Effects of Tillage and Cropping Sequences On Crop Production And Environmental Benefits in the North China Plain

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Research Article

Keywords: Conservation Agriculture, Crop Rotation, Carbon Footprint, Greenhouse Gases Emissions, Carbon Sustainability

Posted Date: January 3rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1126359/v1>

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Abstract

The ever-increasing trend of greenhouse gas (GHGs) emissions is accelerating global warming and threatening food security. Environmental benefits and sustainable food production must be pursued locally and globally. Thus, a field experiment was conducted in 2015 to understand how to balance the trade-offs between agronomic productivity and environment quality in the North China Plain (NCP). Eight treatments consisted of two factors, i.e., (i) tillage practices: rotary tillage (RT) and no-till (NT), and (ii) cropping sequences (CS): maize-wheat-soybean-wheat (MWSW), soybean-wheat-maize-wheat (SWMW), soybean-wheat (SW), and maize-wheat (MW). The economic and environmental benefits were evaluated by multiple indicators including the carbon footprint (CF), maize equivalent economic yield (MEEY), energy yield (EY), carbon sustainability index (CSI), etc. Compared with NT, RT increased the EY and MEEY, but emitted 9.4% higher GHGs. Among different CSs, no significant reduction was observed in CF. The lowest ($2.0 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) and the highest ($5.6 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) CF values were observed under MW and SWMW, respectively. However, CSs with soybean enhanced MEEY and the net revenue due to its higher price compared to that of MW. Although the highest CSI was observed under RT-MW, soybean-based crop rotation could offset the decline in CSI under NT when compared to that for RT. These findings suggest that conservation agriculture (CA) could enhance the balance in trade-offs between economic and environmental benefits. Additional research is needed on how to achieve high crop production by establishing a highly efficient conservation agriculture system in the NCP.

Highlights

- Conservation agriculture (CA) reduced carbon footprint (CF) by proper nitrogen use.
- Indirect and direct N_2O emission was the main contributor to CF.
- Soybean-based CA can balance environmental and economic benefits.
- The lower yield under NT partly offsets its environmental benefits.

1. Introduction

The anthropogenic climate change is challenging global crop production and human survival (Guo, 2015; IPCC, 2018). Agronomic solutions are needed towards the site-specific variations among different regions, and the discrepancy in food supply-demand makes identification of these solutions urgent and complex challenge. According to the Intergovernmental Panel on Climate Change (IPCC, 2013), agricultural activities emitted almost 20% of the global greenhouse gases (GHGs). The improper use of farming practices (e.g., overuse of N fertilizer, high-intensity tillage) are the major direct source of GHGs emissions. In addition, the use of diesel fuel in the process of production, storage, and delivery of agricultural raw materials are indirect source of GHGs emissions (Lal, 2004). Therefore, it is necessary to adopt a set of farming practices with high resource use efficiency, and achieve a win-win strategy to ensure food security and offset GHGs (direct and indirect) emissions.

Best management practices [BMPs, e.g., conservation agriculture] have been identified as effective options to reduce GHGs emissions and maximize economic profits (Janzen et al., 2006; Halvorson et al., 2008). A system-based CA, including minimal tillage, permanent soil cover, and complex crop rotations, has been regarded as one of the systematic solutions for sustainable crop production (Lal, 2015). CA reduces indirect emission of GHGs by decreasing the number of field operations and associated cost inputs (West and Marland, 2002; Lal, 2004). No-till (NT) and crop residue retention (RR), two important principles of CA, can increase soil organic carbon (SOC) sequestration by promoting the formation of soil macro-aggregates and reducing mineralization (Kan et al., 2020a; Kan et al., 2020b; Meng, 2020). However, some long-term studies have indicated that conversion to NT has risks of crop yield reduction during the initial stages of implementation (Huynh et al., 2019). Legume-based crop rotations are recognized as feasible options for nutrient management in CA due to its advantage of biological N fixation (Zeng, 2018). However, the impacts of legume-based crop rotation on the trade-offs between economic profits and environmental benefits of a CA system has not been well documented. Therefore, a comprehensive assessment of productivity and carbon (C) emission is imperatively helpful to establish an efficient CA system.

Carbon footprint (CF) is a useful tool to assess the environmental impacts of agricultural activities (van der Werf et al., 2013; Schenck and Huizenga, 2014). Additionally, CF based on the scales of different energy yield (EY), maize equivalent economic yield (MEEY), carbon sustainability index (CSI), and net benefits were also functional to determine and compare the C efficiency from multiple aspects. CF was widely used to evaluate NT, RR, and strategic tillage practices in some previous studies (Xue et al., 2014; Zhang et al., 2016; Liu et al., 2021) and to compare different cropping systems (Yang et al., 2014; Sun et al., 2021). Under CA system, assessing the comprehensive changes in CF, especially from multiple aspects, for the combination of different principles is valuable to optimize CA system through balancing the trade-offs among cereal production, economic, and environmental profits.

The North China Plain (NCP) is one of the major producers of wheat and maize cereals in China. However, the overuse of agricultural inputs such as fertilizers and the ground water in this area has led to severe environmental problems. There are still opportunities to alleviate environmental pressures from agricultural production through the development of cleaner production technologies, such as improved farming

practices and crop rotation. CA has been adopted in this area since the 1970s (Zhang et al., 2014). Similarly, effects of farming practices on the SOC, yield, economic, and environmental benefits of tillage or crop rotation have been documented for the NCP (Li et al., 2010; Liang et al., 2011; Kan et al., 2020b). Although risks of crop failure under NT have been reported, its environmental benefits and profitability have also been widely reported (Canalli et al., 2020). Nonetheless, the research is lacking for the NCP region with regard to the performance of NT, and how crop rotations interact with it and affect the trade-offs among crop production, economic, and environmental benefits. Thus, it is important to identify the interactions between NT and legume-based crop rotation for establishing an optimized CA system in the NCP. The present study was based on the hypothesis that, in CA system, complex crop rotation, NT, and residue retention promote the balance of economic and environmental tradeoffs, and legume-based crop rotation enhances the net economic benefits. Thus, the objectives of this study were to: 1) evaluate the crop yield, SOC, and CSI under tillage systems combined with different cropping sequences (CSs), and 2) determine a comprehensive assessment of crop yields, economic profits, and environmental costs under CA in this region.

2. Materials And Methods

2.1. Site description

The field experiment was initiated in 2015 at Wujiao Experimental Station of China Agricultural University (37°36' N, 116°21' E) in Hebei Province. The region is a temperate continental monsoon climate, with an average annual temperature of 13.1 °C and average annual rainfall of 531 mm. The rainfall is unevenly distributed during the year, and 60-70% of the annual rainfall is concentrated between June and August. The soil type is Aquic Cambosol of a silt-loam texture (Zhao et al., 2020), containing 11.2% clay, 18.6% and, 70.2% silt. Baseline soil properties in the 0-20 cm layer were 4.97 g kg⁻¹ SOC, 0.81 g kg⁻¹ N, 44.6 mg kg⁻¹ available P, 92.2 mg kg⁻¹ available K, and 7.51 pH.

2.2. Experimental design

The field experiment was laid out according to a split-plot design with three replications. The main plots consisted of two tillage practices (started from October 2015), with rotary tillage (RT) and no-till (NT). The subplots consisted of four different CSs (started from October 2017), including maize-wheat-soybean-wheat (MWSW); soybean-wheat-maize-wheat (SWMW); soybean-wheat-soybean-wheat (SW); and maize-wheat-maize-wheat (MW) (Fig. 1). Soil tillage was done only before seeding of wheat, and no tillage was practiced for summer maize and soybeans. Residue management differed between winter wheat and summer maize seasons. Wheat residues were mulched on the soil surface, while maize and soybean residues were chopped into small pieces (5-10 cm long) using a straw shredder. Detailed information on management practices were shown in previous studies (Virk et al., 2021).

2.3. Soil sampling and analysis

2.3.1. Soil organic carbon storage

Soil samples were obtained at 0-10, 10-20, 20-30, and 30-50 cm depths from each plot near harvesting of each crop (wheat, maize, and soybean) in June and October from 2018 to 2020. After air-drying, soil samples were gently grinded and passed through a 2-mm sieve. The concentration of SOC was determined using a K₂Cr₂O₇-H₂SO₄ oxidation procedure (Bao, 2008). To account for differences in soil bulk density, the SOC storage (Mg ha⁻¹) was calculated on equivalent mass basis by using Eq. (1) and (2) (Ellert and Bettany, 1995). The SOC sequestration rate (kg CO₂-eq ha⁻¹ yr⁻¹) was determined by using Eq. (3).

$$M_{soil,i} = BD_i \times T_i \times 1000$$

1

$$SOC_{storage} = \sum_{i=1}^n [M_{soil,i} \times conc_i + (M_{o,i} - M_{soil,i}) \times conc_{i+1}] \times 0.001$$

2

$$SOC_{sequestrationrate} = \frac{SS_{2020} - SS_{2015}}{4} \times \frac{44}{12}$$

3

where, $M_{soil,i}$ is the soil mass per unit area in the i th layer (Mg ha⁻¹). BD_i is the bulk density of the i th layer (g cm⁻³), T_i is the thickness of the i th layer (m). $conc_i$ is the concentration of SOC in i th layer. $conc_{i+1}$ is the concentration of SOC in $i+1$ th layer. $M_{o,i}$ is the designated equivalent mass of each layer (i.e., the maximum soil mass), i is the soil depth interval, a, d $i = 1, 2, 3$ and 4 for 0-10, 10-20, 20-30 cm, and 30-50 cm layer, respectively. The number of 1000 and 0.001 are unit conversion coefficients. SS2015 and SS2020 are the SOC storage at the beginning of the

experiment and the SOC storage at the harvest of winter wheat in 2020, respectively, and 4 represents the duration of the experiment. The 44/12 is the coefficient that converts C to CO₂.

2.3.2. Crop residues and carbon inputs from crop resides

Crops grain yield were measured in a quadrant of 2 m² for winter wheat and summer soybean in each plot, and double rows of 10 m for summer maize in each plot. The amount of crop residue was calculated as the ratios of grain: straw and root: straw (Zhao et al., 2018).

The C input included aboveground residues and belowground roots. The C input of the aboveground residues was calculated by using Eq. (4), and that of the belowground C input by Eq. (5) (Zhao et al., 2018).

$$C_a = GY \times \frac{1 - WC}{GS \text{ ratio}} \times 0.45$$

4

$$C_b = GY \times \frac{1 - WC}{GS \text{ ratio}} \times RS \text{ ratio} \times 0.45$$

5

where, *GY* represents the grain yield of each season. *WC* represents the water content of the grain, which is 0.125, 0.135, and 0.103 for wheat, maize, and soybean, respectively. *GSratio* represents grain: straw, and wheat, maize, and soybean are 0.846, 0.955, and 0.524, respectively. *RSratio* represents root: straw, and wheat, maize, and soybean are 0.2, 0.28, and 0.196, respectively. The conversion coefficient for crop biomass to C content is 0.45 (Fang et al., 2007).

2.3.3. Net revenue

Net revenue was calculated based on the economic value from grain minus total inputs during crop production. The prices of all grain and inputs were calculated according to the actual local conditions (Liu et al., 2021). The total inputs involved farming, harvesting, fertilizer, herbicide, and irrigation. The economic profit was calculated by Eq. (6) (Ray et al., 2016).

$$\text{Benefit: cost ratio} = \frac{\text{Grain income}}{\text{Total input}}$$

6

2.3.4. Carbon footprints

International Organization for Standardization (ISO) has defined the CF as the sum of GHGs directly and indirectly produced by crops during a single life cycle and can be expressed in carbon dioxide equivalents (CO₂-eq) (ISO, 2013). CF consisted mainly of off-farm input production and on-farm application. The system boundary was from sowing (including seedbed preparation) to the harvesting of crops. The involved inputs, practices, or inventories are shown in Fig. 2.

The N content in aboveground crop residues was calculated with Eq. (7). N₂O emission in this study was calculated by using inputs of N fertilizer, crop residues, and emission factors. Therefore, the direct N₂O emission was calculated by using Eq. (8), and indirect N₂O emission by Eq. (9). The total emission of N₂O was calculated by Eq. (10).

$$F_S = (C_{si} + C_{ri}) \times N_{C(i)}$$

7

$$N_2O_{DE} = (F_S + F_N) \times \sigma_1 \times \frac{44}{28}$$

8

$$N_2O_{IE} = \left[F_N \times FRAC_{GASF} \times \sigma_2 + (F_S + F_N) \times FRAC_{LEACH} \times \sigma_3 \right] \times \frac{44}{28}$$

9

$$GHG_{N_2O} = (N_2O_{DE} + N_2O_{IE}) \times 298$$

where, F_S and F_N are the N content of aboveground crop residues and N fertilizer application. $N_{C(i)}$ is the N content of different crops. σ_1 , σ_2 , and σ_3 are the emission coefficients of N inputs, volatilization of N fertilizer, and N leaching, respectively. $FRAC_{GASF}$ represents the fraction of N fertilizer volatilized (NH_3 and $\text{NO}_x\text{-N}$). $FRAC_{LEACH}$ represents the fraction of N leaching. The value of 44/28 and 298 are the coefficients of N_2 to N_2O and N_2O to $\text{CO}_2\text{-eq}$, respectively (Table 1).

Table 1
GHGs emissions coefficients for different agricultural material inputs.

Item	Abbreviation	Emission factor	Unit	Source
Tillage	EF_T	3.37	$\text{kg CO}_2\text{-eq kg}^{-1}$	Zhang et al. (2013)
Harvest	EF_H	3.37	$\text{kg CO}_2\text{-eq kg}^{-1}$	Zhang et al. (2013)
Nitrogenous fertilizer	EF_N	3.44	$\text{kg CO}_2\text{-eq kg}^{-1}$	Chen et al. (2015)
Phosphatic fertilizer	EF_P	0.4	$\text{kg CO}_2\text{-eq kg}^{-1}$	Chen et al. (2015)
Potassic fertilizer	EF_K	0.3	$\text{kg CO}_2\text{-eq kg}^{-1}$	Chen et al. (2015)
Herbicides	EF_{2H}	18	$\text{kg CO}_2\text{-eq kg}^{-1}$	Yang et al. (2014)
Irrigation consumptions	EF_I	1.12	$\text{CO}_2\text{-eq kW}\cdot\text{h}^{-1}$	Zhang et al. (2013)
N fertilizer volatilization fraction	$FRAC_{GASF}$	0.1	$\text{Kg NH}_3\text{-N} + \text{NO}_x\text{-N volatilized kg}^{-1}$ N input	IPCC, (2006)
N leaching fraction	$FRAC_{LEACH}$	0.3	kg N kg^{-1} N input	IPCC, (2006)
Direct N_2O emission from N fertilizer on upland crops	σ_1	0.01	$\text{kg N}_2\text{O-N kg}^{-1}$ N input	IPCC, (2006)
Indirect N_2O emission from N fertilizer volatilization	σ_2	0.01	$\text{kg N}_2\text{O-N kg}^{-1}$ $\text{NH}_3\text{-N} + \text{NO}_x\text{-N}$ volatilized	IPCC, (2006)
Indirect N_2O emission from N fertilizer leaching	σ_3	0.0075	$\text{kg N}_2\text{O-N kg}^{-1}$ N leaching	IPCC, (2006)
N content of winter wheat	N_{CW}	0.0052	$\text{kg N (kg dry matter)}^{-1}$	NDRC (2011)
N content of summer maize	N_{CM}	0.0058	$\text{kg N (kg dry matter)}^{-1}$	NDRC (2011)
N content of summer soybean	N_{CS}	0.018	$\text{kg N (kg dry matter)}^{-1}$	NDRC (2011)
Winter wheat seed		0.58	$\text{kg CO}_2\text{-eq kg}^{-1}$	Ecoinvent 2.2
Summer maize seed		1.93	$\text{kg CO}_2\text{-eq kg}^{-1}$	Ecoinvent 2.2
Summer soybean seed		0.92	$\text{kg CO}_2\text{-eq kg}^{-1}$	West and Marland (2002)

CO_2 emissions from agricultural inputs (i.e., seeds, chemical fertilizers, herbicides, and diesel fuel produced by farming, harvesting, and irrigation) were calculated by Eq. (11) (Lal, 2004).

$$GWP_{input} = \sum_i^n AI_i \times EF_i$$

where, AI represents the amount of each item of input (Table 2). EF represents its emission coefficient (Table 1). represents different agricultural inputs.

Table 2
Mean agricultural inputs of different tillage practices and cropping sequences.

Item	Treatment		Seed (kg ha ⁻¹)	Tillage ^a (kg ha ⁻¹)	Harvest ^a (kg ha ⁻¹)	Nitrogenous fertilizer (kg ha ⁻¹)	Phosphatic fertilizer (kg ha ⁻¹)	Potassic fertilizer (kg ha ⁻¹)	Herbicides ^b (kg ha ⁻¹)	Irrigation Consumptions (kWh ha ⁻¹)
Winter wheat	RT		300	69.125	42.5	318	103.5	107	0.225	675
	NT		300	62	42.5	318	103.5	107	0.225	675
Summer maize	RT		60	13.5	38.5	339.75	130.435	120	1.5	675
	NT		60	13.5	38.5	339.75	130.435	120	1.5	675
Summer soybean	RT		150	13.5	38.5	183.75	130.435	120	0	675
	NT		150	13.5	38.5	183.75	130.435	120	0	675
The entire	RT	MWSW	405	82.625	81	579.75	233.935	227	0.975	1350
growing season		SWMW	405	82.625	81	579.75	233.935	227	0.975	1350
		SW	450	82.625	81	501.75	233.935	227	0.225	1350
		MW	360	82.625	81	657.75	233.935	227	1.725	1350
	NT	MWSW	405	75.5	81	579.75	233.935	227	0.975	1350
		SWMW	405	75.5	81	579.75	233.935	227	0.975	1350
		SW	450	75.5	81	501.75	233.935	227	0.225	1350
		MW	360	75.5	81	657.75	233.935	227	1.725	1350
RT: rotary tillage; NT: no-till. MWSW: maize-wheat-soybean-wheat; SWMW: soybean-wheat-maize-wheat; SW: soybean-wheat; and MW: maize-wheat.										
^a Diesel consumption at tillage and harvest was calculated by multiplying the actual amount applied by the diesel density.										
^b Herbicide were tribenuron-methyl 10% wettable powder for winter wheat season and Nicosulfuron atrazine oil deflocculant for summer maize season, respectively.										

CF per unit of area (CF_A) (kg CO₂-eq ha⁻¹ yr⁻¹) was calculated by Eq. (12).

$$CF_A = GWP_{input} + GHG_{N_2O} + \Delta SOC$$

12

where, is the mean annual C change in 0-30 cm soil layer.

To unify the average annual crop yield for crops, the actual yield was converted into EY and MEEY. The CF per kg of EY (CF_{EY}) (kg CO₂-eq GJ⁻¹ yr⁻¹) was calculated by Eq. (13) and (14).

$$E_Y = (Y_g \times E_g + Y_s \times E_s) / 10^3$$

13

$$CF_{EY} = \frac{CF_A}{EY}$$

14

where, E_Y (GJ ha⁻¹) represents energy yield. Y_g and Y_s are the yield of grain and straw. E_g and E_s are the calorific value of yield and straw. The grain calorific values of wheat, maize, and soybean were 16.3, 16.3, and 20.9 MJ kg⁻¹, respectively. The straw calorific values of wheat, maize, and soybean were 14.6, 14.6, and 15.1 MJ kg⁻¹, respectively (Chen, 2002).

The CF per kg of MEEY (CF_{MEEY} , kg CO₂-eq kg⁻¹ yr⁻¹) was calculated by Eq. (15) and (16) (Pradhan et al., 2018).

$$MEEY = Y_i \times \frac{P_i}{P_M}$$

15

$$CF_{MEEY} = \frac{CF_A}{MEEY}$$

16

where, (kg ha⁻¹) is the yield, (US \$ kg⁻¹) is the price, is wheat and soybean. The local prices of wheat, maize, and soybean are 0.38, 0.3, and 0.88 US \$ kg⁻¹, respectively.

The CF per unit of economic revenue (CF_E) (kg CO₂-eq⁻¹ \$⁻¹ yr⁻¹) was calculated by Eq. (17).

$$CF_E = \frac{CF_A}{E}$$

17

where, E is the total revenue (US \$ ha⁻¹) (Table 4).

Table 4
Comparison of annual average economic profits (\$ value can be rounded up to the whole \$ and delete cents).

Treatment		Production cost (US \$ ha ⁻¹)	Yield revenue (US \$ ha ⁻¹)	Net revenue (US \$ ha ⁻¹)	input output economic ratio (US \$ ha ⁻¹)
RT	MWSW	1485.29	4974.95	3489.65	3.3
	SWMW	1367.29	4642.20	3274.90	3.4
	SW	1485.29	5342.80	3857.52	3.6
	MW	1249.29	4680.48	3431.18	3.7
NT	MWSW	1358.81	4486.45	3127.64	3.3
	SWMW	1358.81	4083.91	2725.10	3.0
	SW	1524.36	4372.78	2848.43	2.9
	MW	1240.83	3800.31	2559.49	3.1
RT: rotary tillage; NT: no-till. MWSW: maize-wheat-soybean-wheat; SWMW: soybean-wheat-maize-wheat; SW: soybean-wheat; and MW: maize-wheat.					

2.3.5. Carbon sustainability index (CSI)

The carbon sustainability index (CSI) was calculated by Eq. (18) (Lal, 2004).

$$CSI = \frac{C_{output} - C_{emission}}{C_{emission}}$$

18

where, C_{output} is the average C produced by biomass, which includes grain, straw, and root. The average C produced by straw and root was calculated in Eq. (4) and (5), respectively. $C_{emission}$ was calculated by Eq. (12).

2.4. Data analysis

IBM SPSS version 23.0 software was used to perform the analysis of variance (ANOVA). The means and interactions comparisons were analyzed using the least significant difference (LSD) test. The average values of the selected CF-related parameters were standardized to show their performance through radar diagrams (Ladha et al., 2016). Origin Pro 2017 was used to design figures.

3. Results

3.1. Grain yield

EY was significantly affected by tillage practices and CSs ($P < 0.05$, Table 3), while a non-significant interaction was observed between tillage practices and CSs. RT-MW and NT-SW were observed with the highest and lowest EY, respectively. Among different CSs under RT, the EY of MWSW, SWMW, and SW were 15.2%, 17.2%, and 19.5% lower than that of MW, respectively. Similarly, the EY of MWSW, SWMW, and MW were 25.7%, 12.8%, and 28.7% higher than that of SW under NT, respectively. Similarly, tillage and CSs were observed to affect MEEY individually ($P < 0.05$), but with no significant interaction (Table 3). Under RT, SW and SWMW were observed to have the highest and lowest MEEY. Under NT, the highest MEEY was observed under MWSW, which was higher than those under MWSW, SW, and MW by 9.9%, 2.6%, and 18.1%, respectively.

Table 3
Annual average energy and maize equivalent economic yield of different tillage practices and cropping sequences.

Treatment		Energy yield (GJ ha ⁻¹)	Maize equivalent economic yield (kg ha ⁻¹)
RT	MWSW	382.04 b	15102.68 b
	SWMW	373.12 bc	14831.30 bc
	SW	362.86 bc	17069.66 a
	MW	450.74 a	14953.62 b
NT	MWSW	361.38 bc	14333.71 bc
	SWMW	324.17 cd	13047.66 cd
	SW	287.39 d	13970.53 bc
	MW	369.83 bc	12141.57 d
T		<0.05	<0.05
CS		<0.05	<0.05
T×CS		0.207	0.193

T, tillage practices; CS, cropping sequences. RT, rotary tillage; NT, no-till. MWSW, maize-wheat-soybean-wheat; SWMW, soybean-wheat-maize-wheat; SW, soybean-wheat; and MW, maize-wheat. Different letters in the same column indicate significant differences at $P < 0.05$.

3.2. Net revenue

The net revenue of each CS was higher under RT than that under NT (Table 4), that is 11.6%, 20.2%, 35.4%, and 34.1% higher under RT than that under NT for MWSW, SWMW, SW, and MW, respectively (Table 4). RT-SW and NT-MW were observed with the highest and lowest net revenue, respectively. RT-SW was 35.4% higher than that under NT-SW, and NT-MW was 25.4% lower than that under RT-MW. Among RT, SW (the highest) was 17.8% higher than that under SWMW (the lowest). Among NT, MWSW (the lowest) was 22.2% higher than that under MW (the lowest).

Similarly, input output economic ratios were higher under RT than that under NT for the four CSs (Table 4). However, the input output economic ratio of MWSW was almost the same under RT and NT. RT-MW and NT-SW were observed with the highest and lowest input: output economic ratio, respectively. The input: output economic ratio under RT-MW was 12.1%, 8.8%, and 2.8% higher than that under MWSW, SWMW, and SW, respectively. The highest input: output economic ratio under NT was observed for MWSW, which was 10.0%, 13.0%, 8.0%, and 6.5% higher than that under SWMW, SW, and MW, respectively.

3.3. SOC storage

Tillage and CSs were observed to affect SOC storage and SOC sequestration rate at 0-30 cm depth individually ($P < 0.05$, Fig. 3), but without significant interaction between tillage and CSs. The highest SOC storage and SOC sequestration rate were both observed under RT-MW. The SOC storage was 9.4%, 13.5%, 11.1%, 24.5%, 25.3%, 13.9%, 13.4% higher under RT-MW than that under RT-MWSW, RT-SWMW, RT-SW, NT-MWSW, NT-SWMW, NT-SW and NT-MW, respectively. SOC sequestration rate was 9.8%, 15.1%, 21.3%, 47.2%, 42.4%, 17.7%, 14.0% higher under RT-MW than that under RT-MWSW, RT-SWMW, RT-SW, NT-MWSW, NT-SWMW, NT-SW and NT-MW, respectively. For different CSs under RT, SWMW (the lowest) decreased SOC storage by 11.9% compared to MW (the highest). Similarly, among different CSs under NT, SWMW (the lowest) decreased SOC storage by 8.9% compared to MW (the highest). Furthermore, among different CSs under RT, MW increased SOC sequestration rate by 21.3% compared to SW (the lowest). Among different CSs under NT, MW increased SOC sequestration rate by 29.1% compared to SWMW (the lowest).

3.4. Carbon footprints

Significant differences in CF_A were observed among treatments ($P < 0.05$, Table 5). The highest CF_A was observed under NT-SWMW (5584.49 kg CO_2 -eq $ha^{-1} yr^{-1}$), which was 49.9%, 42.9%, 12.3%, 64.3%, 14.2%, 40.4%, and 34.3% higher than that under RT-MWSW, RT-SWMW, RT-SW, RT-MW (the lowest), NT-MWSW, NT-SW, and NT-MW respectively. The highest CF_{EY} was observed under NT-SWMW (17.23 kg CO_2 -eq $GJ^{-1} yr^{-1}$), with the lowest under RT-MW (4.42 kg CO_2 -eq $GJ^{-1} yr^{-1}$), respectively (Table 5). Significant differences in CF_{MEEY} were observed among treatments. NT-SWMW (the highest, 0.43 kg CO_2 -eq $kg^{-1} yr^{-1}$) increased CF_{MEEY} by 28.0–68.9% compared to the other treatments. The lowest CF_{MEEY} was observed under RT-MW (0.13 kg CO_2 -eq $kg^{-1} yr^{-1}$). NT-SWMW was the highest with CF_E (Table 5), which was 113.3% higher than that under RT-SWMW (the lowest).

Table 5

Average carbon footprint of different tillage practices and cropping sequences.

Treatment		CF_A	CF_{EY}	CF_{MEEY}	CF_E
		(kg CO_2 -eq $ha^{-1} yr^{-1}$)	(kg CO_2 -eq $GJ^{-1} yr^{-1}$)	(kg CO_2 -eq $kg^{-1} yr^{-1}$)	(kg CO_2 -eq $\$^{-1} yr^{-1}$)
RT	MWSW	2795.52 g	7.32 e	0.19 e	0.83 g
	SWMW	3187.37 f	8.54 de	0.21 d	0.97 f
	SW	4896.87 b	13.50 b	0.29 c	1.27 d
	MW	1991.74 h	4.42 f	0.13 f	0.58 h
NT	MWSW	4792.39 c	13.26 b	0.33 b	1.53 b
	SWMW	5584.49 a	17.23 a	0.43 a	2.05 a
	SW	3328.53 e	11.58 c	0.24 d	1.17 e
	MW	3669.62 d	9.92 d	0.30 c	1.43 c

CF_A : the CF per unit of area; CF_{EY} , the CF per kg of energy yield; CF_{MEEY} , the CF per kg of maize equivalent economic yield; CF_E , the CF per unit of total revenue. RT: rotary tillage; NT: no-till. MWSW: maize-wheat-soybean-wheat; SWMW: soybean-wheat-maize-wheat; SW: soybean-wheat; and MW: maize-wheat. Different letters in the same column indicate significant differences at $P < 0.05$.

Among CF inventories, the SOC sequestration offset CF_A (Fig. 4) by 34.8%, 33.2%, 23.2%, and 38.2% under RT-MWSW, RT-SWMW, RT-SW, and RT-MW, respectively. Similarly, the SOC sequestration offset 25.6%, 21.1%, 31.5%, and 32.0% of CF_A under NT-MWSW, NT-SWMW, NT-SW, and NT-MW, respectively. The emission of N_2O accounted for 23.1-29.1% of CF_A among treatments. Among indirect emissions from agricultural inputs, fertilizer accounted for most of CF_A (Fig. 4), and it ranged from 13.0–16.1%, irrigation was the secondary contributor and it ranged from 8.1–11.3%, and herbicides contributed the lowest and ranged from 0.03–0.2%.

3.5. Carbon sustainability index (CSI)

The highest CSI was observed under RT-MW, which was 105.8%, 122.3%, 347.7%, 281.2%, 493.0%, 247.7%, and 168.3% higher than that under RT-MWSW, RT-SWMW, RT-SW, NT-MWSW, NT-SWMW, NT-SW, and NT-MW, respectively. The lowest CSI was observed under NT-SWMW. There were no significant differences between RT-MWSW and RT-SWMW.

3.6. Comprehensive assessment of economic and environmental benefits

Among the assessed indicators for different CSs under RT, MW has the highest GY and EY due to increased grain yield, as well as the highest CSI and ΔSOC . SW had the highest MEEY and net revenue. For NT, the highest and lowest GHGs emissions were observed under SWMW and SW, respectively. Furthermore, NT-MWSW has a higher MEEY and net revenue than others. NT-MW had the highest GY, EY, ΔSOC , and CSI (Fig. 6).

4. Discussion

4.1. Crop yields and economic profits

The data presented herein indicate that crop yields of wheat, maize, and soybean were significantly affected by tillage and CS treatments, but non-significant interactions were observed between tillage and CSs. This trend was similar to that reported by Hemmat and Eskandari (2004). However, significant interactions between tillage and crop rotation have been reported in crop yield during dry years (Ray et al., 2012; Huynh, et al., 2019). Results of the present study also show that, despite differences among tillage practices, the EY of MW was higher than that of soybean involved in CSs. This trend may be due to the lower photosynthesis and also photorespiration of soybean than those of maize (Zhang and He, 2020). The MEEY of CSs including soybean were higher than that of MW. Therefore, establishing a CA system based on soybean rotation could increase the MEEY, mainly because of the compensatory effects from high price over the low crop yield of soybean. However,

different results have been reported for previous studies in different regions (Uzoh et al., 2019; Sun et al., 2021). Decreases in crop yield under NT were observed in the present study. Zhang et al. (2013) obtained the lowest yield of NT wheat among the four tillage treatments for a 3-year field study. This trend may be attributed to soil compaction caused by continuous NT, resulting in limited root growth (Kan et al., 2020c) and increased incidence of weeds (Arvidsson et al., 2014).

Similarly, a previous study also reported that a lower input: output economic ratio observed under NT may be due to somewhat lower crop yield. Decline in crop yield under NT may be caused by the reduced number of mechanical operations and agricultural inputs surpassed the cost-saving compensation of adopting NT (Peng and Zhang, 2006). It is generally believed that increase diversification of crop rotation system could enhance the agronomic and environmental benefits of NT (Yang et al., 2014). However, the present study leads to the conclusion that the benefit of SW and MW was higher than that of MWSW and SWMW because of the relative lower grain yield of soybean (Canalli et al., 2020). However, soybean-based CA can improve the economics of cropping systems compared to maize because of its higher economic price.

4.2. SOC storage

The results presented in this study showed a higher SOC storage under RT than that under NT, and highest SOC storage and sequestration rate were observed under RT-MW. Most of the previous studies indicated an enhancement in SOC storage under conservation tillage (Snyder et al., 2009; Kan et al., 2020a), mainly due to reduced surface disturbance, increased soil cover, and enhanced input of substrates (Sindelar et al., 2015). Debate also exists if SOC is enhanced or merely redistributed within the soil profile by conservation tillage (Powlson et al., 2014). Some studies have suggested that NT increased SOC in surface soils, but RT (or plow tillage) increased SOC in deeper soils (Lal, 1997; Blanco-Canqui and Lal, 2008). The data from the present study verifies the results of previous studies that increase in SOC in subsoil is also essential to an objective assessment on SOC storage (Huggins et al., 2007). The results presented herein indicate that SOC sequestration under RT was higher than that under NT when considering storage in the subsoil. The reason of the lower SOC storage and sequestration under NT may be the reduced input of total substrates (relatively lower crop yield) from aboveground biomass input, roots, root exudates, etc.

The SOC content also differed significantly among CS treatments. Soybean-based crop rotation strongly impacted the accumulation of SOC. The highest SOC sequestration in the presented study was observed in WM. Similar results were reported in a previous study in the NCP (Shen et al., 2018). The SOC sequestration of MW was slightly higher than that of SW. Results from present study also show that soybean-based crop rotation may reduce the SOC sequestration capacity of CA when compared to maize in NCP. However, most of the previous studies reported that: decomposition of crop residues could be accelerated by soybean compared to maize, and thus increase SOC content (Huggins et al., 2007; Schmer et al., 2020). The differences may be induced by the reduction of C input (King and Blesh, 2018) and the short experimental duration (Shrestha et al., 2013). Thus, optimizing the field operations and continuous use of NT for a longer duration may offset the negative impacts of soybean-based crop rotation on SOC in CA system.

4.3. Carbon footprints

CF is defined as the sum of GHG emissions and elimination over the whole production process expressed in CO₂-eq based on life cycle assessment using a single impact category (ISO, 2013). Different functional units (e.g., CF_{EY}, CF_{MEEY}, and CF_E) were used to show the trade-offs between GHGs emissions and other ecosystem services (Sun et al., 2021). Liu et al. (2016) reported that reducing tillage intensity and increasing crop diversity can effectively decline the CF of crop production and increase SOC sequestration. But several studies have reported the opposite results (Lal, 2003; Gregorich et al., 2005; Blanco-Canqui and Lal, 2008). Among the eight treatments in the present study, the minimum and maximum values of CF were observed under RT-MW and NT-SWMW, respectively. The consistent results for the three CF indicators (CF_{EY}, CF_{MEEY}, and CF_E) leads to conclusion that CF of RT was lower than that under NT, and soybean-based crop rotation could effectively reduce the CF_E in the CA system even with a relative low yield of soybean.

Among CF inventories and components, SOC sequestration made the largest contribution to offset GHG emissions, which did not increase with the increase in crop diversity under NT. This trend was mainly because of the limitation of the short experiment duration for crop rotation. A previous study concluded that SOC dynamics along with duration of experiment and the robust results need a long-term assessment (Wang et al., 2021). Combining the tillage and CSs, the lowest CF was observed under RT-MW even with the highest consumption of fertilizer and fuel (i.e., the indirect GHGs emission). Such a trend may be attributed to higher yield and SOC sequestration under RT-MW (Yang et al., 2017). CA with soybean-based crop rotation, as shown in the present study may reduce farming inputs (the indirectly GHGs emission) and increase economic profit, but enhance the risks of decrease in crop yield.

4.4. Limitations, implications, and perspectives

The present study assessed the trade-offs between crop productivity and environmental impacts of NT with soybean-based crop rotation in CA system using multiple CF indicators. Among several limitations in data collection and analysis is the fact that N₂O emissions and the emission factor were directly and indirectly affected by N application rates and environmental factors (Castanheira and Freire, 2013). N₂O emission of different planting systems was compared in this study. However, this study did not consider the changes in N₂O emission factors under different

precipitation conditions, which may affect the accuracy of CF calculation. In addition, some other gas emissions (i.e., nitric oxide, C monoxide, and ammonia) also affected some complex atmospheric reactions (Monson and Holland, 2001), and these were not calculated. This trend was mainly because the effect on the C budget was generally too small to have a significant impact on the results. Furthermore, due to the limitation of the small area study, the calculation of the manufacture, storage, and transportation of agricultural inputs was not accurate, and the price of farm products also fluctuated between years. This limitation affected the absolute values of CF under different treatments. The comparisons and relative changes among treatments were creditable. Therefore, this study provides a useful reference for the comprehensive economic and environmental assessment of CA in the NCP.

Previous studies have predicted that global demand for food will double over the next 50 years, posing significant challenges to environmental sustainability and increasing food supply without compromising environmental hazards (Tilman et al., 2002). There have been many studies on how CA improves crop yield and ecosystem services, but few studies on how legume crops will interact with other CA principles (e.g., NT or RR) on the environmental footprint. Conventional agriculture requires excessive amounts of chemicals to boost crop productivity. However, the combination of legume crops in CA can reduce the application of N fertilizer due to its symbiotic nitrogen fixation. We promoted CA (including NT, soybean-based crop rotation, straw mulching) with the best agronomic measures to meet the environmental challenges trying to establish a suitable case.

The analysis presented herein show that combination of soybean-based crop rotation with NT offers great potential to improve the economic and environmental efficiency in the NCP. It will promote the regional sustainable agriculture development. The present study has revealed a future potential to sustain food supply and enhance crop diversity by increasing soybean yield in CA system with the aim to increase the agricultural sustainability. Future research priorities include in-depth studies on how to realize the potential crop yield under CA system under on farm conditions.

5. Conclusions

The results presented support the following conclusions:

1. Despite the risks of declining grain yield in NT (i.e., average of 14.4% lower than that under RT), the fewer inputs and the combined benefits from soybean-based crop rotation could balance the trade-offs with environmental and economic profits
2. N₂O emission was the main contributor to CF, indicating a high potential to reduce GHGs by optimizing fertilizer application and related field management practices.
3. In combination with soybean-based crop rotation, CA could reduce CF due to less input of N fertilizer and more N fixation.
4. The lower yield under NT partly offsets its environmental benefits.
5. The long-term economic and environmental sustainability of agricultural production in the NCP can be improved by establishing a CA system that combines straw return as mulch with suitable crop diversity (especially leguminous crops).

Declarations

Authors Contributions

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Funding

This work was supported by the National Natural Science Foundation of China (32001486).

Data availability

Data are available within the article. The authors confirm that the data supporting the findings of this study are available within the article.

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests.

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Figures

Figure 1

Schematic diagram of the different cropping sequences from October 2018 to June 2020 in the present study. MWSW: maize-wheat-soybean-wheat; SWMW: soybean-wheat-maize-wheat; SW: soybean-wheat; and MW: maize-wheat.

Figure 2

System boundary for calculating GHGs emissions in different tillage practices and cropping sequences.

Figure 3

SOC storage in 2020 and SOC sequestration rate under different tillage practices and cropping sequences. T, tillage practices; CS, cropping sequences. RT, rotary tillage; NT, no-till. MWSW, maize-wheat-soybean-wheat; SWMW, soybean-wheat-maize-wheat; SW, soybean-wheat; and MW, maize-wheat. Different lowercase represents significant difference at $P < 0.05$ between treatments.

Figure 4
Component of carbon footprint of the entire growing season under different tillage practices and cropping sequences. RT, rotary tillage; NT, no-till. MWSW, maize-wheat-soybean-wheat; SWMW, soybean-wheat-maize-wheat; SW, soybean-wheat; and MW, maize-wheat.

Figure 5
Carbon sustainability index (CSI) of different tillage practices and cropping sequences. RT, rotary tillage; NT, no-till. MWSW, maize-wheat-soybean-wheat; SWMW, soybean-wheat-maize-wheat; SW, soybean-wheat; and MW, maize-wheat. Different lowercase represents significant difference at $P < 0.05$ between treatments.

Figure 6

Performance of selected parameters for different tillage practices and cropping sequences using radar chart. GY, grain yield; EY, energy yield; MEEY, maize equivalent economic yield; Δ SOC, the mean annual SOC change in 0–30 cm soil depth; CSI, carbon sustainability index; CF_A , the CF per unit of area; CF_{EY} , the CF per kg of energy yield; CF_{MEEY} , the CF per kg of maize equivalent economic yield; CF_E , the CF per unit of total revenue. RT, rotary tillage; NT, no-till. MWSW, maize-wheat-soybean-wheat; SWMW, soybean-wheat-maize-wheat; SW, soybean-wheat; and MW, maize-wheat.