DYNAMICS OF CARBON FOOTPRINT OF MAIZE PRODUCTION WITH DIFFERENT FUNCTIONAL UNITS IN SHANXI PROVINCE, CHINA

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The reduction of greenhouse gases (GHGs) emissions from agricultural production is an efficient solution to mitigate global climate change. Maize (*Zea mays* L.) is most important grain crop in Shanxi Province, China. The environmental pressure due to large GHGs emissions associated with agricultural inputs during the process of maize production cannot be ignored. Based on the dataset from the National Cost-Benefit Survey for Agricultural Products, changes in carbon footprint (CF) with different functional units were assessed for maize production using life cycle assessment in Shanxi Province, China. The results showed that GHGs emissions sourced from maize production increased from 3633.7 kg CO₂-eq ha⁻¹ in 2004 to 4043.3 kg CO₂-eq ha⁻¹ in 2013 in Shanxi Province. Fertilizers application, soil N₂O emission and irrigation contributed more than 85% of total GHGs emissions. Excluding soil organic carbon (SOC) storage, the CF of maize produced with different functional units (i.e., at yield-, production value-, cost-, net income-scale) showed a decreasing trend from 2004 to 2013. Taking SOC storage into account, the CF of maize with different functional units decreased by 38.3-44.7% compared with that excluding SOC storage. In summary, reasonable fertilizer application and increasing SOC sequestration could be some potential solutions to reduce carbon footprint of maize production in Shanxi Province.

Keywords: Carbon footprint, maize, profit, Shanxi province, climate change.

INTRODUCTION

Global climate change has becoming a focus of attention for scientists, politicians and the public. Anthropogenic greenhouse gases (GHGs) emissions are crucial contributor to global climate change. How to reduce anthropogenic GHGs emissions effectively and mitigate global climate change are drawing the scientists' attention. Agricultural production is one of the major sources resulting in anthropogenic GHGs emissions. The reduction of GHGs emissions from agriculture production plays an important role in mitigating climate change through some effective measures. Quantitative evaluation of GHGs emissions associated with agricultural production is one of the most important parts to reduce global GHGs emissions. The carbon footprint (CF) is considered as a great indicator that could be used to quantitatively assess the impact of anthropogenic activities on climate change (Finkbeiner, 2009). According to International Standardization for Organization (ISO), a definition of CF for a specific product is the sum of GHGs emissions and removals in the whole product process expressed as CO₂-eq based on a life cycle assessment using the single impact category of climate change (ISO, 2013).

Currently, there are many studies on the CF of agricultural products, however, differences in the CF and its components

are observed due to different regions and diverse agricultural products in those studies (Dubey and Lal, 2009; Pathak *et al.*, 2010). Meanwhile, researches on the CF of agricultural products have gradually increased in China (Cheng *et al.*, 2015; Yan *et al.*, 2015). The CF of agricultural products were assessed at area-scale and yield-scale in most current studies, however, little information on other functional units associated with economic perspectives (e.g., the cost, production value, and net income) was presented. The economic benefits from agricultural production could not only largely affect the farmers' willingness to work in agriculture, but also influence GHGs emissions. Therefore, the evaluation of the CF of agricultural products with different functional units is favor to learn the relationship between agricultural production and climate change from multiple perspectives.

The maize (*Zea mays* L.) is one of the three most important food staples in China and plays an essential role in food security and social stability. The maize accounts for ~44.5% (~1.7 million hectares, Mha) of the total sown area of grain crops and ~68.5% (~8.6 million tons, Mt) of the total yield of grain crops in Shanxi Province in 2015 (NBSPRC, 2016). The GHGs emissions from maize production could not be neglected due to large amount of agricultural inputs (e.g., fertilizers, pesticides, diesel) in Shanxi Province. Therefore,

the quantitative assessments of GHGs emissions and its components are important to develop low-carbon technologies for maize production in the region. Meanwhile, the cost of maize production gradually increases with the increase in agricultural inputs, while the maize planting can still earn more money for local farmers compared to other grain crops in Shanxi Province (NDRCPRC, 2005-2014). However, little information on the relationship between GHGs emissions and economic aspect is observed in the process of maize production. Consequently, the objectives of the study were: (i) to analyze the dynamic of GHGs emissions in the process of maize production during 2004 to 2013, (2) to assess the change in CF of maize production with different functional units (e.g., at yield-, production value-, cost-, net income-scale) in Shanxi Province.

MATERIALS AND METHODS

System boundary and functional units: In the study, the CF of maize production was assessed using life cycle assessment approach to provide the theoretical basis for the development of low-carbon agriculture in Shanxi Province. The study mainly analyzed hidden GHGs emissions from agricultural inputs (e.g., chemical fertilizers, diesel oil, pesticides and seeds), soil non-CO₂ GHGs emissions and soil organic carbon (SOC) storage in the process of maize production in Shanxi province. The whole life cycle from raw material exploitation, production, and transportation of agricultural inputs to the farm gate (maize harvest) was defined as the system boundary of the study. The study included: (1) GHGs emissions from production, processing and transportation of agricultural inputs (e.g., fertilizers, seeds, pesticides); (2) energy consumption from farm machinery operations (e.g., tillage, sowing, harvesting, irrigation), and the energy consumption caused by the work of workers; (3) soil non-CO₂ GHGs emissions (i.e., CH₄ and N₂O). Generally, soil CH₄ is not included into the CF calculation of crop product due to little CH₄ emission even CH₄ sink from the soil (Guo and Zhou, 2007), therefore, the CF calculation in the study only took soil N₂O emission into account without CH₄ emission. In addition, the CF of maize was assessed with different functional units at yield-, production value-, cost-, and net income-scale expressed as kg CO₂-eq kg⁻¹, kg CO₂-eq ¥⁻¹, kg CO₂-eq ¥⁻¹, and kg CO₂-eq ¥⁻¹, respectively.

Inventory data collection: The dataset of agricultural inputs and cost-benefit of maize production in Shanxi Province was mainly collected from the National Cost-Benefit Survey for Agricultural Products from 2004 to 2013 (NDRCPRC, 2005-2014). In the dataset, the total cost for maize production included the cost of all resources, consisting the cash, material object, labor and land. In current dataset, nitrogen fertilizer, phosphate fertilizer, potassium fertilizer and compound fertilizer were pure nutrient contents rather than actual use

amount, however, the emission factor indicated the amount of GHGs emissions for per unit agricultural inputs. Therefore, the pure nutrient content of fertilizers was converted to actual use amount, and the conversion coefficient for urea, ammonium bicarbonate, calcium superphosphate, potassium chloride, and compound fertilizers were 46, 17, 17, 55 and 45%, respectively.

Moreover, the energy consumption consisted mainly of diesel used for farm machinery operation in the process of maize production, including tillage, sowing, and harvest. The diesel consumption from farm machinery operation was estimated using total farm machinery operational expenses. The diesel amount was estimated by dividing the direct diesel cost by the price of diesel per kilogram (kg) each year. According to Cui *et al.* (2011), the direct diesel cost for tillage, sowing, and harvest accounted for ~13.9, 5.4 and 14.0% of total farm machinery operational expenses sourced from the National Cost-Benefit Survey for Agricultural Products. In addition, the energy consumption for irrigation sourced from China Rural Statistical Yearbook (NBSPRC, 2005-2014). Due to scarce information, the amounts of pesticides were referred from an investigation with 2.2 kg ha⁻¹ in Shanxi Province (Yan *et al.*, 2015). The emission factors of GHGs for agricultural inputs in the study were shown in Table 1, and the inventories of GHGs emissions for maize production were shown in Table 2.

Table 1. Greenhouse gases emissions factors for different agricultural inputs in the study.

Item	Emission factors
Urea	2.39 kg CO ₂ -eq kg ⁻¹ #
Ammonium bicarbonate	0.6484 kg CO ₂ -eq kg ⁻¹ #
Others N fertilizers	1.526 kg CO ₂ -eq kg ⁻¹ #
Calcium superphosphates	2.676 kg CO ₂ -eq kg ⁻¹ #
Others P ₂ O ₅ fertilizers	1.631 kg CO ₂ -eq kg ⁻¹ #
Potassium chloride	0.7079 kg CO ₂ -eq kg ⁻¹ #
Others K ₂ O fertilizers	0.6545 kg CO ₂ -eq kg ⁻¹ #
Compound fertilizer	1.772 kg CO ₂ -eq kg ⁻¹ #
Diesel oil for machine	4.9866 kg CO ₂ -eq kg ⁻¹ #
Pesticides	12.44 kg CO ₂ -eq kg ⁻¹ #
Maize seed	1.932 kg CO ₂ -eq kg ⁻¹ #
Electricity for irrigation	1.229 kg CO ₂ -eq (kW h) ⁻¹ #
Labor	0.86 kg CO ₂ -eq (person day) ⁻¹ §

The datasets of those emission factors for above agricultural inputs sourced from the IKE eBalance v3.0 (IKE Environmental Technology CO., Ltd, China). §The emission factor for labor sourced from Liu *et al.* (2013)

Carbon footprint calculation: The CF of maize was determined through dividing all GHGs emissions from agricultural inputs and soil N₂O emission in the process of maize production. The CF was calculated by the following Equation (1) and (2) (Gan *et al.*, 2012; ISO 2013):

Table 2. The inventory of greenhouse gases emissions from agricultural inputs in the process of maize production in Shanxi province.

Inputs	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Mechanical operation † (kg ha ⁻¹)										
Tillage	12.43	12.57	12.26	13.92	14.59	14.56	14.41	15.25	18.80	21.85
Sowing	4.80	4.85	4.73	5.37	5.63	5.62	5.56	5.89	7.26	8.43
Harvest	12.46	12.60	12.29	13.95	14.63	14.59	14.45	15.29	18.85	21.90
N fertilizers † (kg ha ⁻¹)										
Urea	155.9	155.5	154.6	168.6	223.4	229.2	216.8	211.0	216.2	212.0
Ammonium bicarbonate	394.2	481.7	428.3	336.7	343.3	255.0	251.7	206.7	95.8	50.0
Others	-	-	10.8	2.5	1.7	-	-	-	-	-
P fertilizers † (kg ha ⁻¹)										
Calcium superphosphates	263.8	322.9	338.8	299.1	298.2	255.9	250.6	186.2	92.6	45.9
Others	7.1	15.9	37.9	4.4	16.8	28.2	1.8	28.2	-	-
K fertilizers † (kg ha ⁻¹)										
Potassium chloride	-	-	0.8	2.7	-	-	-	-	-	-
Others	1.6	14.7	18.3	0.8	-	0.5	-	-	-	-
Compound and mixed fertilizers † (kg ha ⁻¹)										
Compound fertilizers	182.7	120.7	142.7	205.3	168.0	190.0	238.0	304.7	359.7	499.7
Others	22.3	9.7	34.3	-	7.3	-	-	-	19.0	9.0
Seed † (kg ha ⁻¹)	40.8	39.8	38.6	40.4	35.9	34.4	30.3	29.1	24.9	25.4
Pesticides † (kg ha ⁻¹)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Irrigation * (kW h ha ⁻¹)	356.8	466.2	505.4	566.5	692.3	767.0	576.3	630.0	1043.7	700.1
Labor † (day ha ⁻¹)	156.3	147.5	141.0	134.7	143.3	136.4	136.7	135.3	119.6	116.6
Film † (kg ha ⁻¹)	3.8	3.6	3.5	5.1	3.3	3.3	5.0	5.6	7.2	7.5

† The dataset sources form the National Cost-Benefit Survey for Agricultural Products from 2004 to 2013 (NDRCPRC, 2005-2014).

There into, amount of diesel application from farm machinery operation was estimated by the direct diesel cost and the price of diesel. ‡

Pesticides application rate referred from an investigation in Shanxi Province (Yan *et al.*, 2015). * The energy consumption irrigation sources form China Rural Statistical Yearbook (NBSPRC 2005-2014).

$$CF = \frac{CE_{total}}{Y_{maize}} \quad (1)$$

Where, CF is the CF of maize with four functional units at yield- (kg CO₂-eq kg⁻¹ year⁻¹), production value- (kg CO₂-eq ¥⁻¹ year⁻¹), cost- (kg CO₂-eq ¥⁻¹ year⁻¹), and net income-scale (kg CO₂-eq ¥⁻¹ year⁻¹), respectively. CE_{total} is the total GHGs emissions in the process of maize production (kg CO₂-eq ha⁻¹ year⁻¹), which was calculated by Equation (2); Y_{maize} is the maize yield (kg ha⁻¹ year⁻¹), production value (¥ ha⁻¹ year⁻¹), cost (¥ ha⁻¹ year⁻¹), and net income (¥ ha⁻¹ year⁻¹), respectively.

$$CE_{total} = CE_{inputs} + CE_{N_2O} \quad (2)$$

$$CE_{inputs} = \sum_i (Q_{usedi} \times \varepsilon_i) \quad (3)$$

Where, CE_{inputs} is total amount of hidden GHGs emissions associated with agricultural inputs (kg CO₂-eq ha⁻¹ year⁻¹) for maize production; CE_{N_2O} is the cumulative amount of direct and indirect soil N₂O emissions due to N fertilizer application (kg CO₂-eq ha⁻¹ year⁻¹); Q_{usedi} is the amount of a i th individual agricultural input applied in maize production process (kg ha⁻¹ year⁻¹), including fertilizers, pesticides, seed, electrical energy for irrigation, and diesel for farm machinery operation; ε_i is

the emission factor of individual agricultural input (kg CO₂-eq kg⁻¹).

Moreover, soil N₂O emission was estimated using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Nitrogen fertilizer use contributed mainly to direct and indirect emissions of soil N₂O in the process of maize production, which was calculated by equation (4).

$$CE_{N_2O} = DCE_{N_2O} + VCE_{N_2O} + LCE_{N_2O} \quad (4)$$

Where, DCE_{N_2O} is the direct N₂O emission (kg CO₂-eq ha⁻¹ year⁻¹); VCE_{N_2O} is the amount of indirect N₂O produced from atmospheric deposition of N volatilized as NH₃ and NO_x from farmland (kg CO₂-eq ha⁻¹ year⁻¹); LCE_{N_2O} is the amount of N₂O produced from N leaching and runoff (kg CO₂-eq ha⁻¹ year⁻¹). Above N₂O emissions were calculated using the default value from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Farm management practices (e.g., soil tillage, fertilization, straw returned) could affect the SOC concentration and its distribution, then influencing SOC storage. Recently, some studies had taken SOC storage into account for calculating the CF of agricultural product (Gan *et al.*, 2012; Xue *et al.*, 2014).

$$CF_{soc} = \frac{CE_{total} - \Delta SOC}{M} \quad (9)$$

Where, CF_{soc} is the CF of maize production including the change in SOC storage. ΔSOC is the annual change in SOC storage (kg CO₂-eq ha⁻¹ year⁻¹), an estimated increase rate of 1624.3 kg CO₂-eq ha⁻¹ year⁻¹ for SOC storage was used to calculate the CF of maize in Shanxi Province (Lu *et al.*, 2009).

RESULTS

Change in greenhouse gases emissions of maize production:

The GHGs emissions from maize production showed an increasing trend in the past decade in Shanxi Province (Table 3), ranging from 3633.7 kg CO₂-eq ha⁻¹ in 2004 to 4043.3 kg CO₂-eq ha⁻¹ in 2013. Fertilizers application, soil N₂O, and irrigation were major sources of GHGs emissions in the process of maize production, accounting for 35.9-49.5, 27.5-30.7 and 9.0-23.0% of the total GHGs emissions, respectively. The GHGs emissions associated with fertilizers application was mainly caused by nitrogen fertilizer and compound fertilizer use. However, the GHGs emissions from nitrogen fertilizer use showed a decreasing trend from 2008 to 2013, which from compound fertilizer it showed an increasing trend year by year with an increment of 53.8 kg CO₂-eq ha⁻¹ year⁻¹. Meanwhile, the GHGs emissions caused by phosphorus fertilizer use gradually decreased from 2004 to 2013, with a decrement of 60.2 kg CO₂-eq ha⁻¹ year⁻¹. It is clearly that the reduction of GHGs emissions due to phosphate fertilizer and nitrogen fertilizer use was offset by the increase in that from compound fertilizer use. The GHGs

emissions resulted by potassium fertilizer use was a negligible amount in the process of maize production. In addition, soil N₂O emission gradually increased year by year as well with an increment of 11.48 kg CO₂-eq ha⁻¹ year⁻¹. The GHGs emissions from the diesel consumption associated with farm machinery operations (e.g., tillage, sowing, and harvest) also increased by 75.7%, ranging from 148.1 kg CO₂-eq ha⁻¹ in 2004 to 260.2 kg CO₂-eq ha⁻¹ in 2013. Moreover, the film caused to 1.8-4.2% of total GHGs emissions in maize production. The seed use and artificial labor contributed to 1.2-2.2 and 2.5-3.7% of total GHGs emissions, respectively, while pesticide application was less than 0.8% in the study.

Changes in carbon footprint with different functional units:

The yield of maize showed a significant increasing trend over the past decade, ranging from 6.5 t ha⁻¹ to 9.4 t ha⁻¹ with an increment of 0.3 t ha⁻¹ year⁻¹ in Shanxi Province ($P=0.0011$, Fig. 1A). The trend of production value for maize was similar to that of the yield, ranging from ¥7.0×10³ ha⁻¹ to ¥20.7×10³ ha⁻¹ with an increment of ¥1.6×10³ ha⁻¹ year⁻¹ ($P<0.0001$, Fig. 1B). However, the cost of maize production significantly increased from ¥5.4×10³ ha⁻¹ in 2004 to ¥15.6×10³ ha⁻¹ in 2013 with a quadratic trend ($P<0.0001$, Fig. 1C). The net income of maize production showed an increasing trend on a whole but with large interannual fluctuations (Fig. 1D), ranging from ¥1.3×10³ ha⁻¹ to ¥8.5×10³ ha⁻¹. In addition, there is no significant correlation between GHGs emissions and the yield, the production value, the cost, and the net income (Table 4).

Furthermore, changes in CF of maize production with different functional units were evaluated, and distinct differences in the CF among different functional units were

Table 3. Dynamics of greenhouse gases (GHGs) emissions in the process of maize production in Shanxi Province (kg CO₂-eq ha⁻¹).

Items	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Fertilizers										
N fertilizer	628.1	684.1	663.7	625.0	759.0	713.2	681.4	638.2	578.8	539.0
P ₂ O ₅ fertilizer	724.9	906.7	1008.2	812.2	842.9	760.3	675.3	573.8	247.9	122.8
K ₂ O fertilizer	1.2	10.4	13.5	2.5		0.4				
compound fertilizer	363.3	231.0	313.6	363.9	310.7	336.7	421.7	539.9	671.0	901.4
Seed	78.8	76.8	74.5	78.0	69.3	66.4	58.5	56.2	48.1	49.0
Pesticides	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4
Labor	134.4	126.8	121.3	115.8	123.2	117.3	117.5	116.4	102.8	100.2
Agricultural film	85.2	81.8	78.4	115.9	75.0	75.0	112.5	126.1	163.6	170.4
Irrigation	328.3	428.9	465.0	521.2	636.9	705.7	530.2	579.6	960.2	644.1
Machinery operation										
Tillage	62.0	62.7	61.1	69.4	72.8	72.6	71.9	76.0	93.8	108.9
Sowing	23.9	24.2	23.6	26.8	28.1	28.0	27.7	29.4	36.2	42.1
Harvest	62.2	62.8	61.3	69.6	72.9	72.8	72.0	76.2	94.0	109.2
Soil N ₂ O	1114.1	1127.5	1129.3	1126.9	1218.7	1151.3	1165.8	1173.3	1147.0	1228.9
Total	3633.7	3850.9	4040.8	3954.6	4236.9	4126.9	3962.1	4012.4	4170.8	4043.3

The GHGs emissions from agricultural inputs were calculated through multiplying the actual amount of agricultural inputs and relevant emission factors. Soil N₂O was estimated using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Figure 1. Dynamics of the maize yield (A), production value (B), cost (C), and net income (D).

Figure 2. Dynamics of carbon footprint of maize production at yield- (A), production value- (B), cost- (C), net income (D)-scale excluding the change in SOC stock. In addition, A', B', C', and D' indicate carbon footprint at yield-, production value-, cost-, net income-scale including the change in SOC stock, respectively

observed (Fig. 2). Regardless of the change in SOC storage, the CF of maize production showed a decreasing trend for different functional units. Excluding SOC storage, the CF of maize in Shanxi Province ranged from 0.44–0.59 kg CO₂-eq ha⁻¹ at yield-scale (Fig. 2A), 0.20–0.55 kg CO₂-eq ¥⁻¹ at production value-scale (Fig. 2B), 0.26–0.68 kg CO₂-eq ¥⁻¹ at cost-scale (Fig. 2C), and 0.47–2.86 kg CO₂-eq ¥⁻¹ at net income-scale (Fig. 2D), respectively. Including SOC storage, the CF of maize production with different functional units decreased compared to those excluding SOC storage (Fig. 2A', B', C', D'). The CF of maize decreased by 38.3–44.7% at both yield-, production value-, cost-, and net income-scales.

Table 4. The relationship between greenhouse gases emissions and the yield, production value, cost, and net income for the maize production.

	Yield	Production value	Cost	Net income
GHGs emission	0.458 ^{ns}	0.443 ^{ns}	0.466 ^{ns}	0.254 ^{ns}

^{ns} indicates that there is no significant correlation.

DISCUSSION

Influencing factors of GHGs emissions in maize production:
In the study, the GHGs emissions from maize production

increased year by year, mainly due to chemical fertilizers use in Shanxi Province. Rapid increase in chemical fertilizers use, especially nitrogen fertilizer and compound fertilizer, resulted in a mass of soil N₂O emission and hidden GHGs emissions. Meanwhile, most of fertilizers lost into the surrounding environment by volatilization and leaching due to low fertilizers use efficiency at the growth stage of maize, resulted in a series of environmental problems (Galloway *et al.*, 2008). Therefore, the reduction of fertilizers application amount and improvement of fertilizers use efficiency could be important ways to mitigate GHGs emissions from maize production. According to the Zero Increase in Chemical Fertilizers Use Action by 2020 program (MAPRC, 2015), some technical measures were popularizing and implementing to reduce fertilizers use amount and improve fertilizers use efficiency, including the promotion of precision fertilization, the structure adjustment of chemical fertilizer use, the improvement of fertilization method, and the replacement of chemical fertilizers by organic fertilizer. For example, utilizing the “Nation Fertilization According to Soil Test Result” program improved fertilizer use efficiency of maize to 32, 25 and 43% for nitrogen fertilizer, phosphate fertilizer and potassium fertilizer in China since 2005, respectively (MAPRC, 2013). Then, GHGs emissions could be reduced by the implementation of above programs due to the reduction of chemical fertilizers use amount.

In addition, adoption of no-tillage practice could effectively reduce hidden GHGs emissions caused by farm machinery operations and soil N₂O emission in the process of maize cropping (Ussiri *et al.*, 2009). Adoption of water-saving technology could be also a possible solution to reduce GHGs emissions from irrigation. In this study, pesticides were only a small part of total GHGs emissions in maize production. However, farmers generally used excessive pesticides to control pests and weeds, which could result in increased cost of maize production (NDRCPRC, 2005-2014). Meanwhile, excessive use of pesticides could retain in agricultural products and the surrounding farmland, affecting the quality of maize and posing a threat to environment (MAPRC, 2015). Therefore, the use of pesticides should be controlled in the process of maize production. Currently, it is a controversial viewpoint on whether to take the energy consumption of laborer into consideration or not in the CF calculation. West and Marland (2002) considered that the energy consumption of human labor should not be included, because humans respire CO₂ regardless of whether human laborers are working or not. However, Liu *et al.* (2013) deemed that the energy consumption associated with human labor should not be ignored, because human labor was one of the important parts of agricultural production in developing countries. Li *et al.* (2009) calculated also the energy consumption of human labor when calculating GHGs emissions from agriculture production.

Carbon footprint of maize and influence factor: At present,

numerous studies reported the average CF of maize in China, with 0.230 kg CO₂-eq kg⁻¹ (Liu *et al.*, 2015), 0.44 kg CO₂-eq kg⁻¹ (Cheng *et al.*, 2015), and 0.33 kg CO₂-eq kg⁻¹ (Yan *et al.*, 2015). In our study, the CF of maize at yield-scale ranged from 0.44 to 0.59 kg CO₂-eq kg⁻¹ for excluding SOC storage in Shanxi Province, which was higher than those of above-mentioned average value. Taking SOC storage into consideration, the CF decreased to 0.27-0.36 kg CO₂-eq kg⁻¹, similar with the result reported by Yan *et al.* (2015). This may be attributed to differences in the calculation method, the regional scale, and emission factors of agricultural inputs. In the study, the CF was calculated by using life cycle assessment with the GHGs emissions inventory for maize production in detail, which could result in larger GHGs emissions than other studies. Localized emission factors were used to calculate GHGs emissions in current study, which were higher than abroad generally leading to greater CF of maize than that in other studies. In addition, the difference in maize yield could cause the gap of CF among different studies due to the discrepancy of climate condition, cropping system, and agricultural technology.

Taking into account SOC storage, the CF of agricultural product sharply decreased after the adoption of farming management practices associated with SOC sequestration and GHGs emissions reduction (Gan *et al.*, 2012; Xue *et al.*, 2014). In this study, the CF of maize with different functional units decreased after taking SOC storage into consideration. At present, the change in SOC storage was estimated at the rate of 1624.3 kg CO₂-eq ha⁻¹ year⁻¹ in cropland of Shanxi Province (Lu *et al.*, 2009), which could affect strongly the CF after taking SOC storage into consideration. However, the change in SOC storage in maize field is not clear in Shanxi Province, it is necessary to assess it in the future.

Currently, the CF of agricultural products was calculated at area- and yield-scale in most studies. The cost and income of agricultural production strongly influenced farmer planting intention and GHGs emissions in the condition of market economy, however, few studies assessed the CF of agricultural product at economy-scale. It is necessary to quantify the relationship between economic profit and GHGs emissions. In our study, the CF of maize production was evaluated based on different functional units (at yield-, production value-, cost-, net income-scale) in Shanxi Province. The gap of the CF under functional units was observed, especially the CF at net income-scale with great fluctuation was larger than those at other functional units in the study. This may be due to larger fluctuation on net income for maize production among years. In addition, there was an increasing trend for the yield, production value, the cost, and the net income with GHGs emissions for maize production in Shanxi Province. However, decreasing trends were observed for all CFs of maize with different functional units. Therefore, the decrease of the CF of maize under different functional units was not meant to mitigate climate change.

A limitation of the current study: In the study, soil N₂O emission was estimated using the method from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) in Shanxi Province, which could be different with actual N₂O emission from the maize field. In addition, there could be difference in soil N₂O emission among different regions due to the divergence of climatic condition, soil texture, and farm management. In addition, differences in soil water content and soil nitrogen cycle could be presented between film mulching in the north region and non-mulching in the south region of Shanxi Province, which could affect soil nitrification and denitrification resulting in the difference in soil N₂O emission (Kool *et al.*, 2011). In addition, the static closed chamber technology is a comment method to measure soil N₂O flux (Hénault *et al.*, 2012; Berger *et al.*, 2013), and more work should be done by the technology to accurately evaluate soil N₂O emission and the CF of crop for future research. Furthermore, life cycle assessment was generally used to evaluate the environment impact of a product from the cradle to the grave, a detailed inventory dataset within the system boundary was needed to calculate the CF of agricultural product. However, it is more difficult to collect all relevant datasets for the CF calculation at macro-scale than at micro-scale. Therefore, some missing datasets were obtained by other methods, such as soil N₂O emission, the change in SOC stock. To improve the quality of data would assess accurately the CF of a product at a regional scale.

Conclusion: From 2004 to 2013, the GHGs emissions from maize production showed an increasing trend in Shanxi Province. The application of chemical fertilizers, soil N₂O and irrigation contributed >85% of total GHGs emissions in the process of maize production. The yield, production value and cost of maize production significantly increased in Shanxi Province year by year, however, the net income showed a large fluctuation among years. In addition, the CF of maize with different functional units showed a decreasing trend, which was reduced by 38.3-44.7% after taking change in SOC storage into account. Overall, reducing fertilizer use, strengthening mechanical integration and improving SOC sequestration could be some potential solutions to cut down the CF of maize production in Shanxi Province.

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