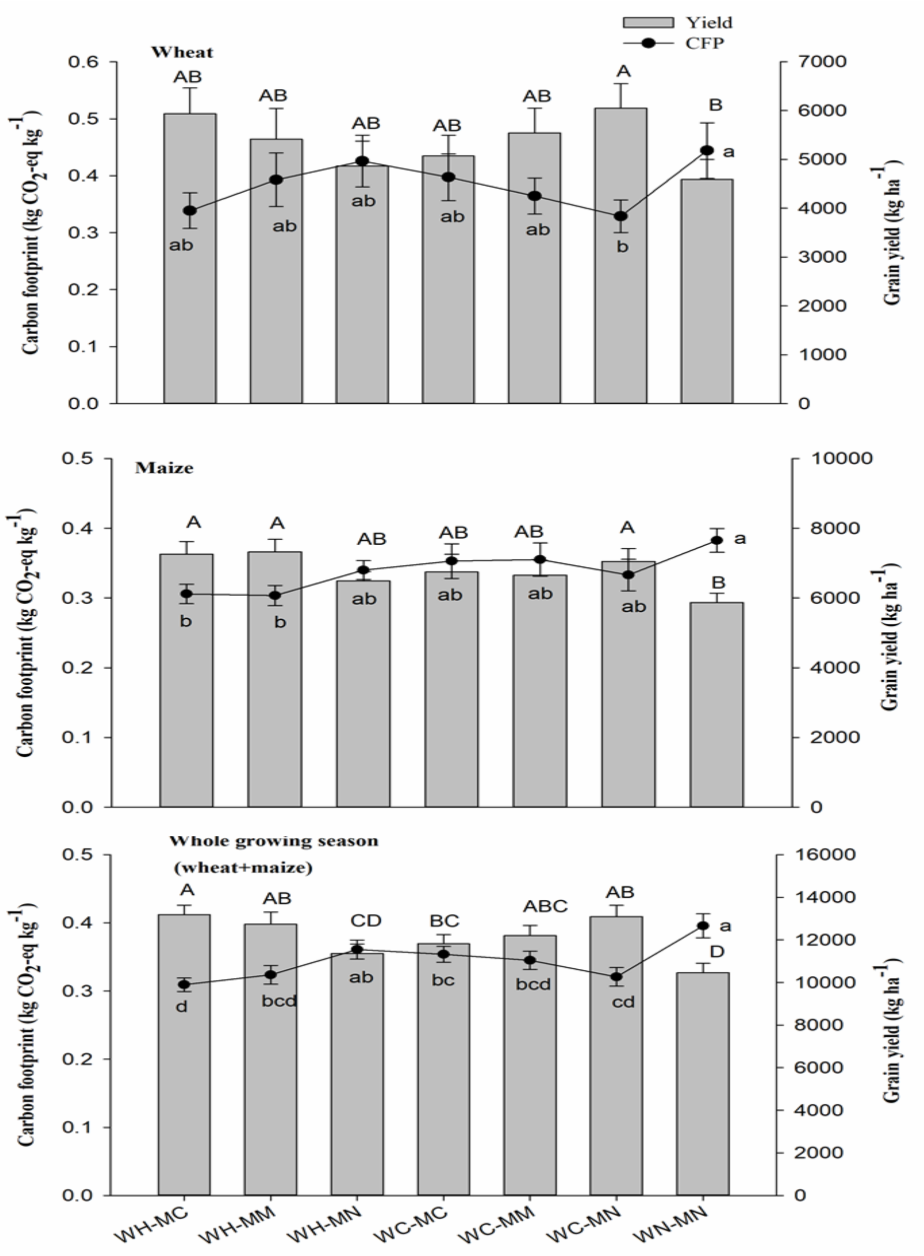

Fig. 4. Ten-year (2008–2018) average grain yield and carbon footprint of wheat, maize, and their combination under different straw-return treatments. Means with different letters (uppercase letters for grain yield, lowercase letters for carbon footprint) are significantly different at *P*<0.05

During the maize season, compared to WN-MN, treatments WH-MM and WH-MC had significantly higher grain yields by 24.6 and 23.5%, respectively, and significantly lower CFPs by 21.1 and 21%, respectively, while WC-MN had a significantly higher grain yield by 20% ($P<0.05$); however, the yields and CFPs of WH-MM, WH-MC, and WC-MN were only slightly different from those of the other non-control treatments (Fig. 4).

Furthermore, in the annual (i.e., both wheat and maize) season, WH-MC and WC-MN showed the highest yields, which were significantly higher by 26 and 25%, respectively, compared to the control, and also showed the lowest CFPs, which were significantly lower by 20.5 and 18%, respectively, compared to the control. The lowest grain yield and highest CFP were observed for WN-MN. Therefore, due to its high grain yield and low CFP, WH-MC can be considered as the best straw-return mode for low GHG emission agriculture.

4. DISCUSSION

This study explored the influence of different straw-return methods on SOC, total GHG emissions (CO_2-eq) from different agrochemical inputs, farm management operations, and the direct emission of N_2O from the application of mineral N fertilizer, and assessed the contribution of these methods to grain yield and CFP.

4.1 SOC Sequestration Potential of different Straw-Return Modes

Straw addition provides large amounts of organic C to cropland soils by promoting the increase of soil microbial biomass and microbial activity. Therefore, the application of crop residue to farm land is an effective practice to enhance and maintain SOC content, thereby increasing SOC sequestration and improving the physicochemical and biological properties of soil, which are directly related to SOC content. Thus, the application of crop residue can improve soil quality and can consequently promote sustainable agriculture and the mitigation of climate change [42,43,44]. Straw incorporation favors the generation of SOC by microbial assimilation of the straw C with concomitant production of metabolic byproducts [45]. In the current study, although 10 years of continuous straw return was found to significantly increase SOC sequestration in the treatments which received straw return from either two crops or one crop (WH-MC, WH-MM, WH-MN, WC-MC, WC-MM, and WC-MN) compared to no straw return (WN-MN), it is worth noting that the SOC change was significantly positively correlated with the amount of plant-based C input (Fig. 5). In the present study, in the treatments in which the straw of one crop was removed (WH-MN and WC-MN) and the control treatment where no straw was returned (WN-MN), the SOC sequestration rate was still positive after 10 years of cropping, which may be due to the fact that the C input from the crop roots and the remaining stubble helped to maintain the SOC balance. A similar result was obtained for a winter wheat–summer soybean cropping system by [20]. Moreover, three meta-analysis studies [46,47,27] found that straw return increases SOC storage. Additionally, our previous meta-analysis in Northern China [48] also found that long-term straw return significantly increased SOC stock and observed a positive relationship between straw C input and SOC sequestration rate. Additionally, the same study found that, in the dominant farmland soil types in Northern China, soils did not attain SOC saturation after more than 20 years of straw return. Straw addition can support the formation of soil aggregates, alter microbial micro-habitats, increase pore-filling, and occlude organic matter in microaggregates, thus protecting SOC against microbial degradation and increasing SOC storage [49]. The present study also investigated the impact of straw return on SOC change under different straw-return modes with treatments receiving straw return from either two crops or one crop. Straw-return mode was found to significantly influence SOC change and SOC sequestration rate. Of the treatments with straw return from two crops (WH-MC, WH-MM, WC-MC, WC-MM), higher SOC storage was observed in WH-MC and WC-MC compared to WH-MM and WC-MM. This observation is most likely to be due to the effect of tillage, as in WH-MM and WC-MM extra sub-soiling tillage was conducted up to a soil depth of 30 cm every two years before wheat sowing; that is, in the MM treatments soil and some straw may have been moved from the 0–20 cm soil layer to below 20cm, and since only the top 0–20 cm of soil was measured in this study this could affect the SOC values. Similarly, in a 10-year experiment with residue return in Northern China, [50] observed a significantly higher SOC sequestration rate in an untilled field compared to a field with hollow and rotary tillage (RT) treatments, with the average SOC sequestration rate of the RT system being 2.74 Mg ha^{-1} C lower. This decrease may be related to changes in the mineralization rate of organic matter by soil microorganisms due to changes in soil structure that result from repeated soil tillage [51].

Of the treatments with straw return from single crop, WH-MN had a higher SOC stock than WC-MN. This suggests that high wheat stubble retention may improve the soil structure, conserve soil water content, and increase the soil biomass production, thus improving SOC storage. Soil organic C stock can generally be increased by agricultural management that increases litter input and reduces tillage intensity [52,33]. Intensive and continuous tillage may cause enormous loss of soil organic C, thus inducing a breakage of the macroaggregate structure [53]. The present study found that both wheat straw return methods integrated with chopped maize straw (WH-MC and WC-MC) enhanced SOC sequestration over the 10-year experiment, suggesting that higher SOC sequestration depends on both the amount and mode of straw return.

4.2 Effect of Straw Return Management and Seasonal differences on GHG Emissions

In general, in the wheat, maize, and combined wheat–maize seasons, it was found that the largest contribution to GHG emissions was from the direct emission of N_2O after nitrogen fertilizer application, while the second-largest contribution was from diesel used for farm operations; the application of phosphorus fertilizer and pesticides were found to contribute less to the total emissions (Fig. 3). Similarly, [54] and [55] found that fossil fuel use, N fertilizer application, and soil disturbance were the main factors affecting GHG production in rainfed field crops. Additionally, [22] also reported a higher emission contribution from fertilizers. In the present study, it was found that the average contribution from individual agricultural inputs to total GHG emissions was higher in the maize season than in the wheat season; the indirect emissions from N fertilizer and the direct emissions of N_2O from its application were greater in the maize season, while the emissions from diesel and phosphorus fertilizer use were higher in the wheat season. The reason for the difference in emissions from fertilizers is due to the fact that N fertilizer was applied at a higher rate during the maize season and P fertilizer was applied at a higher rate during the wheat season. Meanwhile, the difference in emissions from diesel is due to the fact that, in most treatments, before wheat sowing, the maize straw return involved the use of machines for chopping, and tillage for straw incorporation into soil and tillage for sowing was used in all treatments; however, during the maize season, treatments with high wheat stubble straw return and straw removal did not use tillage for straw incorporation, and sowing was conducted without tillage using a seed sowing machine (although straw removal was achieved using a machine);furthermore, the returning of chopped wheat straw involved additional machine use for the chopping and incorporating process.

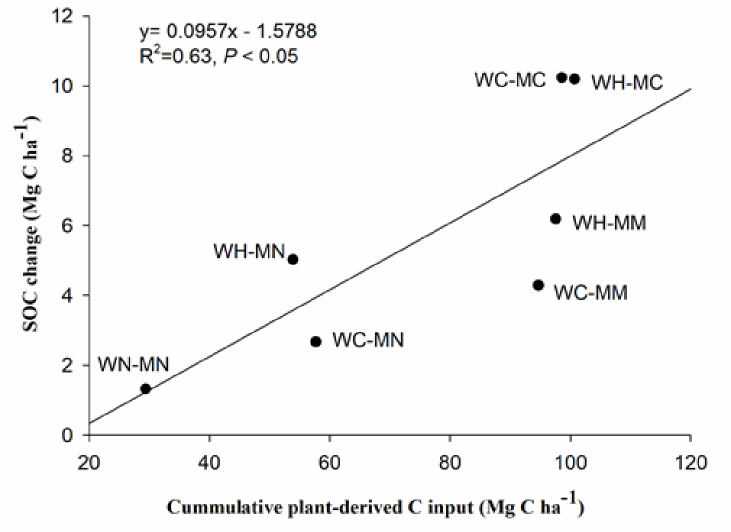

Fig. 5. Correlation between total cumulative plant-derived C input and SOC change in the 10-year experiment for different straw-return modes

The main focus of the present study regarding GHG emissions was to quantify the amount of diesel consumed by each activity based on the straw return type in the field operation for each treatment and its contribution to total emissions. The main difference between the treatments in each crop season was the amount of straw returned, the means of straw return, and the amount of diesel fuel used for all activities in the field operation; the other agricultural inputs (fertilizers and pesticides) were the same for all treatments in each crop type. The use of fertilizers, pesticides, and diesel associated with machinery operation is increasing rapidly in intensive agricultural systems, resulting in larger GHG emissions [56]. In the present study, it was found that the difference in GHG emissions between treatments was lower during the wheat season, since the processes involved in MC and MN (harvesting maize, chopping straw, and sowing) used the same amount of diesel, and additionally, as rotary tillage was used for straw incorporation in the MC treatment, MN also used machine to collect and remove the chopped straw from the field. The MM return mode requires extra sub-soiling every two years, however, MM does not show a significant difference in GHG emissions compared to the other return modes (MC and MN) over the 10-year experiment. In the first three years of the experiment (2008–2010), the straw-return mode in the MM treatment was mulching over the soil surface rather than chopping, which uses less diesel for machine operation, while from 2011 to 2018 the treatment was changed to chopping and sub-soiling. Therefore, the difference in GHG emissions from diesel between the three return modes of maize straw (MC, MM, and MN) was less in the wheat season. During the maize season, the GHG emissions from diesel differed significantly between the wheat straw-return modes (WH, WC, and WN). Treatment WC emitted a large amount of GHG since this operation used more diesel for harvesting, chopping, rotary tillage for straw incorporation, and tillage for sowing. Meanwhile, the non-chopped straw return method (WH) emitted a lower amount of GHG as it required less diesel for harvesting, and sowing was performed with no tillage. Furthermore, treatment WN also consumed a medium amount of diesel for harvesting, to remove straw from field and for sowing. However, WN consumed significantly more diesel, and accordingly had higher GHG emissions, compared to WH, due to the extra diesel usage for straw removal. When considering the combined wheat–maize season, treatments involving high wheat stubble (WH-MC, WH-MM, and WH-MN) produced the lowest GHG emissions, while the treatment involving the integration of chopped wheat and chopped maize with sub-soiling every two years (WC-MM) produced the highest GHG emissions of all the treatments, followed by WC-MC and WC-MN. Treatments in which straw was removed in both seasons showed a medium amount of total GHG emissions. Thus, in this study, straw managements with intensive tillage (for straw incorporation, sub-soiling, and sowing) and chopping processes in both seasons resulted the highest GHG emissions.

4.3 Crop Yield and Carbon Footprint

In this study, in the full annual growing season (wheat + maize) (Fig. 4), straw-return was found to significantly affect grain yield and CFP. Other than WH-MN, the treatments with straw return had significantly higher grain yield and lower CFP compared to the control treatment (WN-MN) ($P<0.05$). Similarly, in an eight-year experiment of wheat–maize rotation cropping, [57] observed that WC-MC and WH-MC had a higher grain yield compared to WN-MN, however WH-MN was not significantly different to the control. These yield increases under straw return may be due to the additional nutrient supply derived from the straw and the consequent enhancement of the soil bio-physical and physicochemical properties [47]. Meanwhile, the lower CFP may be due to the higher yield. The mean CFP over the entire season was 0.34 kg CO_2-eq kg^{-1}. This is similar to the results of [12], who observed a mean CFP of 0.43 kg CO_2-eq kg^{-1}for different tillage practices under wheat–maize cropping in Northern China. Our average result is also close to the values obtained in studies from other parts of the world; for example, [58] measured a CFP of 0.269 kg CO_2-eq kg^{-1}in Western Australia and [59] measured a CFP of 0.343 kg CO_2-eq kg^{-1} in Canada. However, our CFP result is lower than those obtained in other studies [60,41]. This may be due to differences in the system boundary; specifically, we did not use electricity for irrigation, seeds, and labor, and methane emission was not considered due to negligible amounts being produced in upland crops. The main contributors to the variability of CFP between different studies are crop yield and system boundary, including the type and quantities of agricultural inputs, and associated GHG emissions per unit area [61].

In the present study, differences in both yield and CFP were observed between the various straw-return modes. Of the four treatments in which two types of straw were returned (WH-MC, WH-MM, WC-MC, WC-MM), WH-MC and WH-MM resulted in a higher yield and lower CFP compared to WC-MC and WC-MM. The difference in yield might be due to the high wheat stubble retention in WH-MC and WH-MM, which can avoid soil disturbance, decrease water loss, improve maize germination, and inhibit weed growth during the growing season [57]. Meanwhile, the higher CFP in WC-MC and WC-MM might be due to the higher emissions from diesel during farm operations as a result of the larger amount of tillage in both seasons during the straw return process, and may also be due to the lower yield of these two treatments.

Of the straw-return treatments in which only one type of straw was returned (WH-MN and WC-MN), WC-MN showed a significantly higher grain yield and lower CFP compared to WH-MN. This may be due to the fact that high wheat stubble retention was late for incorporation and decomposition up to the wheat season, and the straw’s slow biodegradation may have led to unfavorable effects, such as undegraded straw interfering with subsequent crop growth, thus disrupting traditional crop management [62]. Additionally, in the present study, the CFP was found to be influenced by high grain yield in WC-MN. The WH-MC mode obtained the highest grain yield and lowest CFP of all the investigated modes, achieving a 26% increase in yield and a 20.5% reduction in CFP compared to WN-MN for the combination of the wheat and maize seasons. Therefore, this mode can be concluded to be the best among the studied modes.

However, in the wheat or maize seasons, grain yield and CFP were found to be slightly affected by the treatment type. In the wheat season, only WC-MN had a significantly higher yield and significantly lower CFP compared to the control (WN-MN). A possible reason for the lack of difference in grain yield between the treatments may be due to the low precipitation in Northern China [63]. On the other hand, in all treatments, the application of mineral N fertilizer may lower the decomposition rate of the returned straw. Similarly, our meta-analysis in Northern China [48] found that grain yield was less affected by different fertilizer and straw-return managements. The similar CFP of different treatments in the wheat season was due to these treatments having a similar grain yield (Fig. 4) and the fact that the differences in GHG emissions from farm operations (diesel) among these treatments were insignificant (Table 3). In the maize season, WH-MC and WH-MM achieved a significantly higher grain yield and a significantly lower CFP compared to the control (WN-MN). This can be attributed to the fact that both treatments received high wheat stubble straw with no tillage operation and may therefore have been protected from moisture loss. Moreover, the lower CFPs of these two treatments are due to the higher yield and significantly lower GHG emissions from farm management (Fig. 4, Table 3). Thus, based on the annual season (wheat + maize), the WH-MC treatment had a good effect on improving SOC storage and crop yield, while no surplus maize straw was removed from the field in this treatment.

4.4 Implications of different Straw Management Strategies

In this study, the main factors that influence SOC sequestration, crop yield, and CFP were investigated, and were found to be the following: (1) the mode of straw return and the returned straw amount, and (2) the agricultural inputs and farm operations (chemical fertilizer, pesticide, tillage, diesel amount, and straw disposal). The results show that, in general, all of the six treatments with straw return enhanced SOC and crop yield and lowered CFP compared to the treatment without straw return, and that the enhancement of SOC and crop yield and the reduction of CFP were higher in treatments with double-crop straw return than in treatments with single-crop straw return. However, there is an increasing demand for crop straw for use as a raw material for renewable resources (like lignocellulose ethanol production) and animal feed [64]. Therefore, from the viewpoint of maintaining a balance between improving the sustainability of soil use and meeting the demand for cellulose raw materials or feed for animals, the WH-MC treatment has an obvious disadvantage due to the lack of surplus straw for use in other applications.

Intensive winter wheat–summer maize cropping is the dominant agricultural practice in the North China Plain, which is an important food-production area of China [65]. In China, mixed crop–livestock farming is the dominant farming system, accounting for 87% of the total cropland area and producing 74, 84, 90, and 50% of the country's wheat, maize, beef and mutton, and pork and poultry meat, respectively [66]. In wheat–maize double cropping systems, growers need to reduce the cost of machine use for straw return and increase the amount of extra straw available for sale to animal feed companies while simultaneously increasing crop yield. Thus, considering the ease of farm management, lower diesel requirements, optimum straw return to soil, and the potential of using the excess maize straw for other purposes, high wheat stubble retention and no maize straw return (WH-MN) might be the most preferable for growers among the treatments investigated in this study. Since mineral fertilizer is often too expensive for smallholders and has negative effect on environment and soil health, this study may contribute for better integrated soil fertility management of chemical fertilizer and crop residue over all the world.

Moreover, maize straw is also widely used as industrial raw material. The surplus maize straw produced by the WH-MN treatment can be removed from farmland to improve the utilization rate of straw. With increasing soil organic carbon content, the amount of organic material needed to maintain the balance of soil organic carbon will also increase [67]. In the future, the retention of only high wheat stubble (25–30 cm) (WH-MN) during the maize season could be prioritized to provide all the advantages of straw, increase the ease of management, reduce diesel requirements and accordingly GHG emissions, and increase the SOC storage capacity, especially for integrated crop–livestock farming system in wheat–maize cropping.

5. CONCLUSION

In this study, a 10-year field experiment was conducted to explore the effects of different straw-return modes on SOC contents and the total greenhouse gas emissions from different agrochemical inputs, farm management operations, and the direct emission of N_2O from the application of mineral N fertilizer, and assessed the impact of these modes on grain yield and CFP. Straw return was found to significantly increase SOC, with a cumulative plant-based C-input ranging from 29.4 Mg C ha^{-1} for no straw return (WN-MN) up to 100.7 Mg C ha^{-1}for double-season straw return (WH-MC). However, the SOC change and SOC sequestration rate in WC-MM and WC-MN were slightly higher than those in the control. These results indicate that SOC sequestration is affected by both the amount and mode of straw return. Greenhouse gas emissions from diesel used for farm operations were found to be the second-highest source of greenhouse gas emissions behind N fertilizer, and the WC-MM and WH-MN treatments were shown to produce the highest and lowest GHG emissions, respectively. In the whole wheat–maize cropping season, a higher SOC, higher crop yield, and lower CFP were observed in WH-MC compared to the other treatments, however this treatment produced no surplus of maize straw. Thus, of the investigated treatments, WH-MN most effectively increases SOC and grain yield and reduces CFP compared to the control.

The results of this study suggest that in the future farmers should consider returning maize straw to the field every two or three years in order to both improve fertilization and ensure that the surplus maize straw is generated for use in other applications.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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