Effect of straw retention on carbon footprint under different cropping sequences in Northeast China

Qiulai Song (sql142913@163.com)
Heilongjiang Academy of Agricultural Sciences
Jie Zhu
Beijing Chalk Blue Sky Technology Co.,Ltd
Zhenping Gong
Northeast Agricultural University
Yanjiang Feng
Heilongjiang Academy of Agricultural Sciences
Qi Wang
Heilongjiang Academy of Agricultural Sciences
Yu Sun
Heilongjiang Academy of Agricultural Sciences
Xiannan Zeng
Heilongjiang Academy of Agricultural Sciences
Yongcai Lai
Heilongjiang Academy of Agricultural Sciences

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Effect of straw retention on carbon footprint under different cropping sequences in Northeast China

Qiulai Song[1,2], Jie Zhu[3], Zhenping Gong[4*], Yanjiang Feng[1], Qi Wang[1], Yu Sun[1], Xiannan Zeng[1], Yongcai Lai[1]

1. Institute of Crop Cultivation and Tillage, Heilongjiang Academy of Agricultural Sciences, Harbin, Heilongjiang 150086, China

2. Key Laboratory for Combining Farming and Animal Husbandry, Ministry of Agriculture and Rural Affairs, Harbin, Heilongjiang 150086, China

3. Beijing Chalk Blue Sky Technology Co., Ltd, Beijing 100102, China

4. College of Agriculture, Northeast Agricultural University, Harbin 150030, China

*Corresponding author:Zhenping Gong， E-mail address: gzpyx2004@163.com

Abstract

Inappropriate farm management practices can lead to increased agricultural inputs and changes in atmospheric greenhouse gas (GHG) emissions, impacting climate change. This study assessed the potential of straw retention to mitigate the negative environmental impact of different cropping systems on the Songnen Plain using the life cycle assessment (LCA) method combined with field survey data. Straw retention (STR) and straw removal (STM) treatments were established in continuous corn (CC) and corn-soybean rotation (CS) systems in a split-plot experiment. The effects of straw retention on the carbon footprint (CF) of cropland under different cropping systems were compared. The CF under CC was 2434.0–2706.9 kg CO_2 ha^{-1} yr^{-1}, 49.3%–57.3% higher than that under CS. Nitrogen fertilizer produced the most CO_2, accounting for 66.2%-80.4% of the CF. The carbon balances of the CC and CS systems with STR were positive, with annual carbon sequestrations of 9632.5 and 2715.9 kg CO_2 ha^{-1}

yr^{-1}, respectively. The carbon balances of the CC and CS systems with STM was negative, with annual carbon sequestrations of -3589.2 and -3006.2 kg CO_2 ha^{-1} yr^{-1}, respectively. This study demonstrates that STR under CC cultivation is an environmentally friendly practice for agricultural production, can help achieve high-yield and low-carbon production in rainfed cropland, and can support the sustainable development of grain production in Northeast China.

Keywords: straw retention; continuous corn; corn-soybean rotation; carbon footprint; forming factors； carbon balance.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

All data generated or analysed during this study are included in this published article [and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

QS set the goal of the study, analyzed the data related to the carbon footprint, and was a major contributor in writing the manuscript. JZ performed the gas collection in the field. ZG guided the entire study, and was a major contributor in writing the manuscript. YF conducted the literature retrieval work. QW analyzed the data of carbon balance. YS analyzed and explained the carbon emission data of diesel fuel. XZ analyzed and explained the indirect carbon emission data of fertilizer. YL analyzed and explained the data related to the carbon footprint. All authors read and approved the final manuscript.

1. Introduction

Greenhouse gas (GHG) emissions are the most critical factors influencing global climate change, and climate change poses a serious threat to the natural environment and human economic development (IPCC 2013). Agricultural ecosystems are a primary source of GHGs released by human activity (Duxbury 1994; Linquist et al. 2012). Different management practices in cropland affect the mineralization of soil organic matter, changing carbon emissions. Moreover, different inputs of chemical fertilizers, human activities, and fuels create variation in carbon emissions from agricultural inputs under different management practices, indirectly influencing the energy consumption and carbon cycling of the system (Li et al. 2002; Lal 2004; Larsen and Hertwich 2011; Wang et al. 2015a; Zhang et al. 2015; Meier et al. 2020). The carbon footprint (CF), the impact of carbon emissions on the global environment, is an assessment of direct or indirect CO_2 emissions caused by particular activities or accumulated during the life cycles of particular products (Peters 2010; Duan et al. 2011; Adewale et al. 2019). Many factors are involved in the CF associated with field crop production, including not only CO_2 emissions from cropland soils and crops themselves but also diesel directly used by agricultural machinery during agricultural production, electricity consumed by irrigation, and indirect CO_2 emissions caused by the production and transportation of chemical fertilizers, pesticides, and seeds (Liu et al. 2016; Lal et al. 2019).

The CF is affected by many factors, such as regional conditions, agricultural production systems, and crop type (Günther et al. 2017; Houshyar and Grundmann 2017; Yadav et al. 2017; Liu et al. 2018; Xue et al. 2018). To quantify the CFs of different agricultural production systems around the world, many studies of regional agricultural CF, crop CF, and food CF have been conducted (Hillier et al. 2009a; Nelson et al. 2009; Wang et al. 2015b). Previous studies have quantified the CFs of different crops and patterns of variation in different regions (Hillier et al. 2009b; Röös et al. 2010; Clay et al. 2012; Gan et al. 2014; Wang et al. 2015a; Wang et al. 2016; Günther et al. 2017; Houshyar and Grundmann 2017; Pishgar-Komleh et al. 2017; Yadav et al. 2017; Heusala et al. 2020), providing a basis for reducing carbon emissions in agricultural production processes. Other studies focus on technologies and approaches for reducing the CF associated with crop production, with the goal of mitigating the contribution of agricultural production systems to global climate change. The CF of crop production can be reduced by changing management methods and implementing low-carbon technologies, such as conservation tillage, optimized irrigation, and fertilizer application (Zhang et al. 2016; Yadav et al. 2018). Wang et al. (2020) assessed the CFs of four different cropping systems: cotton monoculture (CM), winter wheat intercropped with cotton (WIC), wheat cropping followed by transplanted cotton (WTC), and direct-seeded cotton after winter wheat harvest. The results indicated that CM was the best cropping system in low-fertility plots, whereas WIC was the cropping system with the lowest CF in high-fertility plots due to low inputs of fertilizer, labor, and diesel. Therefore, appropriate improvements in cropping patterns and farming practices can reduce the CFs of crop production (Wang et al. 2020). STR also has an important influence on CF. Lal et al. (2019) demonstrated that STR increased CFs by approximately 10%. Li et al. (2020) further pointed out that CF is strongly affected by the amount of straw used, and when compared with no STR treatments, CF did not increase until field application of one-third of the STR, then increased as straw application was further increased. Bai et al. (2021), under the same natural conditions in semiarid areas of Northwest China, showed that STR increased greenhouse gas emissions, but due to the strong acceleration of SOC accumulation, CF decreased by 44.5-55.4%. Therefore, the effects of STR on CF observed by different researchers in different regions are inconsistent. These studies have systematically elucidated the impact of changes in cropping systems on CFs as well as the response of soil carbon emissions and CF to farming practices, including STR. However, little has been reported on the impact of the combined effects of cropping system changes and STR on CF.

The Songnen Plain in Northeast China is a major grain-producing area. This plains region is located in Heilongjiang and Jilin Provinces. Rainfed cropland in this region is mainly planted with corn and soybean. The cropping system involves one harvest per yea, and the major cropping patterns are continuous corn (CC) and corn-soybean rotation (CS). In recent years, the Chinese government has completely prohibited burning crop straw in the field and has vigorously promoted straw return technology. The area of crop straw return has increased year by year in the Songnen Plain. However, there is no systematic study of the effects of STR on CF under two cropping patterns (CC and CS) on the Songnen Plain. We hypothesized that CFs are jointly influenced by changes in cropping patterns (CC and CS) and straw use patterns (STR and STM). Our objective was to evaluated the impact of STR on CFs using life cycle assessment (LCA) under two cropping patterns (CC and CS) on the Songnen Plain through direct measurement of soil carbon emissions and indirect emission inventories.

2 Materials and methods

2.1 Experimental site

The field experiment was conducted at the Xiangfang Experimental Practice Base of Northeast Agricultural University. During the experimental period, the total annual rainfall was 485 mm (2013) and 454 mm (2014). This study began in 2012, and data were collected from 2013 to 2014. The cropping patterns at the experimental site were mainly CC and CS. The basic fertility of the experimental soil was as follows: organic matter: 30.71 g kg^{-1}; total nitrogen: 1.48 g kg^{-1}; total phosphorus: 0.40 g kg^{-1}; total potassium: 16.28 g kg^{-1}; NO_3^--N: 78.79 mg kg^{-1}; NH_4^+-N: 26.04 mg kg^{-1}; available potassium: 187.00 mg kg^{-1}; available phosphorus: 23.63 mg kg^{-1}.

2.2 Experimental design

A two-factor split-plot design was used in this study. The main plot factor was cropping pattern (continuous corn cropping *vs.* corn-soybean rotation), and the sub-plot factor was straw management (straw retention *vs.* straw removal). There were four treatments: continuous corn cropping with straw retention (CC-STR), continuous corn cropping with straw removal (CC-STM), corn-soybean rotation with straw retention (CS-STR), and corn-soybean rotation with straw removal (CS-STM). Each treatment had three replicates for a total of 12 plots, with 780 m^2 per plot. For the CC-STR treatment, after the previous corn crop was harvested mechanically, the crop straw was pulverized using a straw return machine producing a straw length of ≤10 cm, with deep loosening and stubble removal from the ridge body, a 25 cm loosening depth, and a 32 cm wide ridge top, with corn sown the following spring. For the CC-STM treatment, residual straw was removed after harvest. The field was plowed in autumn (depth=25 cm), and a rotary cultivation ridger was used to break the upturned soil and simultaneously build the ridges, with corn sown the following spring. For the CS-STR treatment, straw and soil preparation were the same as for the CC-STR treatment, with soybean sown the following spring. For the CS-STM treatment, residual straw was removed after harvest. The field was plowed in autumn (depth=25 cm), and a rotary tillage ridger was used to break the upturned soil and simultaneously build the ridges, with soybean sown the following spring. In all four treatments, the ridge spacing was 70 cm. During the crop seedling stage, the soil was cultivated with medium tillage. During the two-year experimental period, the same crop cultivar, fertilization, and weeding schemes were used. The Dongnong 253 corn (*Zea mays* L.) cultivar was sown mechanically on May 2 and harvested on October 6, with a mean density of 65,000 plants kg ha^{-1}. The specific rates of fertilizer application for corn were as follows: urea (46% N), 300 kg ha^{-1} (75 kg ha^{-1} sowing and 225 kg ha^{-1} topdressing); diammonium hydrogen phosphate (18% N and 46% P_2O_5), 150 kg ha^{-1}; and potassium sulfate (30% K_2O), 75 kg ha^{-1}. The Kenfeng 16 soybean (*Glycine max*) cultivar was mechanically sown on May 2 and harvested on September 28 with a seeding rate of 43.66 kg ha^{-1} and a mean density of 269,500 plants kg ha^{-1}. The rates of fertilizer application for soybean were as follows: diammonium hydrogen phosphate (18% N and 46% P_2O_5), 150 kg ha^{-1}, and potassium sulfate (30% K_2O), 75 kg ha^{-1}. For chemical weeding, 96% emulsifiable concentrate of Dual Gold mixed with 72% emulsifiable concentrate of 2,4-D butyl ester was applied for closed weed control a week after sowing of corn and soybean, with a dosage of 975 ml ha^{-1} and 1125 ml ha^{-1}, respectively. In addition, 55% Gengjie was sprayed at the four-to-five leaf stage of corn with a dosage of 1575 ml ha^{-1}, and 36% fomesafen-quizalofop-p-ethyl-clomazone was sprayed on soybean plants after development of one to three compound leaves, with a dosage of 1650 ml ha^{-1}.

2.3 Calculation of cropland CF

The boundary of cropland CF was determined following the principles of LCA (Mohammadi et al. 2013) from soil preparation after harvest to the harvest of the current crop. The carbon flux changes of the elements in the carbon cycle of the system were determined and calculated according to the CF equation proposed by Liu et al. (2013); She et al. (2017); Feng et al. (2020). The CF was calculated as follows:

$$CF = GWP_{N_2O} + GWP_{input} \tag{1}$$

where CF is the total carbon emissions of crop production, GWP_{N_2O} is the total emissions produced by synthetic nitrogen fertilizer and crop residual nitrogen (kg CO_2 ha^{-1} yr^{-1}), and GWP_{input} is the indirect GHG emissions from the production, storage, transportation, and use of agricultural inputs.

GWP_{N_2O} emissions was estimated based on the rates of synthetic nitrogen fertilizer and crop residual nitrogen by the method determined by the IPCC (2019). The GWP_{N_2O} emissions were calculated as follows:

$$\mathrm{GWP}_{\mathrm{N_2O}} = GWP_{N_2O_{SNF}} + GWP_{N_2O_{CRN}} \tag{2}$$

$$\mathrm{GWP}_{N_2O_{SNF}} = Q_{SNF} \times [EF + (F_{\mathrm{volatilization}} \times \mathrm{E}_{\mathrm{volatilization}}) + (F_{\mathrm{leach}} \times \mathrm{E}_{\mathrm{leach}})] \times 44/28 \times 298 \tag{3}$$

$$\mathrm{GWP}_{\mathrm{N_2O}} = Q_{CRN} \times [EF + (F_{\mathrm{leach}} \times \mathrm{E}_{\mathrm{leach}})] \times 44/28 \times 298 \tag{4}$$

where $\mathrm{GWP}_{N_2O_{SNF}}$ represents N_2O emissions from farmland resulting from synthetic nitrogen fertilizer application (kg CO_2 ha^{-1} yr^{-1}), $\mathrm{GWP}_{N_2O_{CRN}}$ represents N_2O emissions from crop residual nitrogen (kg CO_2 ha^{-1} yr^{-1}), Q_{SNF} represents the amount of synthetic nitrogen fertilizer (kg N ha^{-1} yr^{-1}), Q_{CRN} represents the crop residue nitrogen (kg N $ha^{-1}yr^{-1}$), EF is the direct emission factor (kg N_2O-N/kg N, 0.01), $F_{volatilization}$ is the volatilization rate of synthetic nitrogen fertilizer as NH_3-N and NOx-N, (15%), $E_{volatilization}$ is the emission factor for N_2O volatilized as NH_3-N and NOx-N (0.014), F_{leach} is the percent nitrogen loss via nitrate leaching and runoff in the total nitrogen input (24%), E_{leach} is the emission factor for N_2O from nitrate leaching (0.011), 44/28 is the conversion factor for N_2O-N to N_2O, and 298 is the global warming potential of N_2O over a 100-year period (Yang et al. 2014; IPCC 2019; Wang et al. 2020).

GWP_{input} is the CO_2 emissions from agricultural inputs during agricultural production, calculated as follows:

$$\mathrm{GWP}_{\mathrm{input}} = \sum_{i=1}^{n} \mathrm{AL_i} \times \mathrm{EF_i} \tag{5}$$

where AL_i is the ith input variable and EF_i is the emission factor for the ith input variable. The emission factors were mainly derived from Liu et al. (2013) and Yang et al. (2014) (Table 1). Specifically, diesel input was determined by measuring diesel fuel consumption during soil preparation, seeding, intertillage, and harvesting, using a multifunction fuel consumption meter (Shuangshuo Electronics Co., Ltd., Zibo, Shandong Province, China). The measurement was performed on a row length of 100 m and repeated three times. Agricultural chemical inputs were calculated as the amounts of chemical elements according to the inputs recorded in Subsection 2.2, and the agricultural inputs are listed in Table 2.

2.4 Calculation of cropland carbon balance

Net biome productivity (NBP) is the change in net carbon storage of the cropland ecosystem, calculated as follows (Huang et al. 2013; She et al. 2017):

$$NBP = NPP - CR - R_s \quad (6)$$

where NPP is the net primary productivity, CR is the grain and straw removed with crop harvest, and Rs is the heterotrophic soil microbial respiration. NPP includes carbon sequestered by crop grains, straw, and roots. NPP was calculated by measuring the grain yield at harvest combined with the dry weight ratio and carbon content measured in various parts of the plants. CR includes crop grains, stalks, and cobs removed from the field after harvest. Under the STR treatment, only the corn and soybean grains were harvested from the field, while under STM, corn grains, cobs, and stalks and soybean grains, pods, and stalks were all harvested from the field. Rs was estimated from the actual field measurement of total soil *in situ* respiration according to the ratio of heterotrophic respiration to total *in situ* respiration for the same area as reported by (Zhu 2015) (64.9% for corn and 75.7% for soybean).

The total soil *in situ* respiration was measured using the static box-infrared gas analyzer method. Gas samples were collected every 7 to 10 days from April 5 to November 8. Sampling boxes were made of stainless steel, 50 cm long, 25 cm wide and 50 cm high. Gas samples were collected between 8:30-10:30 am on sunny days. Five sampling sites were randomly selected in the treatment plots. Sampling boxes were inserted between two ridges and sealed with approximately 5 cm of soil, and gas was then transferred into 500 ml aluminum foil bags using a 100 ml glass syringe. The CO_2 concentration was determined using a GXH-3010E1 infrared analyzer (Institute of Beijing HUAYUN Analytical

Instrument Co., Ltd.).

The CB of cropland was used to indicate the difference between CF and NBP as follows:

$$CB = NBP - CF \tag{7}$$

2.5 Statistical analysis

The data were analyzed using descriptive statistics in Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA) and IBM SPSS 19.0 (SPSS Inc., Chicago, IL, USA). The results included mean standard deviations (SD) for three replicates. A Duncan test was used for comparison between treatments (α= 0.05).

3 Results and analysis

3.1 CF of cropland under different cropping patterns

The CO_2 emissions estimated based on N_2O produced by nitrogen fertilizer and straw application were the greatest contributor to the CF (Fig. 1). The proportion of direct N_2O emissions to total emissions: CC-STR 58.2%, CC-STM 50.8%, CS-STR 54.5%, CS-STM 48.2%. STR resulted in higher N_2O emissions from both CC and CS systems. The second greatest contributor was indirect CO_2 emissions from the production, storage, and transportation of nitrogen fertilizer, accounting for 30.2% and 33.6% of total emissions from CC and 27.7% and 29.2% of total emissions from CS. In addition, diesel consumption by agricultural machinery operations from sowing to harvesting produced considerable carbon emissions. In both CC and CS, carbon emissions from diesel consumption were higher under STM (226.4–246.3 kg CO_2 ha^{-1} yr^{-1}) compared with STR (164.9180.4–180.4 kg CO_2 ha^{-1} yr^{-1}).

The CF of CC was higher than that of CS (Table 4). Due to the large amount of nitrogen in crop straw, the CF of CC with STR (2706.9 kg CO_2 ha^{-1} yr^{-1}) was 11.2% higher than that of CC with STM

(2434.0 kg CO_2 ha^{-1} yr^{-1}) and 5.6% higher under CS.

3.2 Soil heterotrophic respiration under different cropping patterns

The total soil heterotrophic respiration of CC was similar to that of CS(Fig. 2). Total emissions ranged from 5139.4 to 7492.9 kg CO_2 eq ha^{-1} yr^{-1} under CC and from 5072.2 to 6902.3 kg CO_2 eq ha^{-1} yr^{-1} under CS. STR significantly increased total heterotrophic respiration by 45.79% under CC and 36.08% under CS compared with STM.

3.3 NPP under different treatments

Corn with higher grain yield produced more biomass and NPP than soybean, leading to differences in yield, biomass, and NPP under different cropping patterns. CC produced significantly higher crop yields than CS. STR significantly reduced soybean yield, while its effect on corn yield was not significant compared with STM. Overall, STR resulted in a decrease in the yield, biomass, and NPP of the CS system (Table 3).

3.4 CB of cropland under different cropping patterns

The NBP of the CC and CS systems with STR were 12,339.3 and 4436.4 kg CO_2 ha^{-1} yr^{-1}, respectively (Table 4). The CB of cropland was also positive, with annual carbon sequestrations of 9632.5 and 2715.9 kg CO_2 ha^{-1} yr^{-1}, respectively. In contrast, the NBP of the CC and CS systems with STM was negative, with values of -1155.2 and -1376.2 kg CO_2 ha^{-1} yr^{-1}, respectively. For CO_2 produced by soil N_2O and agricultural inputs, there was a strong carbon source effect, with an annual carbon release of -3589.2 and -3006.2 kg CO_2 ha^{-1} yr^{-1}, respectively. These results indicate that straw retention plays a significant role in carbon sequestration under both the CC and CS systems.

4. Discussion

4.1 Variations in CF under different cropping patterns

Different cropping patterns alter the inputs and outputs of agricultural ecosystems, leading to variations in CF (Gan et al. 2012; Yang et al. 2014; Wang et al. 2020). In our study, the CF of CC was significantly greater than that of CS due to greater agricultural inputs as well as straw and nitrogen fertilizer inputs in corn cultivation compared with soybean cultivation, in turn increasing carbon emissions from the continuous cropping system. Similar results were reported by Yadav et al. (2018) and Lal et al. (2019).

N_2O emissions were the largest contributor to total CF, followed by indirect N_2O emissions from nitrogen fertilizer production, storage, and transportation. This result agrees with the findings of Yadav et al. (2018). However, Jat et al. (2019) and Lal et al. (2019) reported that fertilizer application makes the greatest contribution, followed by N_2O emissions and diesel emissions, not fully consistent with these results. These contradictory results may be explained by noting that Jat et al. (2019) and Lal et al. (2019) did not consider N_2O volatilization and leaching.

Despite differences in these studies, they all demonstrate that indirect N_2O emissions from the production, storage, and transportation of nitrogen fertilizer as well as direct N_2O emissions from the application of nitrogen fertilizer are the most important components of total GHG emissions from crop production (Hillier et al. 2009a; Cheng et al. 2011; West et al. 2014; Wang et al. 2020). Therefore, reducing nitrogen fertilizer input and adopting a sustainable application method are crucial practices to mitigate agricultural GHG emissions from fertilizer application (Bacenetti et al. 2016; Feng et al. 2020). It should be noted that reducing nitrogen fertilizer may affect yield and that the amount of nitrogen fertilizer should be adjusted by comprehensively considering CF changes per unit of yield. In this study, diesel input was the third highest contributor to the CF (6.7–13.9%). During soil preparation, minimal tillage and no-tillage with a reduced number of agricultural machinery operations can reduce GHG emissions (Yadav et al. 2018).

4.2 Carbon balance of cropland under different cropping patterns

Carbon sequestration and carbon emissions are two processes that coexist in agricultural production. GHGs such as CO_2 and N_2O are directly or indirectly emitted into the atmosphere, while plants absorb atmospheric CO_2 through photosynthesis (Soussana et al. 2007; Smith et al. 2010; Liu et al. 2018; Feng et al. 2020). The CB of cropland can directly characterize changes in net carbon flow in cropland systems (Feng et al. 2020). Generally, if all crop straw is returned to the farmland, it is equivalent to the amount of GHG released after the straw is decomposed. Therefore, neither straw carbon sequestration nor straw carbon emission is considered in general (Feng et al. 2020). However, our study aimed to assess the effects of STR and STM on the CB of cropland under two different cropping patterns; thus, crop straw inputs were considered. Although this approach may exaggerate the carbon sequestration effect of STR, the carbon sequestration trend was clear. Huang et al. (2019) obtained CFs based on changes in soil organic carbon storage in Jilin Province, showing that net carbon sequestration was 744.96 kg CO_2 ha^{-1} yr^{-1} under CC with minimal tillage and STR. In our study, following straw retention, the carbon sequestered by CC was 9632.5 kg CO_2 ha^{-1} yr^{-1}, and the carbon sequestered by CS was 2715.9 kg CO_2 ha^{-1} yr^{-1}. The carbon sequestration of CC reported here is higher than that reported by Huang et al. (2019), but this result may reflect the carbon sequestration effect of straw return. Due to differences in study methods and boundaries, discrepancies exist in results obtained from the same region by different researchers, but the data all reflect the advantage of straw retention in carbon sequestration. Lemke et al. (2010) and Huang et al. (2019) reported that if there is not enough crop straw to return, cropland soil will become a CO_2 source. Our study reaches a similar conclusion. Both cropping patterns were a source of atmospheric CO_2 under STM.

4.3 Limitations and implications of this study

This study ignores GHG emissions from agricultural labor and agricultural machinery manufacturing, transportation, maintenance, and management. From the life cycle perspective, these GHG emissions are not negligible (Liu et al. 2013). If these factors are considered in CF calculations, the absolute value of CF may change. This study compared the effects of planting pattern changes and straw utilization on CF to determine the best planting pattern, rather than obtaining an absolute value for the CFs of planting patterns. Although the calculation method employed in this paper requires improvement, it can provide a basis for further research and guide low-carbon agricultural production and is relevant to national carbon emission and environmental impact assessments.

5. Conclusions

When considering carbon sequestered during crop growth, the CB under two different cropping patterns with STR was positive compared with STM due to enhanced soil carbon sequestration under STR. Fertilizer application was the most important factor contributing to carbon emissions. Higher CF was observed under CC compared with CS due to lower fertilization of soybean, regardless of straw management. Therefore, STR under both CC and CS patterns is an environmentally friendly agricultural practice that can achieve high yields and low carbon production in the rainfed cropland of the Songnen Plain, Northeast China, and support the sustainable development of food production. These results can help identify a suitable cropping pattern for corn and soybean production on the Songnen Plain with improved energy use efficiency and reduced CF and production costs without compromising system productivity.

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Figures

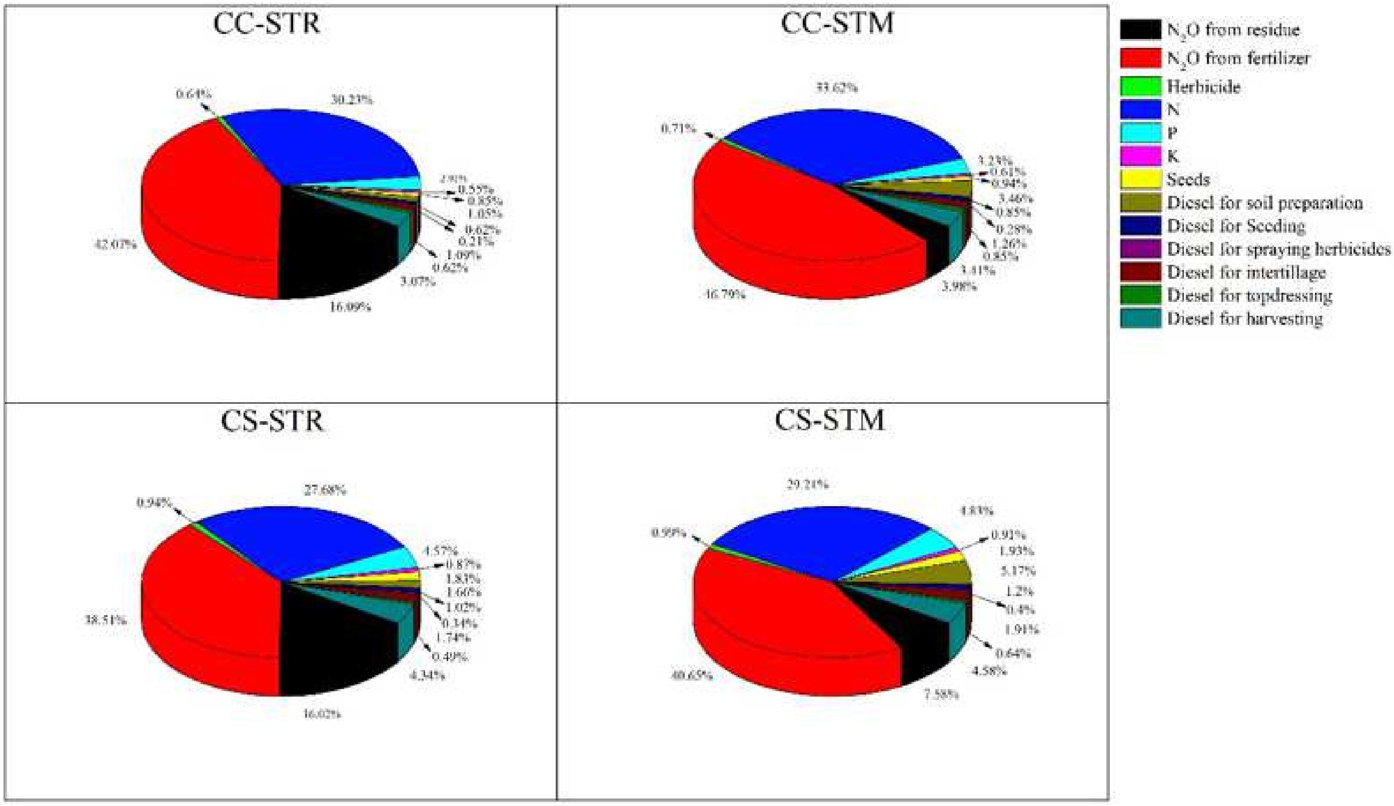

Figure 1

Share of different inputs in the carbon footprints of continuous corn cropping and corn-soybean rotation cropping systems (two-season average)

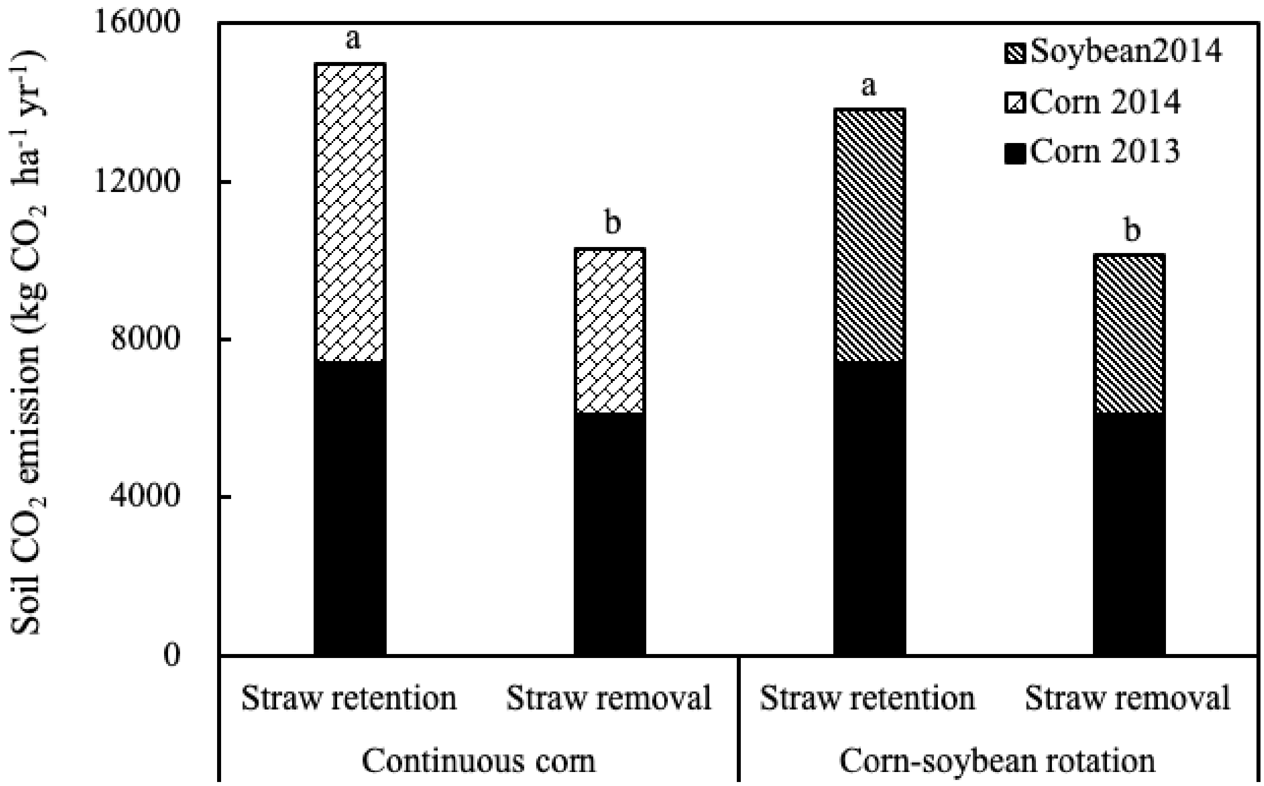

Figure 2

Soil heterotrophic respiration under different cropping patterns