Received: 9 October 2022 | Revised: 27 December 2022 | Accepted: 5 January 2023

DOI: 10.1002/ldr.4610

RESEARCH ARTICLE

WILEY

Optimal straw management co-benefits crop yield and soil carbon sequestration of intensive farming systems

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Funding information
Agricultural Production System in Shandong (SDAIT-02-07); Agricultural Science and Technology Innovation Project of Shandong Academy of Agricultural Sciences, Grant/Award Number: CXGC2022A08; National Key R&D Program of China, Grant/Award Number: 2018YFD0300602

Abstract

Straw retention has been widely recommended to sequester more soil organic carbon (SOC) in agricultural soils, while carbon sequestration may not respond linearly to additional carbon input amount. The response of SOC, greenhouse gas (GHG) emissions and economic income to different straw management methods in intensive wheat-maize double cropping systems still need systematical study. An 8-year field experiment was conducted in the Huang-Huai-Hai Plain to investigate the impacts of optimal straw management (wheat straw was *all crushed and spread on the soil surface, maize* straw was all crushed and returned t into 0-15 cm soil layer) and optimal straw management (wheat straw was *all crushed and spread on the soil surface*, while maize straw was all harvested for feed) on SOC sequestrations, carbon economy and economic income. The results showed that only returning wheat straw into the field could maintain a similar crop yield (15.0 Mg ha^{-1}) and SOC sequestration amount (9.06 Mg C ha^{-1}) to the conventional straw management method. While this optimal straw management method kept a stable SOC sequestration rate of 1.24 Mg ha^{-1} yr^{-1} when the SOC sequestration rate decreased from 1.76 to 1.20 Mg ha^{-1} yr^{-1} in the conventional method. The optimal management method also further reduced GHG emissions by 85.4% and using maize straw as stock feed increased net income by 28.3%. Only returning wheat straw could realize economic and environmental benefits win-win in the wheat-maize double cropping systems, which provides important background knowledge about safe and sustainable agriculture.

KEYWORDS

farming system, greenhouse gas emission, soil carbon sequestration, straw return, wheat-maize double cropping system

1 | INTRODUCTION

Crop straw is one of the important by-products of agricultural production, and has attracted increased attention in recent years. Straw return, as an important source of carbon to supplement the soil carbon pool, is beneficial to soil quality and crop grain yield (Poeplau et al., 2015; Zhao et al., 2020). Since the early 2000 s, crop straws have been returned to the field in China for these benefits facilitated by the policy to prohibit straw burning (Liu et al., 2022). However, long-term excessive straw return into the field can cause poor soil conditions that are also prone to diseases, leading to decreased grain yield. This is particularly the case in the intensive cropping systems of China, where the total straw production can reach 1.04 billion tons (Li et al., 2017). This indicates an urgent need to optimize straw management and develop a long-term strategy to achieve SOC sequestration while mitigating the adverse effects of crop straw return.

Organic matter is the basis and core of soil fertility, which plays an important role in maintaining crop yield and agricultural environmental sustainability. SOC accounts for about 58% of the soil organic matter mass, which can only be maintained through the input of carbon and nutrients to avoid loss of soil quality. Straw return is a viable way of increasing SOC storage in most agricultural systems. In China, a meta-analysis revealed that crop straw return increased SOC by 12% (Zhao et al., 2015). Straw retention and incorporation greatly improved soil fertility (Bu et al., 2020; Yin et al., 2018), which in turn increased crop grain yield by 6.8–12.3% (Han et al., 2018; Qi et al., 2019). Simultaneously, the SOC sequestration rate may decline with time (Luo et al., 2014) and fresh carbon input may stimulate the decomposition of existing SOC due to priming effects (Luo et al., 2015; Luo et al., 2016). A meta-analysis based on 176 field studies found that continuous straws return increased SOC concentration by about 12.8%, leading to much smaller or no additional SOC sequestration after 12 years (Liu et al., 2014). In addition, excessive straw return damages soil carbon and nitrogen balance and reduces nitrogen use efficiency and crop yield (Buysse et al., 2013; Fang, Nazaries, et al., 2018). In such cases, the use of part of the crop straw for other purposes like stock feed would result in a better economic return. In China, the demand for straw feed is more than 15 million tons a year, and maize straw stalk feed has extensive development space and prospects. The straw harvest has been mechanized, which further improved the efficiency of straw harvest.

Straw management plays an important role in balancing SOC sequestration and environmental outcomes. Over the last decades, the amount of straw return increased continuously, which also promoted the increase of N_2O emissions from farmland (Abalos, Recous, et al., 2022). The global N_2O emission contributed by straw return is over 0.87 million tons (FAO, 2021). On the positive side, the SOC sequestration by straw return can regulate atmospheric GHG concentrations, by offsetting part of the GHG emissions from farmland (Muhammad et al., 2019). In addition, improving crop straw utilization efficiency can directly reduce CO_2 emissions. A large portion of straw carbon is re-released back into the atmosphere after being returned to the field. Therefore, a comprehensive evaluation of SOC sequestration, GHG emission, and farmland income is greatly significant to construct sustainable and low-carbon production models.

Coordinating straw return and feeding rate may be a useful way to maintain the crop yield and the SOC sequestration while reducing farmland GHG emissions. Here we present data from an 8-year field experiment on the effects of straw management on grain yield and SOC of the intensive winter wheat-summer maize double cropping system. Our objectives were to; (1) investigate how retention of crop straw from one or both crops impacts the crop productivity and SOC (2) analyze the carbon economy by GHG emissions produced per unit amount of crop yield or economic return; and (3) discuss long-term straw management strategies that increase economic return, maintain crop productivity and increase SOC sequestration. This study challenges the general view that more straw return leads to more carbon sequestration, and can be used as a reference for improving straw management that optimizes soil carbon sequestration and carbon economy.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was started in October 2012, to investigate the impacts of different tillage methods. The study site is located at Longshan Experimental Base of Maize Research Institute, Shandong Academy of Agricultural Sciences, China (117° 32′ E, 36° 43′ N), which is close to the middle of the Huang-Huai-Hai Plain, characterized by a temperate continental monsoon climate. The experiment was conducted from October 2012 to 2020, and the average annual rainfall and temperature were 600.8 mm and 12.8°C. The sunshine duration and frost-free season were over 2500 hr and 200 d. The soil type of the study site is Eutrochrepts, with 1.48% organic carbon, 0.85 g kg^{-1} total nitrogen, 19.3 g kg^{-1} available phosphorus, 46.4 g kg^{-1} available potassium, and pH in the 0–20 cm soil of 7.6 at the start of the experiment in 2012. The winter wheat-summer maize double cropping system is the domain cropping system in the study region.

2.2 | Experimental design

Two straw management methods were carried out in the experiment, that is, conventional and optimal methods. In the conventional straw management method, both wheat and maize were harvested with a combine harvester, while crop straw was crushed and spread on the soil surface. In the optimal method, wheat straw was crashed and spread on the surface at harvest, while maize straw was sold as fodder after harvest. For both straw management methods, maize stubble was pulverized and rotary tillage was carried out before wheat sowing. Maize was planted directly without ploughing after the wheat harvest. The field operation process is shown in Figure 1.

Each straw management method had three replicates, and each replicate had a plot area of 18 × 45 m^2. Winter wheat variety "Jimai 22" was sown from October 15 to October 18 with row spacing of about 24 cm (the width of the planting row is 8 cm) and with a seed rate of about 173 kg ha^{-1}. The winter wheat was harvested from June 8 to June 12 in the next year. Summer maize variety "Ludan 9066" was sown from June 15 to 18 June with an average row spacing of 60 cm and plant density of 75,000 plants ha^{-1}. The maize was harvested from October 8 to 12 October. Both the wheat and maize were mechanically sown and harvested.

The irrigation and fertilizer management in both treatments were consistent with the local traditional management methods. Wheat was irrigated at the sowing, jointing, and flowering stages, each with 60 mm of water. Maize was irrigated (60 mm) after sowing to ensure the emergence of seedlings. A water meter was used to accurately

FIGURE 1 The operation process of farmland production. The pictures show the types of machinery and projects involved in the wheat-maize double cropping system. The arrows indicate the order of work. [Colour figure can be viewed at wileyonlinelibrary.com]

control the amount of irrigation. The basal fertilizer for both wheat and maize was compound fertilizer of 600 kg ha^{-1} (N, P_2O_5, and K_2O content were 102 kg ha^{-1}, respectively). And topdressing is 225 kg ha^{-1} of urea for both wheat and maize (at the jointing stage of winter wheat and the twelve-leaf stage of summer maize). A mechanical ditch was used for base fertilizer at sowing. Fertilizers were topdressed manually before irrigation or rainfall to reduce fertilizer loss via volatilization. Pests, diseases, and weeds during crop growth were properly controlled.

2.3 | Field measurements

2.3.1 | Crop biomass and grain yield

During the wheat harvest period, three 1-m^2 plots were randomly sampled in each plot. Aboveground biomass was measured after oven-dried at 80°C. In each treatment, wheat ears from three 1 m^2 plots of the undisturbed area were harvested to measure wheat grain yield. During the maize harvest period, 3 rows, each with two plants was randomly sampled and oven-dried at 80°C for biomass measurements. The number of ears per ha, the percentage of empty stalks, and the percentage of double ears were counted. Three 12-m^2 ears of maize from the undisturbed area were harvested to determine the grain number per ear, the water content of grains, the weight of 500 grains, and the yield of maize grains was calculated.

2.3.2 | SOC and bulk density

Soil samples from 0–20, 20–40, 40–60, 60–80, and 80–100 cm layers were collected after maize harvest each year. A soil auger with a diameter of 30 mm was used to collect 5 random points in each plot. After natural air drying, soil samples were cleared of crop residues and other sundries, then ground and put through a 2 mm screen for later use. The SOC content was determined using a Vario TOC analyzer (Elementar, Germany).

Soil bulk density (BD, g cm^{-3}) was measured after the maize harvest, in undisturbed soil layers taken from each plot with borers (50 mm long, 50.5 mm radius) (Zhang et al., 2022). The BD of each soil layer was measured with the ring knife method with borers (100 cm^3 volume and 50 mm diameter).

2.4 | Calculations

2.4.1 | Crop C input

Crop C input (C_{input}, Mg ha^{-1}) comes from crop straw, stubble, roots, root exudates, and seeds. The calculation formulas are as follows:

$$C_{input} = C_{straw} + C_{stubble} + C_{root} + C_{exudates} + C_{seed} \cdots \quad (1)$$

$$C_{straw} = B_{straw} \times C_{plant} \cdots \quad (2)$$

$$C_{stubble} = P_{stubble} \times B_{straw} \times C_{plant} \cdots \quad (3)$$

$$C_{root} = P_{root} \times B_{straw} \times C_{plant} \cdots \quad (4)$$

$$C_{seed} = S_{amount} \times C_{plant} \cdots \quad (5)$$

Where: C_{straw}, $C_{stubble}$, C_{root}, $C_{exudates}$, and C_{seed} are the C inputs of crop straw, stubble, root, root exudates, and seeds, respectively (Mg C ha^{-1}). B_{straw} is crop straw biomass (Mg ha^{-1}), C_{plant} is the C content of crop plants, 42.5% for winter wheat, and 44.4% for summer maize, respectively (Zhang et al., 2010). $P_{stubble}$ is the ratio of stubble to straw biomass (%), 26% for winter wheat, and 3% for summer maize (Wang et al., 2015). P_{root} is the ratio of root to straw biomass (%), 24% for winter wheat, and 29% for summer maize (Bolinder et al., 2007). S_{amount} is the amount of wheat or maize seeds. The C inputs from the wheat and maize root exudates were considered to be equal to that of their roots (Bolinder et al., 1999).

2.4.2 | SOC stock and sequestration rate

The SOC stock (C_{stock}, Mg C ha^{-1}) and the SOC sequestration rate (C_{rate}, Mg C ha^{-1} yr^{-1}) were calculated by the following equation:

$$C_{stock} = C \times BD \times H \times 0.1 \cdots \tag{6}$$

$$C_{sequestration} = C_{stock} - C'_{stock} \cdots \tag{7}$$

$$C_{rate} = \frac{(C_{stock} - C_{initial})}{n} \cdots \tag{8}$$

Where: C (g C kg^{-1}) was SOC content and BD (g cm^{-3}) was bulk density. H is the thickness of the soil (cm) and 0.1 is the unit conversion factor. C_{stock} is the SOC amount (Mg C ha^{-1}). $C_{initial}$ is the initial SOC amount of the previous year (Mg C ha^{-1}). n is the interval time (yr).

2.4.3 | Grain carbon harvest and loss

In both treatments, the carbon contained in the grain was considered as grain harvest carbon, not treated as carbon loss from the system. For the optimal straw management method, the maize straw was sold as animal stock feed for economic benefits, and the carbon contained in the maize straw was therefore not considered a direct C loss from the cropping system. In this study, indirect C losses such as leaching and runoff are not considered due to the smaller contribution to the total C loss. Grain harvest C ($C_{harvest}$, Mg C ha^{-1}) is the amount of C harvested by crop grain and was calculated with the following equation:

$$C_{harvest} = Y_{grain} \times C_{grain} \cdots \tag{9}$$

Where: Y_{grain} (Mg C ha^{-1}) is crop grain yield. C_{grain} is the C content of crop grains, the average grain C content of wheat and maize was 0.48 and 0.47 Mg Mg^{-1}, respectively, measured using the $K_2Cr_2O_7$–H_2SO_4 oxidation method (Nelson & Sommers, 1982).

To calculate the C loss (C_{loss}, Mg C ha^{-1} yr^{-1}), as follows:

$$C_{loss} = C_{input} - C_{sequestration} - C_{harvest} \cdots \tag{10}$$

Where: C_{input} (Mg C ha^{-1} yr^{-1}) is the total C from crops put into the soil. $C_{sequestration}$ (Mg C ha^{-1} yr^{-1}) is SOC sequestration in soil, and $C_{harvest}$ (Mg C ha^{-1} yr^{-1}) is C harvested through grains.

2.4.4 | Carbon use efficiency

C use efficiency is evaluated by grain yield produced (C_g, Mg Mg^{-1}) and SOC sequestration (C_s, Mg Mg^{-1}) per unit C input, respectively, calculated using the following equation:

$$C_g = \frac{C_{harvest}}{C_{input}} \cdots \tag{11}$$

$$C_s = \frac{C_{sequestration}}{C_{input}} \cdots \tag{12}$$

$C_{harvest}$ (Mg C ha^{-1}), $C_{sequestration}$ (Mg C ha^{-1}), and C_{input} (Mg C ha^{-1}) are the C harvested through grains, C sequestration into the soil and the total amount of organic C put into the soil per ha.

2.4.5 | Economic benefits

Production value (P_{value}, USD ha^{-1}) and net income (P_{income}, \$US ha^{-1}) were calculated with the following equation:

$$P_{value} = Y_{grain} \times P_{grain} + Y_{straw} \times P_{straw} \cdots \tag{13}$$

$$P_{income} = P_{value} - P_{cost} \cdots \tag{14}$$

Y_{grain} (Mg ha^{-1}) and P_{grain} (\$US Mg^{-1}) are the crop grain yield and the unit price of a crop grain, respectively. Y_{straw} (Mg ha^{-1}) and P_{straw} (\$US Mg^{-1}) are the maize straw yield and the unit price of maize straw, only maize straws of treatment S are sold as feed for economic gain. P_{cost} (\$US ha^{-1}) is the total economic input of seed, fertilizers, pesticides, irrigation, machinery, and labour. The inputs and unit price are shown in Table 1.

2.4.6 | Environmental benefits

Indirect C emissions ($C_{indirect}$) were calculated as follows:

$$C_{indirect} = C_{fertilizer} + C_{pesticide} + C_{fungicides} + C_{irrigation} + C_{machinery} + C_{manpower} \cdots \tag{15}$$

where, $C_{fertilizer}$, $C_{pesticid}$, $C_{fungicide}$, $C_{irrigation}$, $C_{machinery}$, and $C_{manpower}$ are the C emissions related to the use of fertilizer, pesticide, irrigation, machinery, and labour during crop production, respectively, with the coefficients listed in Table 2.

Total C emissions from farmland systems (T_C) were calculated using the following equation:

$$T_C = C_{loss} + C_{indirect} \cdots \tag{16}$$

Where: C_{loss} (Mg C ha^{-1}) is the C loss from farmland soil.

TABLE 1 The input cost of farmland production with different straw management ($US ha^{-1} yr^{-1}).

Items	The unit price	Conventional		Optimal	
		Wheat	Maize	Wheat	Maize
Seeds	wheat: 0.99 $US kg^{-1} Maize: 5.91 $US kg^{-1}	170	133	170	133
Compound fertilizer	0.94 $US kg^{-1}	562	562	562	562
Urea	0.55 $US kg^{-1}	124	124	124	124
Pesticides	10.9 $US kg^{-1}	86.1	86.1	86.1	86.1
Fungicide	10.2 $US kg^{-1}	49.4	49.4	49.4	49.4
Irrigation	0.13 $US kg^{-1}	32.5	10.8	32.5	10.8
Machinery	0.8 $US kWhr^{-1}	116	83.6	116	97.4
Manpower	12.54 $US d^{-1}	191	191	191	216

Note: Unit prices are estimated based on local market conditions (Huang-Huai-Hai Plain).

TABLE 2 Indirect C emissions related to management on farmland. with different straw management.

Resources inputs			C conversion factor	C emission (Mg C ha^{-1} yr^{-1})	
	Conventional	Optimal		Conventional	Optimal
Compound fertilizer (kg ha^{-1} yr^{-1})	1200	1200	0.90 kg C kg^{-1}	1.08	1.08
Urea (kg ha^{-1} yr^{-1})	450	450	1.74 kg C kg^{-1}	0.78	0.78
Pesticides (kg ha^{-1} yr^{-1})	15.7	15.7	3.90 kg C kg^{-1}	0.06	0.06
Fungicides (kg ha^{-1} yr^{-1})	9.70	9.70	5.10 kg C kg^{-1}	0.05	0.05
Irrigation (kg kWhr^{-1} yr^{-1})	334	334	0.92 kg C kWh^{-1}	0.31	0.31
Machinery (L ha^{-1} yr^{-1})	250	267	2.63 kg C L^{-1}	0.66	0.7
Manpower (d ha^{-1} yr^{-1})	30.4	32.4	0.92 kg C d^{-1}	0.03	0.03

Greenhouse gas (GHG) emissions from farmland systems (GHG, Mg CO_2-eq ha^{-1} yr^{-1}) in terms of CO_2 equivalents (GHG, Mg CO_2-eq ha^{-1} yr^{-1}) were calculated as follows:

$$\mathrm{GHG} = T_C \times 3.67 + E_{N_2O} \times 265 \times 0.001 \cdots \tag{17}$$

where 3.67 is the conversion coefficient (C converted to CO_2). E_{N_2O} (kg ha^{-1}) is N_2O emission from farmland. The average N_2O emissions with conventional and optimal straw management methods are estimated to be 5.23 and 4.12 kg ha^{-1} yr^{-1}, using default emission factors established by IPCC 2019. The emission factors for N additions from synthetic fertilizers and crop residues using default emission factors established by IPCC 2019 (0.5% and 1.6% for the wheat season and maize season, respectively). 265 is N_2O emissions in CO_2 equivalents. 0.001 is the unit conversion factor.

Yield-scaled C emission ($C_{\text{yield-scaled}}$) and yield-scaled GHG emission ($\mathrm{GHG}_{\text{yield-scaled}}$) were calculated as follows:

$$C_{\text{yield-scaled}} = \frac{T_C}{Y_{\text{grain}}} \cdots \tag{18}$$

$$\mathrm{GHG}_{\text{yield-scaled}} = \frac{\mathrm{GHG}}{Y_{\text{grain}}} \cdots \tag{19}$$

Net income-scaled CO_2 ($C_{\text{net income-scaled}}$) and yield-scaled GHG ($\mathrm{GHG}_{\text{net income-scaled}}$) are calculated as follows:

$$C_{\textit{net}\ \text{income-scaled}} = \frac{T_C}{P_{\text{income}}} \cdots \tag{20}$$

$$\mathrm{GHG}_{\textit{net}\ \text{income-scaled}} = \frac{\mathrm{GHG}}{P_{\text{income}}} \cdots \tag{21}$$

2.5 | Statistical analysis

Microsoft EXCEL 2016 (Microsoft Corp., Remond, WA, USA) was used to process the experimental data. Statistical analysis was performed with SPSS 20.0 (SPSS, Inc., Chicago, IL, USA) statistical software. The significant difference used was the Duncan multiple range Test ($p < 0.05$).

3 | RESULTS

3.1 | Crop carbon input

During the 8 years from 2012 to 2020, the cumulative C input in optimal straw management was 48.54 Mg C ha^{-1}, which was 34.3% lower

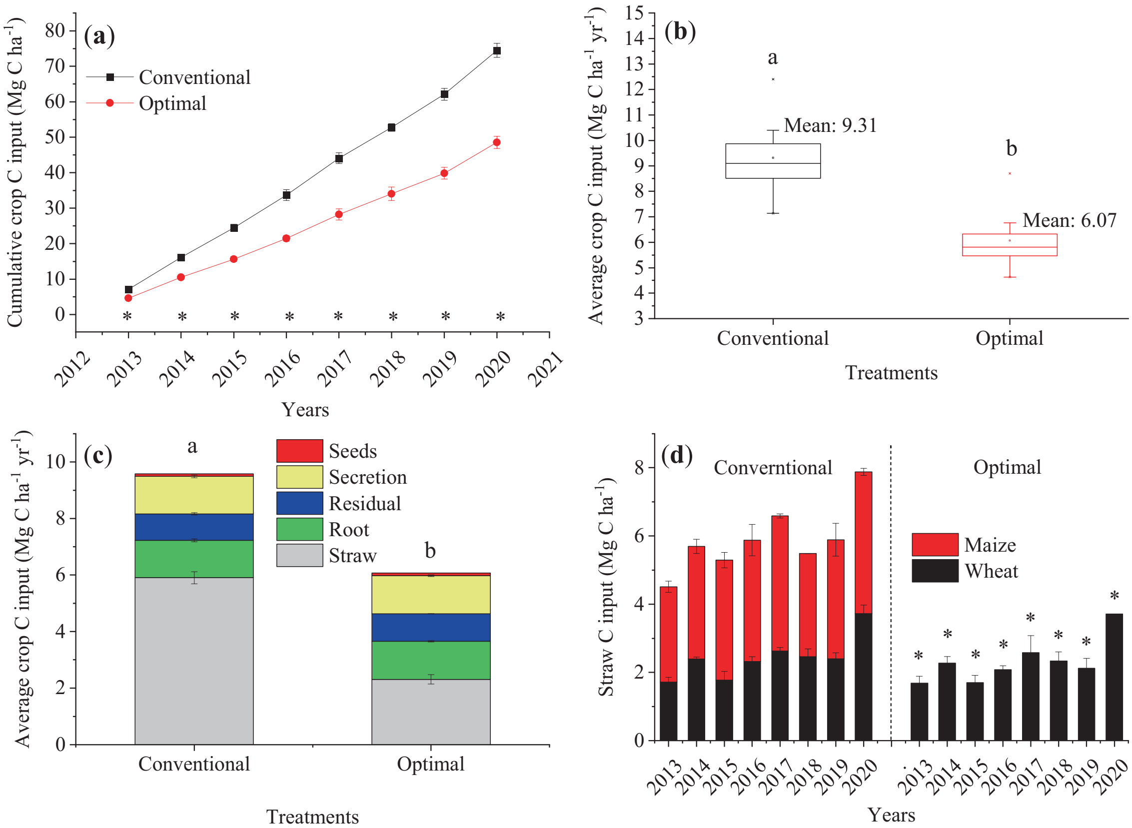

FIGURE 2 Cumulative crop carbon input (a), average crop carbon input (b), composition of crop carbon input (c), and crop straw carbon input (d) in two different straw return treatments. Boxplots show the median and interquartile range. The black box show the 10, 25, 50, 75, and 90 percentiles. '*' and different lower-case letters indicate significant differences with $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

than that in conventional straw management. The average annual C input in optimal and conventional straw management methods was 6.07 Mg C ha^{-1} and 9.31 Mg C ha^{-1}, respectively (Figure 2a,b). The carbon inputs into the wheat-maize double cropping system were mainly from carbon fixation by the photosynthesis of wheat and maize. The number of carbon inputs by seeds was very minimal compared to the carbon fixed by the crop (Figure 2c).

For both straw management, the average annual C input from roots, stubble root exudates, and seeds were estimated as 3.04–3.09, 2.14–2.21, 3.04–3.09, and 0.10 Mg ha^{-1}, respectively, with no significant difference between the two straw management methods (Figure 2c). The difference mainly attributed to different amounts of straw input. This also resulted in the difference in C input between the optimal and conventional straw management, with the annual average input of 2.31 and 5.90 Mg C ha^{-1}, respectively (Figure 2d).

3.2 | Grain carbon harvest

The average total crop grain yields over 8 years in optimal and conventional straw management were 14.95 Mg ha^{-1} and 14.98 Mg ha^{-1}, respectively, with no statistically significant difference ($p > 0.1$) (Figure 3). Maize yield in the optimal method is 4.08% lower than conventional, but wheat yield in the optimal method is 5.99% higher than conventional. There was no significant difference in the annual grain C harvest between the optimal and conventional straw management, which were 6.25 Mg C ha^{-1} yr^{-1} and 6.27 Mg C ha^{-1} yr^{-1}, respectively (Figure 3). Compared with conventional straw management, the grain C harvest of wheat in optimal straw management increased by 5.99%, while that of maize decreased by 5.20%, as a result of the relative change in grain yields.

3.3 | Soil carbon sequestration

Both optimal and conventional straw management led to an increase in SOC stocks in the 8 years of the experimental period (Figure 4). At the end of the 8-year experiment, SOC amounts in the whole soil profile (0–100 cm) increased by 9.06 and 9.57 Mg C ha^{-1} in optimal and conventional straw managements, respectively (Figure 4c). This implies that a more than doubled amount of straw return in conventional straw management (108 Mg ha^{-1}) only led to 5% more SOC sequestration after 8 years. The C sequestration rate in conventional straw management decreased from 1.76 Mg C ha^{-1} yr^{-1} in 2014 to 1.20 Mg C ha^{-1} yr^{-1} in 2020, while the SOC sequestration rate in optimal straw management remained nearly constant (Figure 4).

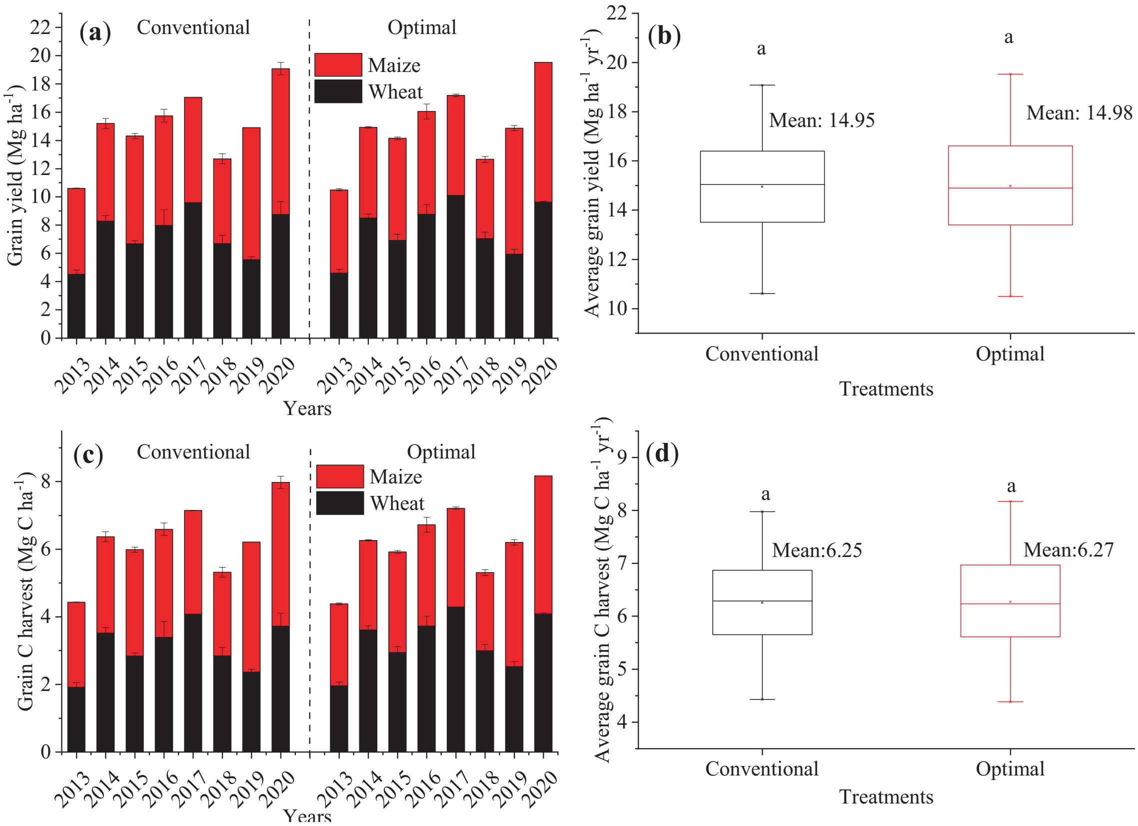

FIGURE 3 Crop grain yields (a-b) and grain C harvest (c-d) in two different straw return treatments. The box plots show the 10, 25, 50, 75, and 90 percentiles. [Colour figure can be viewed at wileyonlinelibrary.com]

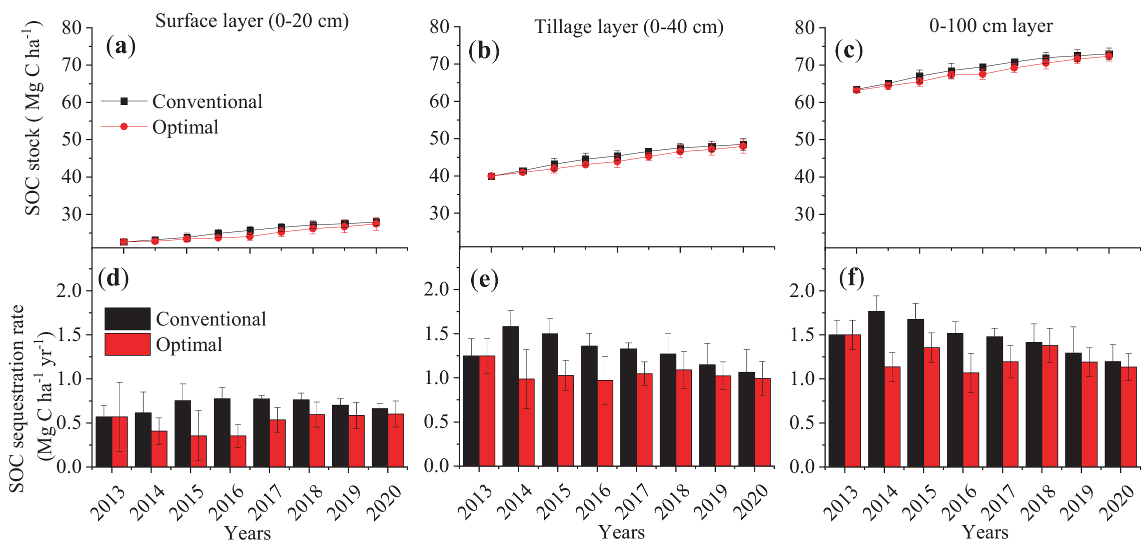

FIGURE 4 Soil organic C amount (a–c) and SOC sequestration rate (d–f) in two different straw return treatments. The error bars indicate standard error. [Colour figure can be viewed at wileyonlinelibrary.com]

SOC increased mainly in the 0–20 and 20–40 cm soil layers (Figure 5). The change in SOC content in deeper soil was not significant. SOC in the 0–20 cm layer of optimal straw management was 27.4 Mg C ha^{-1}, only 1.77% smaller than that of conventional straw management, and the difference was not significant (Figure 4a). SOC amount in the 0–40 cm soil of optimal straw management was 47.9 Mg C ha^{-1}, which was only 0.55 Mg C ha^{-1} less than that in conventional straw management (Figure 4b).

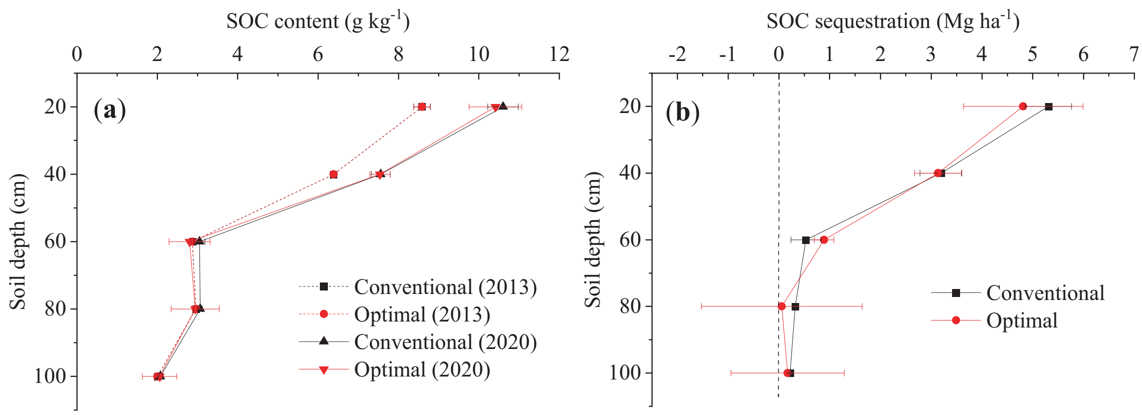

FIGURE 5 Soil organic carbon (SOC) contents in 2012 and 2020 (a) and SOC sequestration (b) during 8 years of treatments. The error bars indicate standard error. [Colour figure can be viewed at wileyonlinelibrary.com]

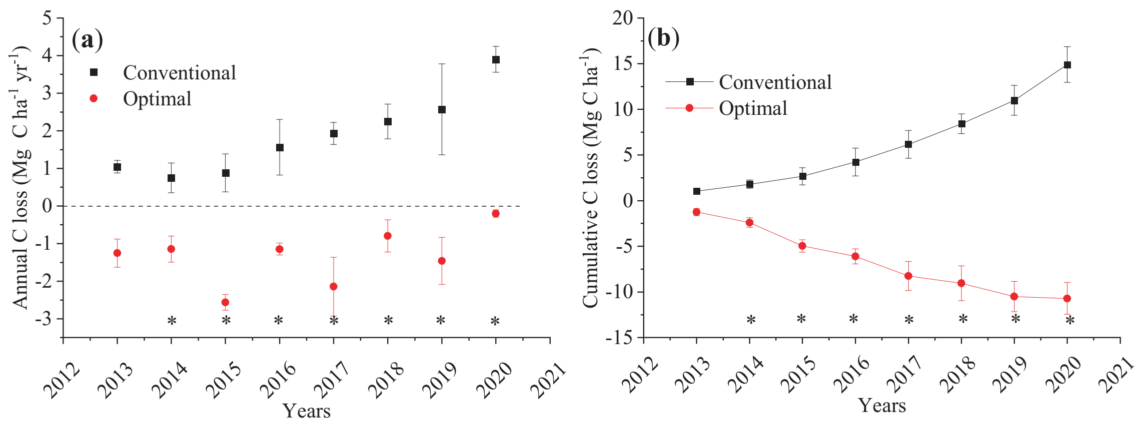

FIGURE 6 Annual (a) and cumulative (b) carbon balances of wheat-maize double cropping systems with two straw return treatments. The error bars indicate the standard error, and '*' indicate significant differences with $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

3.4 | Carbon loss from the system

The average annual and total loss of carbon from the system were significantly higher in conventional straw management compared to that in optimal straw management (Figure 6). The average annual C loss in conventional straw management was 1.86 Mg C ha^{-1} yr^{-1}, and the total C loss increased with the increase of duration, reaching 14.9 Mg C ha^{-1} after 8 years. These results demonstrate that the total SOC sequestration and C harvest in grain were much less than the total carbon inputs. However, in the optimal straw management, the C loss was negative, implying the total SOC sequestration and C harvest in grain was more than the total C inputs. The average annual gain of carbon in optimal straw management was 1.34 Mg C ha^{-1} yr^{-1}, with a total grain C of 10.7 Mg C ha^{-1} after 8 years.

3.5 | Carbon use efficiency

The SOC sequestration per unit C input was 54.2% higher in optimal straw management than that in conventional straw management, and both of them decreased with time (Figure 7a,b). The average grain yield produced per unit C input in optimal straw management was 1.04 Mg Mg^{-1}, 54.8% higher than that in conventional straw management due to the removal of maize straw in optimal straw management not being considered as carbon input into the system (Figure 7).

3.6 | Economic and environmental benefits

The net income of optimal straw management was 3299 USD ha^{-1}, which was 727 USD ha^{-1} (28.3%) higher than that in conventional straw management (Figure 8a). The difference was mainly due to the income of maize straw as feed in optimal straw management, and reduced labor and machine costs of crushing maize straw and returning it to the field. The total GHG emission in the optimal straw management was 3.27 Mg CO_2-eq ha^{-1} yr^{-1}, which was only 22.2% of the 14.7 Mg CO_2-eq ha^{-1} yr^{-1} in conventional straw management (Figure 8b).

The GHG emission to produce unit grain yield in optimal straw management was 0.23 CO_2-eq Mg^{-1}, which was only 22% of that in conventional straw management (1.01 CO_2-eq Mg^{-1}) (Figure 8c). Similarly, the GHG emissions per net income in optimal straw management were reduced by a factor of 5.54 as compared to that in conventional straw management (Figure 8d).

4 | DISCUSSION

4.1 | Soil carbon sequestration

Eight years of straw management experiments in this study indicated that soil carbon sequestration did not respond linearly to C input, for example, more C input resulted in little change in SOC (Figure 4a–c). The average annual C input in the conventional straw management method (wheat + maize straw) was 3.24 Mg C ha^{-1} more than that in the optimal management (wheat straw), while only resulted in 0.07 Mg C ha^{-1} yr^{-1} more SOC sequestration. The quantity and quality of carbon input as well as energy availability in the soil determines the substrate utilization by microorganisms therefore on long-term SOC sequestration (Wang et al., 2022). Compared with wheat straw, maize straw has higher C:N and lignin content, which was harder to decompose. After harvesting maize, the maize straw was retained and incorporated into the soil during a winter season with low temperatures and rainfall, which was not conducive to microbial activity and straw decomposition (Buranov & Mazza, 2008; Tharayil et al., 2011). In addition, as the annual straw production could reach 20 Mg ha^{-1} (~10 Mg C ha^{-1}) in the wheat-maize double cropping systems, conventional straw management (wheat + maize straw) may exceed the soil humification capacity as a result of the imbalance between C and nutrient inputs (Cui et al., 2020; Kirkby et al., 2013). Adding more carbon-rich but nutrient-poor (N, P, S) maize straws may limit microbial carbon use efficiency (Fang, Singh, et al., 2018; Kirkby et al., 2014).

In this study, the SOC sequestration rate of conventional straw management decreased from 1.76 Mg ha^{-1} yr^{-1} in 2012 to 1.20 Mg ha^{-1} yr^{-1} in 2020, while the rate in optimal straw management was relatively stable (1.24 Mg ha^{-1} yr^{-1}). This indicated that the SOC under the conventional straw management method was going to reach SOC equilibrium more quickly. SOC in optimal straw management may take more time to reach SOC equilibrium and get a larger equilibrated SOC eventually. Previous studies also showed that the annual sequestration rate reached a peak at about 10 years and continued at lesser rates over another 16 years (West & Six, 2007), while the sequestration rates and durations can differ greatly between individual sites and management practices (Berhane et al., 2020; Kechavarzi et al., 2010; Zhao et al., 2022).

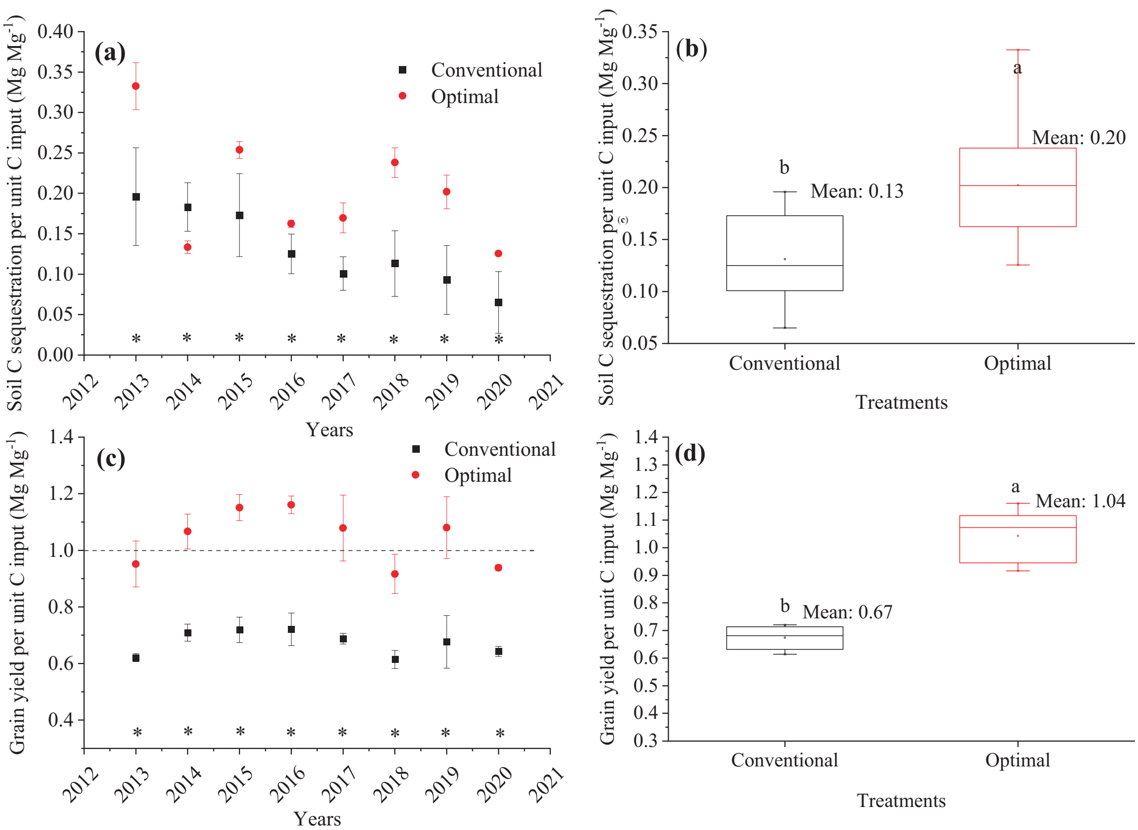

FIGURE 7 Soil C sequestration (a-b) and grain yield (c-d) per unit C input in two straw return treatments. The error bars indicate standard deviation. The black box plots show the 10, 25, 50, 75, and 90 percentiles. '*' and different lowercase letters indicate significant differences with $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

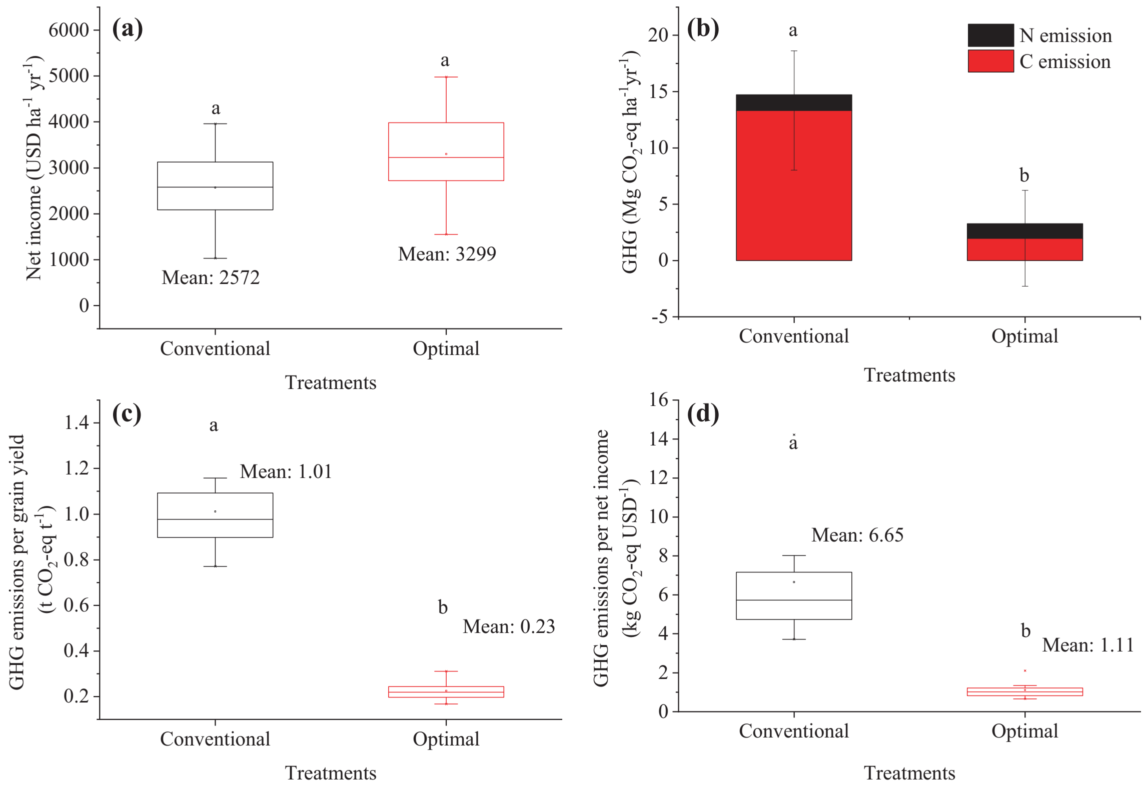

FIGURE 8 Annual net income (a), GHG emissions (b), GHG emission per unit yield (c), and GHG emission per unit net income (d) of the wheat-maize double cropping systems with optimal and conventional straw management. The black box plots show the 10, 25, 50, 75, and 90 percentiles. The different lower-case letters indicate significant differences with p < 0.05 [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Carbon loss and GHG emission

The carbon loss and GHG emission in conventional straw management were 11.43 Mg CO_2-eq ha^{-1} yr^{-1} more than that in optimal straw management (Figures 2 and 6). Higher carbon input resulted in little change in SOC sequestration, yet leading to more CO_2 and N_2O emissions from crop residue (Abalos, Rittl, et al., 2022; Wu et al., 2022). SOC sequestration in conventional straw management (more carbon input) could not offset more GHG emissions, which showed less carbon neutralization potential (Luo et al., 2017; Wang et al., 2018).

In our study, N_2O emissions were calculated according to the default nitrogen input (chemical nitrogen and straw nitrogen) emission coefficients of IPCC 2019. This is widely recognized by relevant research around the world. Other factors including soil type, temperature, water content, and farmland management, also affect N_2O emissions (Zhou et al., 2017), which was not considered here.

4.3 | Opportunities for improving straw management of intensive farming systems

Based on analysis of the data from the 8-year straw management experiment, our results clearly showed that retention of wheat straw was a much better option than retention of both wheat and maize straw in the wheat-maize double cropping systems in the Huang-Huai-Hai Plain. Single (wheat) straw retention led to similar crop grain yield and total soil C sequestration after 8 years, with much greater net income and less total GHG emissions. This provides the scientific basis for optimizing long-term straw management in these highly productive agroecosystems to maximize both economic and environmental benefits, and maintain crop productivity while increasing systems sustainability. Our results demonstrate that in the wheat-maize system, maize straw should be better used for stock feed for economic purposes, rather than returned to the field for soil carbon sequestration.

In this study, we used empirical values to calculate crop carbon inputs in the forms of crop residue (not straw), roots, and root exudates (Fan et al., 2014; Liu et al., 2019) as well as the indirect emissions, which may over-or underestimate these carbon terms, however, such uncertainty is unlikely to change the general conclusions as the difference in the amount of straw return between the two straw management dominated the SOC inputs. We assumed that the maize straw in conventional straw management was used and sold for stock feed. This is a reasonable assumption because maize straw is suitable for fodder, and it has been increasingly used in that way to obtain additional economic income due to the increased emphasis on meat production. Both the economic return and carbon economy as shown in Figure 6 can be subject to variations in prices and costs assumed in this study, but the relative magnitude between the two straw management regimes is unlikely to change.

5 | CONCLUSIONS

The intensive wheat-maize double cropping system in the Huang-Huai-Hai Plain produces a large amount of straw biomass due to its high productivity. Return of the straw from both crops is likely to exceed the humification capacity of the soil, leading to no benefit in terms of productivity and soil C sequestration in the long term. Only returning wheat straw into the field, and using maize straw as stock feed, led to increased net income and reduced field GHG emissions, while maintaining crop productivity and soil carbon sequestration, realizing economic and environmental benefits a win-win result.

AUTHORS' CONTRIBUTIONS

Liang Wang: conceptualization, investigation, methodology, data curation, writing-original draft, writing-review and editing. Enli Wang: methodology, writing-review and editing. Xin Qin: Methodology, Data curation, Writing-review & editing. Yingbo Gao: writing-review and editing. Hui Zhang: Writing-review & editing. Zongxin Li: writing-review and editing, conceptualization, supervision, funding acquisition. Kaichang Liu: supervision, funding acquisition.

ACKNOWLEDGMENTS

This study is funded by the Agricultural Production System in Shandong (SDAIT-02-07) and the Agricultural Science and Technology Innovation Project of Shandong Academy of Agricultural Sciences (CXGC2022A08). This work also was gratefully supported by the National Key R&D Program of China (No. 2018YFD0300602).

CONFLICT OF INTEREST

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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How to cite this article: Wang, L., Wang, E., Qian, X., Gao, Y., Zhang, H., Li, Z., & Liu, K. (2023). Optimal straw management co-benefits crop yield and soil carbon sequestration of intensive farming systems. *Land Degradation & Development*, 1–12. https://doi.org/10.1002/ldr.4610