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Carbon footprint of a winter wheat-summer maize cropping system under straw and plastic film mulching in the Loess Plateau of China

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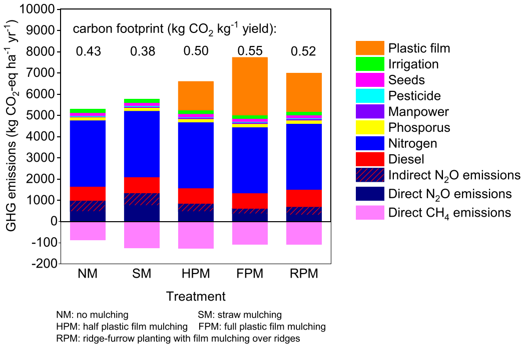
HIGHLIGHTS

- Direct N_2O emissions decreased for plastic mulching but increased for straw mulching.
- Nitrogen fertilizer was the greatest contributor to total GHG emissions.
- N_2O emissions were the second largest contributor to total emissions for NM and SM.
- Straw mulching had the lowest CF due to lower GHG emissions and the highest yield.
- Plastic film mulching significantly increased CFs.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of this study was to calculate the carbon footprint (CF) of straw and plastic film mulching practices in order to identify the optimum field management for low-carbon agriculture. A four-year field experiment was conducted to determine the effects of different mulching measurements on greenhouse gas (GHG) emissions, grain yield, and CF of a winter wheat-summer maize cropping system in the Loess Plateau of China. Mulching treatments were no mulching (NM), straw mulching (SM), half plastic film mulching (HPM); full plastic film mulching (FPM), and ridge-furrow planting with film mulching over ridges (RPM). Plastic film mulching decreased N_2O emissions compared with NM. However, SM significantly increased direct N_2O emissions by 59.2% and indirect N_2O emissions by 16.2%. Average annual total GHG emissions calculated by life cycle assessment were 5199–7631 kg CO_2-eq ha^{-1} yr^{-1}. Nitrogen (N) fertilizer was the largest contributor to total GHG emissions, accounting for >41%. For plastic film mulching treatments, the second greatest contributor was plastic film, accounting for 21.1–35.7% of total GHG emissions. In contrast, the second greatest contributor was direct and indirect N_2O and CH_4 emissions under NM (17.2%) and SM (21.6%). Emissions from diesel consumption was the third largest component of total GHG emissions. All mulching treatments showed significantly greater annual grain yield than the NM treatment. The CF of summer maize yield was higher than that of winter wheat. SM showed the lowest CF (0.38 kg CO_2-eq kg^{-1}), and plastic film mulching increased CFs compared with NM. These results suggest that SM should be the priority mulching practice used to increase yield and to reduce the CF of winter wheat-summer maize production in the Loess Plateau, China. Optimizing N fertilizer application rates should be one of the key production strategies employed to mitigate agricultural GHG emissions.

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1. Introduction

The rising concentrations of greenhouse gases (GHGs) in the atmosphere are the primary cause of global warming (IPCC, 2014). Agriculture is an important source of GHGs, accounting for approximately 11% of the total anthropogenic emissions (Wollenberg et al., 2016). The increasing demand for food due to the ever-growing population requires agriculture to produce more grain (Chen et al., 2014). Therefore, it is necessary to develop farming practices with less GHG emissions in order to mitigate global warming and achieve sustainable agricultural development (Lal, 2004).

Mulching techniques (i.e., straw mulching and plastic film mulching) have played important roles in crop production in arid, semi-arid, and sub-humid areas (Kader et al., 2017). Straw mulching, as a low-cost and readily available practice increases crop yield and provides long-term benefits by improving soil properties, nutrient cycles, and enzyme activities (Akhtar et al., 2018; Chen et al., 2019; Yong et al., 2016). Plastic film mulching can reduce soil evaporation, regulate soil temperature, and increase water-use efficiency (WUE) and crop yield (Gu et al., 2020; Gu et al., 2019; Wang et al., 2019). Recently, more attention has been given to the effect of mulching practices on soil GHG emissions, mainly including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Berger et al., 2013; Chen et al., 2017). Many previous studies have evaluated the effect of mulching practices on crop yield and environment in terms of soil GHG emissions per unit of yield (Chen et al., 2017; Cuello et al., 2015; Liu et al., 2014). Every step of an agricultural production system generates GHGs. These steps include nitrogen (N) application, irrigation, the production of plastic film, and mechanical operations (Gan et al., 2012; He et al., 2018a). Managing the trade-offs between productivity and environmental sustainability of mulching practices cannot be comprehensively done by only considering direct emissions from soil.

Carbon footprint (CF) is an effective indicator for evaluating environmental impacts of agricultural activities (Weinheimer et al., 2010). CF is defined as the sum of GHGs (expressed in CO_2 equivalent, abbreviated as CO_2-eq) emitted by a service or a product during the entire process based on a life cycle assessment (LCA). LCA is a methodology framework used to evaluate the environmental impact of a product, service, or system during its life cycle ("from cradle to grave") (ISO/TS, 2013). LCA provides a good approach for quantifying the GHGs generated during the entire agricultural production process (Brentrup et al., 2004). Cheng et al. (2015) estimated mean CFs for the main crops of China using national statistical data, and showed that rice (*Oryza sativa* L.) had the largest CF, followed by wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). Determining the major contributors of total GHG emissions might provide important information for mitigating agriculture emissions. For instance, reducing CH_4 emissions is considered to be one of the most effective ways to decrease GHG emissions in paddy rice because direct CH_4 accounts for the largest component of total GHG emissions (Cheng et al., 2015). Some studies have reported that N fertilizer production was the main component of total carbon emissions in dryland production systems (Hillier et al., 2009; Yan et al., 2015). Some farming practices (e.g., conservation tillage, irrigation, diversified crop rotations) are effective in lowering the CF of crop production (He et al., 2019; Liu et al., 2016; Yang et al., 2014).

Straw and plastic film mulching have been used extensively for crop production in the Loess Plateau of China where precipitation is low (Bu et al., 2013; S. Li et al., 2013). Any changes in agricultural inputs have the potential to alter total GHG emissions and their components (Lal, 2004). Straw mulching can increase soil N_2O emissions because of the additional N source (Hu et al., 2016). For plastic film mulching, the production of plastic film was an important contributor to the CFs of dryland wheat and maize production (He et al., 2018a; Xiong et al., 2020; Xue et al., 2018). Considering that straw and plastic film mulching can significantly improve crop yields, we hypothesize that both straw and plastic film mulching would not increase the CF at the yield scale even though they might increase the GHG emissions. To test this hypothesis, a four-year study was conducted to quantify the GHG emissions associated with agricultural inputs, and to evaluate the effects of different mulching practices on CF using the LCA methodology. The specific objectives of this study were to (1) evaluate the effects of different mulching practices on GHG emissions, grain yield, and CF, and (2) identify the winter wheat-summer maize cropping system technology with the lowest CF in the Loess Plateau, China.

2. Materials and methods

2.1. Site description

The field experiment was carried out for four consecutive years from 2013 to 2017 at the Experimental Station of Water Saving Irrigation, Northwest A&F University, in Yangling, Shaanxi Province of China (34°20′N, 108°24′E, and elevation 521 m). In this region, winter wheat is usually sown in mid-October and harvested in early June of the next year. Summer maize is sown in mid-June and harvested in early October. The region has a sub-humid climate with an average daily temperature of 14.3 °C and annual precipitation of 571 mm from 1988 to 2017. Soil texture in the 0–10 cm layer (sampled in October 2013) is silty clay loam, consisting of 17% clay, 75% silt, and 8% sand. The basic properties of the topsoil (0–20 cm) are as follows: soil organic carbon (SOC), 8.14 g kg^{-1}; total soil N, 0.95 g kg^{-1}; soil $NO^{-}3$-N, 5.41 mg kg^{-1}; soil $NH^{+}4$-N, 1.35 mg kg^{-1}; available soil phosphorus, 20.91 mg kg^{-1}; available soil potassium, 134 mg kg^{-1}; pH (H_2O, 1:1), 8.20; field capacity, 27.92% (*v*/v); bulk density, 1.37 g cm^{-3}.

2.2. Experimental design and field management

The experiment was initiated in October 2013 with five treatments and three replications per treatment: NM (no mulching), SM (straw mulching, 4000 kg ha^{-1} $season^{-1}$ wheat straw), HPM (half plastic film mulching, covering 50% of the soil surface), FPM (full plastic film mulching, covering 100% of the soil surface), RPM (ridge-furrow planting with film mulching over ridges, covering approximately 67% of the soil surface). The plastic film was clear, had a density of 0.75 g cm^{-3}, and was 0.008 mm thick. The ridges for the RPM treatment were 30–cm wide and 15–cm tall during the wheat seasons, and 60–cm wide and 15–cm tall during the maize seasons. Each plot had a net area of 10 m^2 (5–m long and 2–m wide), with 15 plots in total. Individual plots were separated by 0.5–m buffer strips and arranged in a randomized complete block design. Wheat (cultivar Xiaoyan 22) was planted at a rate of 187.5 kg ha^{-1}, with 30–cm row spacing. Nitrogen fertilizer (urea) at 150 kg N ha^{-1} yr^{-1} was applied to wheat, 80% of which was surfaced broadcast as a base fertilizer application before planting, and 20% was top-dressed at the jointing stage. Maize (cultivar Qinlong 11) with a row of spacing of 60–cm and 40–cm spacing between plants within rows, received a base fertilizer application of 225 kg N ha^{-1} yr^{-1}. P fertilizer (calcium superphosphate) was also surfaced broadcast as a base fertilizer at 100 kg P_2O_5 ha^{-1} yr^{-1} and 90 kg P_2O_5 ha^{-1} yr^{-1} for wheat and maize, respectively. Crop aboveground residues were removed at harvest and 4000 kg ha^{-1} $season^{-1}$ wheat straw was used for straw mulch for the SM treatment. For the HPM treatment, wheat was planted between mulch strips, and maize seeds were dibbled on the mulch and planted in holes. For the FPM treatment, both wheat and maize were dibbled on the mulch and planted in holes. For the RPM treatment, both wheat and maize were planted between mulch strips. The field was irrigated with drip irrigation, and the pipes were placed under the plastic film mulch or straw mulch. Depending on the soil moisture conditions, each crop season was irrigated one or two times (30 mm per irrigation). The drip irrigation materials were reused during the experiment. Other field management practices were similar to the local field operations.

2.3. Data collection and analysis

Direct N_2O and CH_4 emissions from soil were measured in situ (from October 2013 to October 2017) using closed static chamber and gas chromatography techniques. In the center of each plot, a stainless-steel base frame with a groove (50 cm × 50 cm × 20 cm) was permanently inserted 20 cm into the soil between the wheat rows or maize plants. No plants were grown within the base. For the HPM treatment, a film (25–cm wide) was used to cover 50% of the area of the base, gases can be released from the bear soil. For the FPM treatment, 100% of the area of the base was covered by the film, the edge of film was inserted 1–2 cm into the soil around the border of the base. A seam (for wheat) or hole (for maize) was made in the film to simulate the actual plant growing outside the gas sample area, thus gases could be released through the seam or hole. For the RPM treatment, a ridge with 25–cm wide and 15–cm high was made on one side of the base. The ridge was covered by the film, and the edge of film was also inserted into the soil around the border of the base, thus gases can be released from the furrow. A static chamber (50 cm × 50 cm × 50 cm) made of stainless steel was placed into the groove on the base frame when collecting gas samples. The groove of the base frame was filled with water to seal the chamber. The chamber was equipped with a small fan to mix the gas, a thermometer to measure temperature and a polyvinyl chloride (PVC) gas channel with a three-way stopcock. Air samples were collected from the chamber by connecting a 60-ml gas-tight plastic syringe equipped with a three-way stopcock with the three-way stopcock on the PVC gas channel. The gas samples were collected mostly between 9:00 and 11:00 am every 7–10 days. Four samples were collected at 10 min intervals after chamber closure. N_2O and CH_4 concentrations were analyzed with a gas chromatograph (Agilent 7890A, Agilent Technologies, Inc., Santa Clara, USA). The details regarding the measurements of CH_4 and N_2O fluxes and calculations of seasonal CH_4 and N_2O emissions have been described by Chen et al. (2017).

At crop harvest, wheat grain samples were obtained from a 1–m^2 area in the middle of each plot, and 10 maize plants were randomly selected for maize grain samples within each plot. The grain samples were oven-dried at 75 °C to a constant weight. Final yield was calculated as the average of the three replicates for each treatment.

2.4. Carbon footprint calculation

The LCA methodology was applied to estimate total GHG emission of different mulching technologies throughout the whole process of winter wheat and summer maize production. The system boundaries were from cradle (production and transportation of raw materials, e.g., fertilizers, pesticides, diesel and film) to the farm gate (wheat and maize grain harvest) (Fig. 1). The estimated total GHG emissions (in terms of kg CO_2-eq) included agricultural inputs and non-CO_2 GHG emissions from soil. The following categories were computed for the wheat and maize production system in this study: (1) production and transportation of fertilizers, pesticides, and seeds; (2) production and transportation of diesel for machinery used for tillage, sowing, harvesting, straw mulching, ridging, and film mulching; (3) electricity for irrigation; (4) direct soil N_2O and CH_4 emissions and indirect N_2O emissions from NH_3 volatilization and N leaching; (5) manpower; (6) plastic film application, removal and disposal. The annual agricultural inputs were exactly the same. In this study, all the maize straw and most of the wheat straw were treated as recycled waste products so that downstream burdens and credits associated with its management (via composting and anaerobic digestion) were attributed to the subsequent compost and biogas products. Only 2.5% of the wheat straw (4000 kg ha^{-1} per crop season) was returned into the straw mulching plots. Thus, the disposal of straw was not included in this definition of system boundary. The CF for yield production was calculated using Eqs. (1) and (2) (Gan et al., 2012):

$$CF = Total\ GHG\ Emissions/Grain\ yield \tag{1}$$

$$Total\ GHG\ Emissions = \sum_{i=1}^{n} AI_i \times EF_i + (N_2O_{direct} + N_2O_{indirect}) \times 265 + CH_4 \times 28 \tag{2}$$

where, CF (kg CO_2-eq kg^{-1}) is the carbon footprint of grain yield; AI_i is the agricultural inputs shown in Tables S1 and S2; EF_i is the specific GHG emission factor shown in Table S3; 28 and 265 are the global warming potential (GWP) factors for CH_4 and N_2O over a 100-year time horizon, respectively (IPCC, 2014); N_2O_{direct} (kg N_2O ha^{-1}) and CH_4 (kg CH_4 ha^{-1}) are the direct N_2O and CH_4 emissions from soil obtained

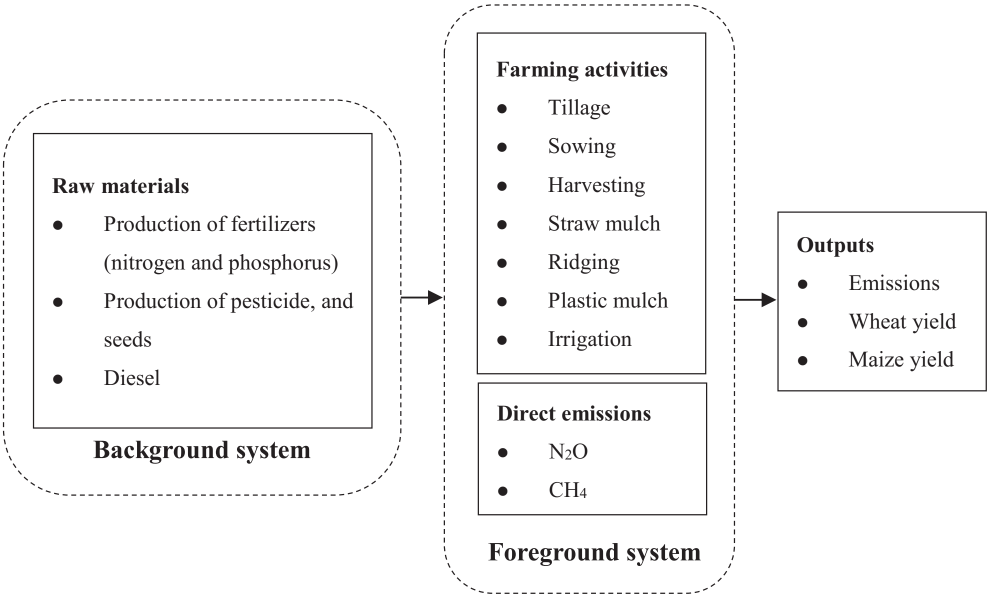

Fig. 1. System boundaries for carbon footprint analysis in the wheat or maize cropping system.

from field measurements; $N_2O_{indirect}$ (kg N_2O ha^{-1}) is the indirect N_2O emissions from NH_3 volatilization and N leaching.

Indirect N_2O emissions were calculated according to the Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Straw mulching increases NH_3 volatilization and N leaching due to the extra N input from straw. However, most literature sources have reported that plastic film mulching can reduce NH_3 volatilization and N leaching (Chen et al., 2020; Gu et al., 2019; Li et al., 2021; Yang et al., 2015). Similar to previous studies that shared the same study site with our study (Chen et al., 2020; Li et al., 2021; Yang et al., 2015), the percentages of NH_3 volatilization and N leaching reduced by film mulching compared with the no mulching practice were used to estimate NH_3 volatilization and N leaching under plastic film mulching systems based on the Guidelines of IPCC (2006). The indirect N_2O emissions were calculated as follows:

$$N_2O_{indirect} = N_2O_{vol} + N_2O_{leach} \tag{3}$$

$$N_2O_{vol} = (N_{Synthetic} + N_{straw}) \times Frac_{vol} \times EF_{vol} \times (1-\alpha) \times \frac{44}{28} \tag{4}$$

$$N_2O_{leach} = (N_{Synthetic} + N_{straw}) \times Frac_{leach} \times EF_{leach} \times (1-\beta) \times \frac{44}{28} \tag{5}$$

where $N_{Synthetic}$ is the amount of synthetic fertilizer N input; N_{straw} is the amount of N input from crop straw, calculated by multiplying the amount of straw mulching by the N content of straw (0.0076 kg N kg^{-1}) (A. Zhang et al., 2017); $Frac_{vol}$ is the fraction of N fertilizer volatilized as NH_3 and NO_x-N; $Frac_{leach}$ is the fraction of N leaching; EF_{vol} is the emission factor for the volatilization of N fertilizer; EF_{leach} is the emission factor for N leaching (Table S3); α and β are the percentages of NH_3 volatilization and N leaching reduced by film mulching compared with the no mulching practice (α: 25% for FPM, 12% for HPM and RPM, β: 60% for FPM, 30% for HPM and RPM) (Chen et al., 2020; Li et al., 2021; Yang et al., 2015); 44/28 is the factor used to convert N_2 to N_2O.

2.5. Statistical analyses

One-way ANOVA and the least significant difference (LSD) were computed to evaluate the differences between treatments, with the level of significance at $P < 0.05$. All statistical analyses were conducted using SPSS 20 (https://www.ibm.com/products/spss-statistics, Chicago, IL, USA). Origin (https://www.originlab.com, Version 9.0, USA) was used to prepare the figures.

3. Results

3.1. Direct N_2O and CH_4 emissions

Over four winter wheat-summer maize rotations, the cumulative N_2O emissions were 7.13, 11.36, 7.07, 5.46, and 4.62 kg N_2O ha^{-1} in NM, SM, HPM, FPM, and RPM, respectively (Fig. 2c). The highest direct N_2O emission was observed for the SM treatment due to dramatically greater emissions in 2014–2015 and 2015–2016. The cumulative direct N_2O emission of straw mulching in the summer maize season was significantly higher than in the winter wheat season (Fig. 2a–b). The amounts of direct CH_4 emissions from soil were negative (Fig. 2d–f), indicating that the soil was a sink for CH_4. A greater negative value indicates that the soil absorbed more CH_4. The cumulative direct CH_4 emissions during the four wheat-maize rotations were −12.5, −17.9, −18.0, −15.4, and −15.5 kg CH_4 ha^{-1} in NM, SM, HPM, FPM, and RPM, respectively (Fig. 2f). The cumulative CH_4 absorption in the winter wheat season was greater than in the summer maize season (Fig. 2d–e). Compared with NM, different straw and plastic film mulching

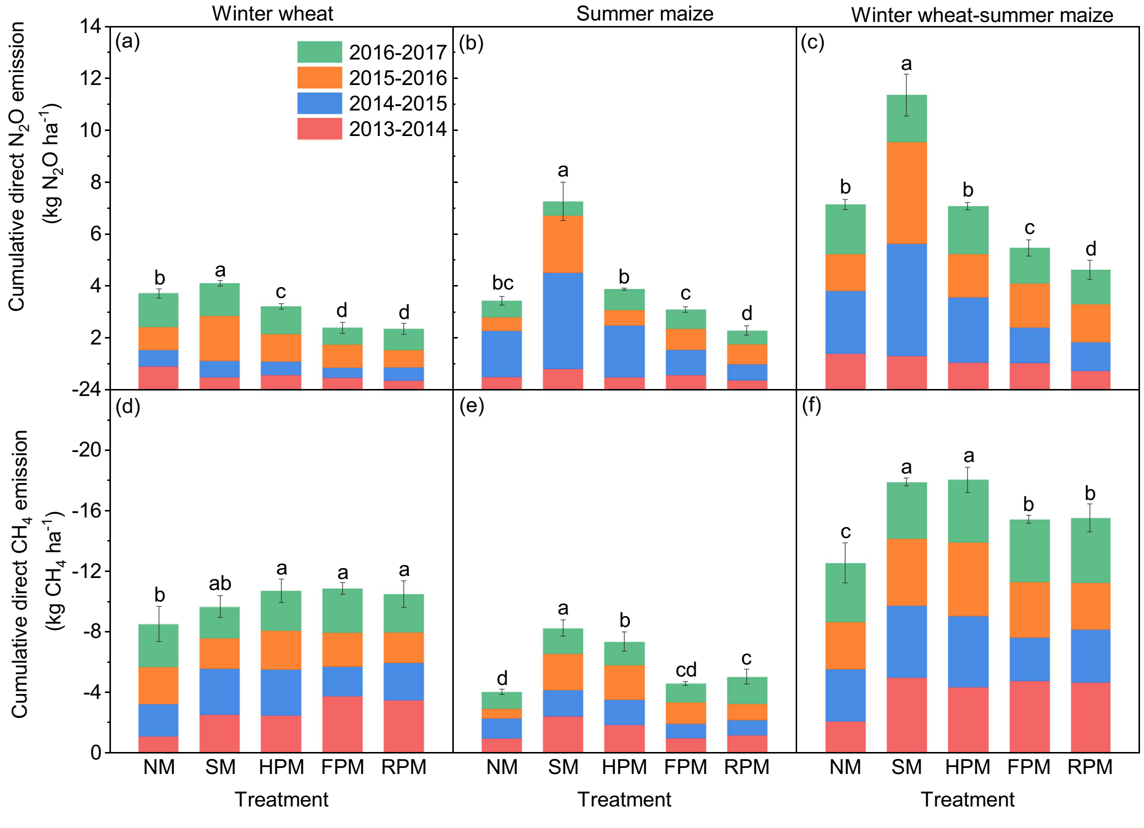

Fig. 2. Cumulative direct N_2O (a–c) and CH_4 (d–f) emissions under different mulching treatments over four winter wheat and summer maize cropping seasons. The error bar for each bar represents the standard error ($n = 3$). Different lowercase letters in each panel indicate significant differences ($P < 0.05$) among treatments according to the LSD test. NM, no mulching; SM, straw mulching; HPM, half plastic film mulching; FPM, full plastic film mulching; RPM, ridge-furrow planting with film mulching over ridges.

Table 1
Greenhouse gas (GHG) emissions (kg CO_2-eq ha^{-1} yr^{-1}) under five different mulching treatments in the winter wheat and summer maize cropping system at Yangling, China.

Item		Winter wheat					Summer maize					Winter wheat-summer maize				
		NM	SM	HPM	FPM	RPM	NM	SM	HPM	FPM	RPM	NM	SM	HPM	FPM	RPM
Production and transportation of materials	Nitrogen	1245	1245	1245	1245	1245	1868	1868	1868	1868	1868	3113	3113	3113	3113	3113
	Phosphorus	79	79	79	79	79	71	71	71	71	71	150	150	150	150	150
	Pesticides	19	19	19	19	19	16	16	16	16	16	35	35	35	35	35
	Seeds	109	109	109	109	109	34	34	34	34	34	143	143	143	143	143
Diesel		343	384	366	366	422	328	369	351	351	392	671	753	717	717	814
Plastic film		0	0	682	1363	909	0	0	682	1363	909	0	0	1364	2726	1818
Electricity for irrigation		70	70	70	70	70	97	97	97	97	97	167	167	167	167	167
Manpower		13	26	30	33	32	13	26	30	33	32	26	52	60	66	64
GHG emissions from agricultural inputs		1878	1932	2600	3284	2885	2427	2481	3149	3833	3419	4305	4413	5749	7117	6304
Indirect N_2O emissions		203	244	153	103	153	305	346	230	155	230	508	590	383	258	383
Total GHG emissions		2267	2380	2889	3468	3119	2933	3253	3586	4163	3767	5199	5633	6475	7631	6885

The GHG emissions were the mean value for four wheat seasons, four maize seasons, and four crop rotations of wheat and maize from October 2013 to October 2017. NM, no mulching; SM, straw mulching; HPM, half plastic film mulching; FPM, full plastic film mulching; RPM, ridge-furrow planting with film mulching over ridges.

treatments all increased soil CH_4 absorption in both wheat and maize seasons.

3.2. Total GHG emissions

Annual total GHG emissions under the five different mulching treatments during the winter wheat-summer maize rotation ranged from 5199 to 7631 kg CO_2-eq ha^{-1} yr^{-1} and exhibited the following order: FPM > RPM > HPM > SM > NM (Table 1). In particular, SM increased the GHG emissions from agricultural inputs by only 2.5% while increasing the total GHG emissions by 8.3% during the wheat-maize rotation, as compared with NM. However, 33.5%, 65.3%, and 46.4% higher GHG emissions from agricultural inputs were observed for HPM, FPM, and RPM, respectively, compared with NM due to the application of plastic film and the additional diesel consumed for the ridging operation. In comparison with NM, straw mulching increased the indirect N_2O emissions by 16.1%, while plastic film mulching practices decreased those by 24.6–49.2%. The GHG emissions in the maize season were higher than those in the wheat season under all five mulch treatments due to the higher rate of N fertilizer application in the maize growing season.

3.3. Components of the total GHG emissions

The relative contributions of the components of total GHG emissions for the winter wheat and summer maize seasons were compared across different mulching systems (Fig. 3). During the winter wheat-summer maize rotation, the production and transportation of N fertilizer was the largest contributor to total GHG emissions for all mulching practices, accounting for 59.9%, 55.3%, 48.1%, 40.8%, and 45.2% of emissions under NM, SM, HPM, FPM, and RPM, respectively. In the three plastic film mulching systems, plastic film was the second largest contributor to total GHG emissions accounting for 21.1–35.7%, followed by diesel. However, direct and indirect N_2O and CH_4 were the second largest component of total GHG emissions under NM (17.2%) and SM (21.6%). Of these, indirect N_2O emissions from NH_3 volatilization and N leaching accounted for 9.7% and 10.5%, direct N_2O and CH_4 emissions from soil accounted for 7.4% and 11.1% of the total GHG emissions under NM and SM, respectively. Thus, the proportion of direct and indirect N_2O and CH_4 emissions under SM was higher than that of NM mainly due to the higher direct N_2O emissions from soil, particularly during the summer maize season. Emissions from diesel were the third largest contributor to total GHG emissions under all treatments. While in the straw mulching system, diesel for straw mulching contributed only 1.5% to total GHG emissions. Direct and indirect N_2O and CH_4 emissions were also the main contributor after diesel under plastic film mulching systems, accounted for 6.7%, 8.4%, and 13.0% of the total GHG emissions under HPM, FPM and RPM, respectively. In addition, electricity for irrigation, manpower and applications of phosphorus fertilizer, seeds, and pesticides contributed only minimally to the total GHG emissions of the winter wheat-summer maize cropping system.

3.4. Yield and carbon footprint

The cumulative grain yield of both wheat and maize was significantly increased by 24.3%, 7.1%, 15.9%, and 10.0% in SM, HPM, FPM, and RPM, respectively, compared with NM (Fig. 4c). SM improved

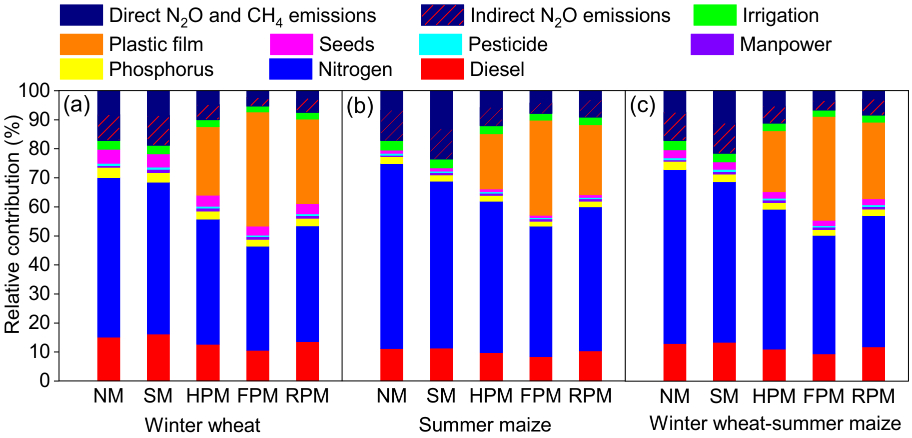

Fig. 3. Relative contributions of the components of total GHG emissions for five different mulching treatments at Yangling, China, during (a) the winter wheat season, (b) the summer maize season, and (c) the winter wheat-summer maize rotation. NM, no mulching; SM, straw mulching; HPM, half plastic film mulching; FPM, full plastic film mulching; RPM, ridge-furrow planting with film mulching over ridges.

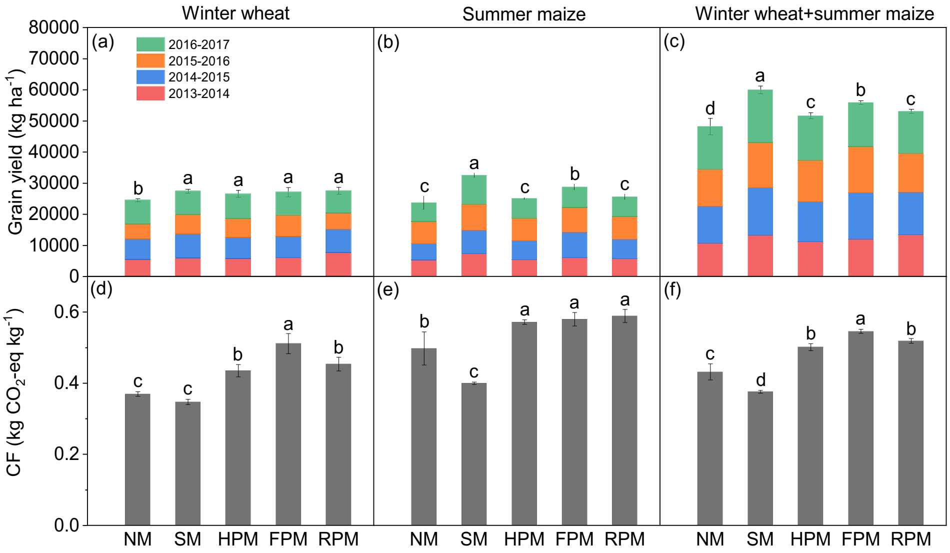

Fig. 4. Grain yield (a–c) and carbon footprint (CF, d–f) under five different mulching treatments in the winter wheat season, the summer maize season, and the winter wheat-summer maize rotation at Yangling, China. CFs refers to the carbon footprints for four wheat seasons (d), four maize seasons (e), and four crop rotations of wheat and maize (f) from October 2013 to October 2017. The error bar for each bar represents the standard error (n = 3). Different lowercase letters in each panel indicate significant differences ($P < 0.05$) among treatments within the same crop season according to the LSD test. NM, no mulching; SM, straw mulching; HPM, half plastic film mulching; FPM, full plastic film mulching; RPM, ridge-furrow planting with film mulching over ridges.

crop yields the most of all treatments for the wheat-maize rotation. Yield under FPM was significantly greater than under HPM and RPM. Compared with NM, the four mulching treatments of SM, HPM, FPM, and RPM significantly increased wheat yield by 11.8%, 8.3%, 10.8%, and 12.1%, respectively, while there were no significant differences in wheat yield observed among SM, HPM, FPM, and RPM (Fig. 4a). In the maize season, only SM and FPM significantly increased maize yield (by 37.2% and 21.3%, respectively) compared with NM (Fig. 4b).

The CFs under the five different mulch treatments ranged from 0.38 to 0.54 kg CO_2-eq kg^{-1} over the winter wheat-summer maize rotation (Fig. 4f). The CF of SM was significantly lower (13.0%) than observed with NM. The CFs for HPM, FPM, and RPM were significantly higher than seen for NM (by 16.0%, 26.4%, and 20.1% respectively). In addition, of the three plastic film mulching treatments, FPM significantly increased CF in the wheat seasons, leading to a significant increase for the wheat-maize rotation. The SM treatment had the lowest CFs among all treatments in all seasons.

4. Discussion

4.1. Effects of mulching on direct and total GHG emissions

Soil N_2O is generated primarily from the processes of nitrification and denitrification associated with N fertilizer applications (Bremner, 1997). Straw not only provides an additional source of C and N to the soil, but also affects soil nitrification and denitrification processes by changing soil physical and chemical properties (Millar and Baggs, 2005; Miller et al., 2008). Most studies have concluded that straw increases soil N_2O emissions (Hu et al., 2014; Ma et al., 2010). However, there have been some studies reporting that straw return to the soil could decrease (Ma et al., 2019) or have no significant effect on soil N_2O emissions (Shan and Yan, 2013; Xia et al., 2014). In our study, there were significantly higher N_2O emissions under SM compared with NM during the wheat-maize rotation. This is likely the result of straw providing sufficient C and N substrates to the soil to stimulate N_2O emissions (Hu et al., 2016), and due to the improved soil hydrothermal environment under straw mulching having a positive effect on microbial activity and also increasing N_2O emissions (Chen et al., 2017). The annual cumulative N_2O emissions will increase with the extension of straw mulching time due to the decay of previous straw, also depend on the climate (Hu et al., 2016). The effect of film mulching on soil N_2O emissions is different under different climate, soil type, and field management conditions (Berger et al., 2013; Nan et al., 2016). The main reason for the decrease in N_2O emissions under plastic film mulching is that the film prevents gas exchange between the soil and the atmosphere, and thereby significantly reduces the peak N_2O emissions after fertilization (Fig. S1). This result is consistent with observations from other studies (Z. Li et al., 2013; Liu et al., 2014). Drylands are generally considered to be a sink for CH_4 (Dalal et al., 2008). In our study, both straw mulching and plastic film mulching increased the soil's ability to take up CH_4. Straw mulching enhanced CH_4 absorption probably due to the improved soil physical properties (e.g., air-filled porosity, bulk density) (Chen et al., 2017; Yagioka et al., 2015). Plastic film mulching likely provided a suitable soil temperature for methanotrophic microorganisms, thus increasing the absorption of CH_4 (Nan et al., 2016).

The total GHG emissions for the winter wheat and summer maize production were similar to the results obtained from an analysis of National Statistics data in China (Cheng et al., 2015). In our study, the total GHG emissions in the maize seasons were higher than those in the wheat seasons. This trend is somewhat inconsistent with the results reported by Zhang et al. (2016). This inconsistency may be related to the different rates of fertilizer applications. In addition, both plastic film mulching and straw mulching increased the total GHG emissions compared with NM in our study, and this result is consistent with the results under plastic film mulching reported by Zhao et al. (2019) in the same area of China as where our study was conducted. Plastic film mulching can reduce direct N_2O emissions (Fig. 2) and indirect N_2O emissions from NH_3 volatilization and N leaching because of the film barriers and higher N uptake efficiency (Chen et al., 2020; Li et al., 2021; Yang et al., 2015). But the extra emissions from plastic film application and disposal significantly increased the total GHG emissions because of the higher emission factor (He et al., 2018a; He et al., 2018b; Wang et al., 2017; Zhao et al., 2019). Apart from the atmospheric environment, plastic film waste also resulted in soil environmental contamination (Steinmetz et al., 2016). Although large fragments of the plastic film can be removed and recycled, this process is hampered by practical difficulties, that are time-consuming and high costly (Steinmetz et al., 2016). Plastic film residues accumulated in the soil induces a series of negative impacts, such as destruction of soil structure, decreases in the soil microorganism community and reductions in crop production (Qi et al., 2018; Zhang et al., 2019). In recent years, some other mulching materials (e.g., biodegradable plastic film, straw) have been recognized as alternatives to plastic film (Wang et al., 2019; Zhao et al., 2019). However, the cost of biodegradable plastic film is currently considered too high to be promoted for use in large-scale operations (Gao et al., 2019). Straw as a locally available mulch materials, about 41.8% of the harvested straw would need to be used if straw mulching practice was scaled up. The use of straw for mulching has important implication for avoiding biogas and compost production. Because the remaining straw will be used for anaerobic digestion and composting. But straw mulching practice also has disadvantages, such as difficulty in controlling weed, introducing pests, and increasing the risk of N losses through direct N_2O emissions, NH_3 volatilization and N leaching (Chen et al., 2017; Chen et al., 2020; Kader et al., 2017; Li et al., 2021). In our study, the increased direct and indirect N_2O emission was the main reason for the increase in total GHG emission from straw mulching. The direct N_2O emission observed in our study was different from the emission in Zhao et al. (2019). This might be due to the different calculation method. The CO_2 emissions from soil were not included in our analysis, because they are offset by carbon fixation and oxidation through photosynthesis by crop plants in the long-run (Smith et al., 2014). Generally, changes in total SOC are the result of the balance between C input and output over a relatively long time (i.e., 5–10 years) (Conant et al., 2010). Some previous studies have reported that straw returned to the soil surface could mitigate GHG emissions because of improved soil C sequestration (Liu et al., 2018). Plastic film mulching has been shown to reduce (Cuello et al., 2015; He et al., 2018a), or have no effect (Yong et al., 2016; F. Zhang et al., 2017) on SOC. In our study, changes in total SOC under different treatments were not significant ($P > 0.05$) over the four-year experimental period (Fig. S2). Thus, SOC was not taken into account. As we continue conducting this experiment, we look forward to considering SOC in the calculation of total GHG emissions to investigate its long-term effects.

4.2. Effects of mulching on grain yield and carbon footprint

By definition, the carbon footprint for yield is simultaneously related to yield and carbon emissions (Hillier et al., 2009). In this study, both straw mulching and plastic film mulching significantly increased winter wheat and summer maize yield. Straw mulching can improve soil moisture and soil fertility, and thus increase crop yield (Atreya et al., 2008; Chen et al., 2010). Plastic film mulching can reduce soil water evaporation, improve soil temperature, and significantly promote crop growth (F. Zhang et al., 2018). Consistent with Zhao et al. (2019), we observed significant and similar wheat yield increases under both straw mulching and plastic film mulching. However, straw mulching increased maize yield significantly better than plastic film mulching. This difference may be related to the accelerated decay of straw providing additional nutrients for the growth of maize in the summer with a suitable hydrothermal environment (Qin et al., 2015).

In our study, the CF for maize production was higher than that for wheat. This result contrasts with results of previous studies, such as Benbi (2018) and Cheng et al. (2015). This inconsistency might be related to system boundaries, agricultural inputs, and data collection (Gan et al., 2012). Xue et al. (2018) and He et al. (2018a) found that plastic film mulching was beneficial in reducing the intensity of GHG emissions. The yield-based CF of plastic film mulching was decreased with decreasing annual precipitation (He et al., 2018b). In dry years, greater yield under film mulching could offset the effect of larger GHG emissions on CF, leading to a lower CF (Xiong et al., 2020; Xue et al., 2014). In our study, the hypothesis that the CF would not be increased was not confirmed for plastic film mulching practices. However, it was confirmed for straw mulching practice. Film mulching in the present study had larger CFs because the increased crop yields could not offset the additional GHG emissions from plastic film application. Straw mulching had the lowest CF with the most favorable yield and relatively less GHG emissions. In summary, straw mulching appears to be the most appropriate option to reduce the carbon footprint of wheat and maize production in sub-humid areas of the Loess Plateau of China.

4.3. Contributions of GHG emissions

Quantifying the GHG emissions produced at every step of agricultural production can provide suggestions for agricultural emission mitigation (Hillier et al., 2009). The largest contributor of the total GHG emissions in this study was the production of N fertilizer, and this result was consistent with previous studies (Hillier et al., 2009; W. Zhang et al., 2018; F. Zhang et al., 2018). In addition, the direct and indirect N_2O emissions induced by N fertilization also accounted for a large proportion of the total GHG emissions. Therefore, reducing N fertilizer applications is of great importance for reducing total GHG emissions from agricultural inputs, and also for reducing direct N_2O emissions, NH_3 volatilization, and N leaching (Rees et al., 2013; Li et al., 2021; Wang et al., 2014; W. Zhang et al., 2018). Excessive N use to achieve higher crop yields is presently a common production practice in China (Liu et al., 2019). A meta-analysis showed that the effect of straw mulching on wheat yield at a low N input (<120 kg N ha^{-1}) was even better than at a high N input level (Qin et al., 2015). With a plastic film mulching system, the suitable N application rate for maize production was 160–220 kg N ha^{-1} (Wang et al., 2020). All of these recommended suitable N rates are relatively lower than the N rates used in this study (i.e., 150 kg N ha^{-1} for wheat and 225 kg N $ha^{-1}$for maize). Higher N fertilizer inputs have been reported to not always increase crop yields, but almost always increase environmental risks associated with increased GHG emissions, NH_3 volatilization, and N leaching (Cui et al., 2008; Yang et al., 2014). As a result, the CF would be greater as the rate of N fertilizer increases (Zhang et al., 2013). Optimizing N fertilizer application rates can be one of the key options to mitigate agricultural GHG emissions and reduce the CF of crop production (Ju et al., 2009). Other measures are available for reducing GHG emissions, such as advanced fertilizer producing technologies (Zhang et al., 2013) and replacing partial chemical fertilizers with organic fertilizers or microbial fertilizers (Gong et al., 2020; Zhou et al., 2019). A few studies have reported that diesel fuel or electricity for pumping groundwater accounted for the largest proportion of the total GHG emissions (Wang et al., 2015). In our study, the emissions from electricity for irrigation accounted for 2.1–3.2% of total GHG emissions. These values were lower than those reported by D. Zhang et al. (2017). This difference might be due to the drip irrigation system used in our experiment that is more water efficient than traditional flood irrigation (Qin et al., 2016). Therefore, increasing investment in research regarding efficient agricultural machinery should also receive attention in the future (Zhang et al., 2016).

5. Conclusion

This study showed the effects of different mulching practices on GHG emissions, yields, and carbon footprints in a winter wheat-summer maize cropping system in the Loess Plateau of China. The total GHG emissions for maize were higher than the emissions for wheat. Greater total GHG emissions for plastic film mulching were due to the application of plastic film. The increased direct and indirect N_2O emissions were the main reason for the increase in the total emissions of straw mulching as compared with NM. The greatest crop yield and the lowest carbon footprint was observed with the straw mulching treatment. The three plastic film mulching practices significantly increased crop yield compared with NM, but at the cost of greater GHG emissions, resulting in the greater carbon footprint along with potentially environmental issues for practices employing plastic mulch. To manage the tradeoffs between productivity and environmental sustainability, the adoption of straw mulching should be considered to be the priority practice for winter wheat-summer maize production in the Loess Plateau of China. In addition, because N fertilizer was the largest contributor to total GHG emissions, optimizing N fertilizer application rates should be one of the key options used to mitigate agricultural GHG emissions and reduce the CF of crop production.

CRediT authorship contribution statement

Xiaoqi Luo: Performing the experiments, Investigation, Data curation, Writing – Original draft, Writing– review & editing. **Yiting Guo**: Analyzing the data, Software, Writing – Original draft. **Rui Wang**: Investigation, data searching, Writing – Original draft. **Naijiang Wang**: Performing the experiments, Writing – review & editing. **Cheng Li**: Performing the experiments, Writing review & editing. **Xiaosheng Chu**: Performing the experiments, Data curation. **Hao Feng**: Supervision, Designing the experiments, Project administration, Funding acquisition, Data curation, Visualization, Writing – review & editing. **Haixin Chen**: Supervision, Funding acquisition, Data curation, Investigation, Analyzing the data, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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