

# Carbon footprint for wheat and maize production modulated by farm size: a study in the North China plain

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## Abstract

**Purpose** – The relationship between farm size and greenhouse gas (GHG) emissions has not been clearly defined. This paper aims to assess and compare the impact of farm size on greenhouse gas (GHG) emissions derived from wheat and maize production in the North China Plain (NCP), one of the most important agricultural regions in China.

**Design/methodology/approach** – A field survey through face-to-face interviews was conducted to collect the primary data, and life cycle assessment method, a worldwide comparable framework, was then adopted to characterize the farm-size effect on greenhouse gas (GHG) wheat and maize production in NCP.

**Findings** – It was confirmed that GHG emissions from N fertilizer production and use were the primary contributor to total carbon footprint (CF). As farm size increased, maize yield increased but wheat yield barely changed, while area-scaled and yield-scaled CF declined for both crops. These results were supposed to relate to utilize the inputs more efficiently resulting from increased application of modern agriculture methods on larger operations. It was also found maize not only had higher grain yields, but possessed much smaller CFs. More notably, the reduction of CF with farm size seemed to be more sensitive for maize as compared to wheat. To further mitigate GHG emissions, farm size should better be larger for wheat than for maize.

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**Originality/value** – This study provides useful information guide for Chinese agriculture in increasing crop production, raising farm income and relieving environmental burdens caused by the misuse of agricultural resources.

**Keywords** Carbon footprint, North China plain, Farm-size impact, GHGs, Maize and wheat production

**Paper type** Research paper

## Introduction

To satisfy the rising food demand caused by rapid population growth, modern agricultural inputs (such as fertilizers, fuel and pesticides) have been increasingly applied to support high-yield grain production. However, their excessive use has also induced a series of negative environmental effects, including soil acidification, water eutrophication and greenhouse gas (GHG) emissions (Ju *et al.*, 2009; Tilman *et al.*, 2011). The agricultural sector is one of the largest GHG sources in the world, accounting for 52 and 84% of global anthropogenic CH<sub>4</sub> and N<sub>2</sub>O emissions (Rakotovoao *et al.*, 2017). These emissions have caused elevated atmospheric concentrations of GHGs that contribute to climate change. However, as global agriculture will need to produce 60% more grain in 2050 than the mean of 2005–2007 (FAO, 2013), improved agronomic practice and cleaner management methods are urgently needed for increasing crop yield while reducing GHG emissions.

China is the world's largest emitter of agricultural GHG, accounting for 13.6% of the global total (FAO, 2017). As it must feed about 20% of the global population using less than 9% of global arable land, Chinese agricultural production should emphasize high resource-use efficiency for minimizing environmental burdens (Ebenstein *et al.*, 2011). However, from 1996 to 2005, Chinese grain yields were elevated only by 10% at the cost of 51% more chemical fertilizers, resulting in low nutrient-use efficiency and high environmental costs (Chen *et al.*, 2011; Chen *et al.*, 2014b). These problems are mainly due to the small scale and household-based operation of Chinese agriculture, as small farms with highly fragmented plots hamper the application of advanced technology (e.g. mechanization) and use agricultural inputs inefficiently (Yan *et al.*, 2015a; Wang *et al.*, 2017a). On the other hand, more than 250 million Chinese farmers have migrated to cities and engaged in non-agricultural work during the last three decades, due to rapid economic development and urbanization. Some farmers have rented or transferred their fields to other farmers (who have become more specialized operators) or farmers' cooperatives, concentrating farmland management and expanding farm size (Tan *et al.*, 2013; Liu *et al.*, 2017). Therefore, the ways in which farm size affects GHG emissions and crop production have been drawing increasing research attention.

Carbon footprint (CF) is a term used to quantify the total “cradle to grave” GHG emissions (including direct and indirect aspects) of a production process, based on the life cycle assessment (LCA) principle. CF estimation has been widely applied in crop production to characterize the contributions of different resource inputs to climate change, allowing comparisons that help identify cleaner and more climate-resilient technologies or management techniques (West and Marland, 2002; Wang *et al.*, 2015a). For example, with respect to farm size, Sefeedpari *et al.* (2013) showed that larger wheat farms in Iran produced lower GHG emissions per area than small farms due to better management. In contrast, Rakotovoao *et al.* (2017) found no dependence of CF on farm size in Madagascar and emphasized that small and large farms could both achieve low GHG emissions by properly integrating different agricultural practices, and Lal (2004) even pointed out that smaller Moroccan sugar beet farms used resources more efficiently than larger ones. In South China,

Yan *et al.* (2015a) found that the CF of rice production for larger aggregated farms was 25% lower than for small household-scale farms. A subsequent study in North China found that, for wheat and maize production, GHG emissions per area of larger farms (>0.5 ha) showed a decreased trend compared with smaller farms (<0.5 ha) (Yan *et al.*, 2015b). Although the last two studies were spatially concentrated within China, they generally focused on a small study area (in only one province), only divided farms into two groups, and used a relatively small sample size (usually less than 100). These deficiencies greatly limited the broader application of the conclusions and did not allow a comprehensive assessment of the influence of farm scale on grain production CF or the selection of optimal management practices for different crops. Consequently, the study adopting greater sampling number in larger spatial-scale region was urgently required to clarify the relationship between farm size and GHGs emissions, particularly in intensive agricultural areas of China.

Therefore, the authors used a questionnaire survey to investigate the status of crop production in the North China Plain (NCP), one of the most vital grain production bases in China. Using the LCA method, the impact of farm size (through a three-group analysis) on crop production with regard to grain yield and climate change effect were analyzed into three parts. First, GHG emissions during wheat and maize production and the contributions of different factors were quantified and compared; the authors subsequently evaluate the relationship between grain yield and GHG emissions at different farm scales and characterize differences between wheat and maize. In the last part, the uncertainties associated with LCA and potential measures to lower GHG emissions for future agricultural production was pointed out. Our results would offer instructive guideline to the policymakers for the climate change mitigation and adaptation in China.

## 2. Materials and methods

### 2.1 Study area

The NCP covers 300,000 km<sup>2</sup> across most of Shandong, Hebei and Henan Provinces in northern China and is known as “China’s granary” because it provides 40 and 25% of the country’s wheat and corn production, respectively, from only 23.2% of the nation’s cropland (3.3% of total area) (Cui *et al.*, 2018). Currently, intensive agricultural inputs are used to maintain high crop yields, causing serious environmental problems (Wang *et al.*, 2016).

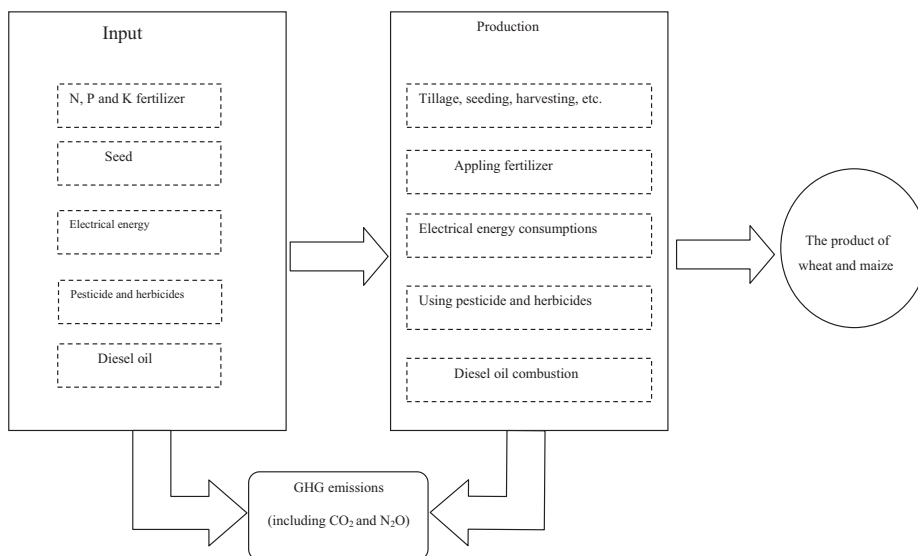
### 2.2 Calculating carbon footprint

The CF of crop production in the NCP’s wheat-maize rotation system was calculated by taking into account all GHG emissions directly originating from (farm management) or indirectly caused by (material inputs and machinery exhaust) agricultural activity (Figure 1). Because soil carbon changes were barely detectable over a crop season, their impacts were not considered in this assessment.

Indirect GHG emissions induced by agricultural inputs include those produced during the manufacturing of agricultural materials (such as nitrogen, phosphate or potassium fertilizers and pesticides) and energy consumption by machinery operation (such as for tilling, seeding, harvesting and irrigating). The authors calculated the total amount of GHG emissions caused by agricultural inputs ( $CF_M$ , kg CO<sub>2</sub>eq kg<sup>-1</sup>) as:

$$CF_M = \sum (I_i \times EF_i) \quad (1)$$

where  $i$  is the input type,  $I_i$  is the quantity of the  $i$ th material’s inputs or energy costs used in crop production (kg for fertilizer and pesticides, L for diesel and petrol oil and kw h for



**Figure 1.** Schematic diagram of CF estimation for the NCP's wheat-maize rotation system

electricity), and  $EF_i$  is the GHG emission factor for the individual agricultural input (kg CO<sub>2</sub>eq kg<sup>-1</sup>).

The direct GHG (N<sub>2</sub>O) emissions deriving from added N fertilizer were calculated as:

$$CF_{N_2O} = I_N \times EF_{N_2O} \times \frac{44}{28} \times 298 \quad (2)$$

where  $I_N$  is the amount of added N in fertilizer during a single crop season (kg N),  $EF_{N_2O}$  is the emission factor for N<sub>2</sub>O caused by N fertilizer addition, 44/28 is the conversion factor for changing the molecular weight of N<sub>2</sub> to N<sub>2</sub>O, and 298 is the global warming potential (GWP) factor over a 100-year period for N<sub>2</sub>O, which considers the effect of CO<sub>2</sub> as 1.

All emission factors used for agricultural inputs were drawn from previous research (Table 1). CH<sub>4</sub> emissions were not considered because their impacts can be ignored for upland fields. Consequently, total CF (CF<sub>t</sub>, kg CO<sub>2</sub>eq) was the sum of indirect and direct GHG emissions:

Input	Emission factor	Source
N fertilizer	8.30 kg CO <sub>2</sub> eq kg <sup>-1</sup> N	(Zhang <i>et al.</i> , 2013)
P fertilizer	0.61 kg CO <sub>2</sub> eq/kg <sup>-1</sup> P <sub>2</sub> O <sub>5</sub>	(West and Marland, 2002)
K fertilizer	0.44 kg CO <sub>2</sub> eq kg <sup>-1</sup> K <sub>2</sub> O	(West and Marland, 2002)
Wheat seed	0.40 kg CO <sub>2</sub> eq kg <sup>-1</sup>	(West and Marland, 2002)
Maize seed	3.85 kg CO <sub>2</sub> eq kg <sup>-1</sup>	(West and Marland, 2002)
Electricity for irrigation	0.80 kg CO <sub>2</sub> eq kW <sup>-1</sup> h	(Zhu <i>et al.</i> , 2018)
Pesticide and herbicides	18 kg CO <sub>2</sub> eq kg <sup>-1</sup>	(West and Marland, 2002)
Diesel oil	2.63 kg CO <sub>2</sub> eq L <sup>-1</sup>	(Yan <i>et al.</i> , 2015a)
Direct N <sub>2</sub> O emissions from N fertilizer	0.01 kg N <sub>2</sub> O-N kg <sup>-1</sup> N	(IPCC, 2006)

**Table 1.** Emission factors for each agricultural input considered

$$CF_t = CF_M + CF_{N_2O} \quad (3)$$

Additionally,  $CF_Y$  (kg CO<sub>2</sub>eq kg<sup>-1</sup> grain) was defined as the yield-scaled CF, adopted to evaluate the GHG emission per unit of crop production:

$$CF_Y = \frac{CF_T}{Y} \quad (4)$$

where  $Y$  is the crop yield (kg ha<sup>-1</sup>).

### 2.3 Farm surveys

The primary materials were collected through face-to-face interviews from October 2016 to October 2017. To ensure the credibility of the original data, field survey was completed in three steps. The representative of typical rural area of maize or wheat-based agriculture in Shandong, Henan and Hebei provinces was first selected. Then, under the cooperation of the local agricultural extension centers, three to four typically agricultural counties in each province were chosen according to cropland area, with at least four villages per county. Third, farmers of each village were randomly selected beside the field during field-labor time by the interviewers. The face-to-face interview was done by students of our university who had undergone proper training, and the interview procedure was not interfered by any external disturbances. A questionnaire was sent to the heads of individual farm households, specialized operators or farmers' cooperatives, as these people had the most complete information and were decision makers during crop management. The questionnaire asked about:

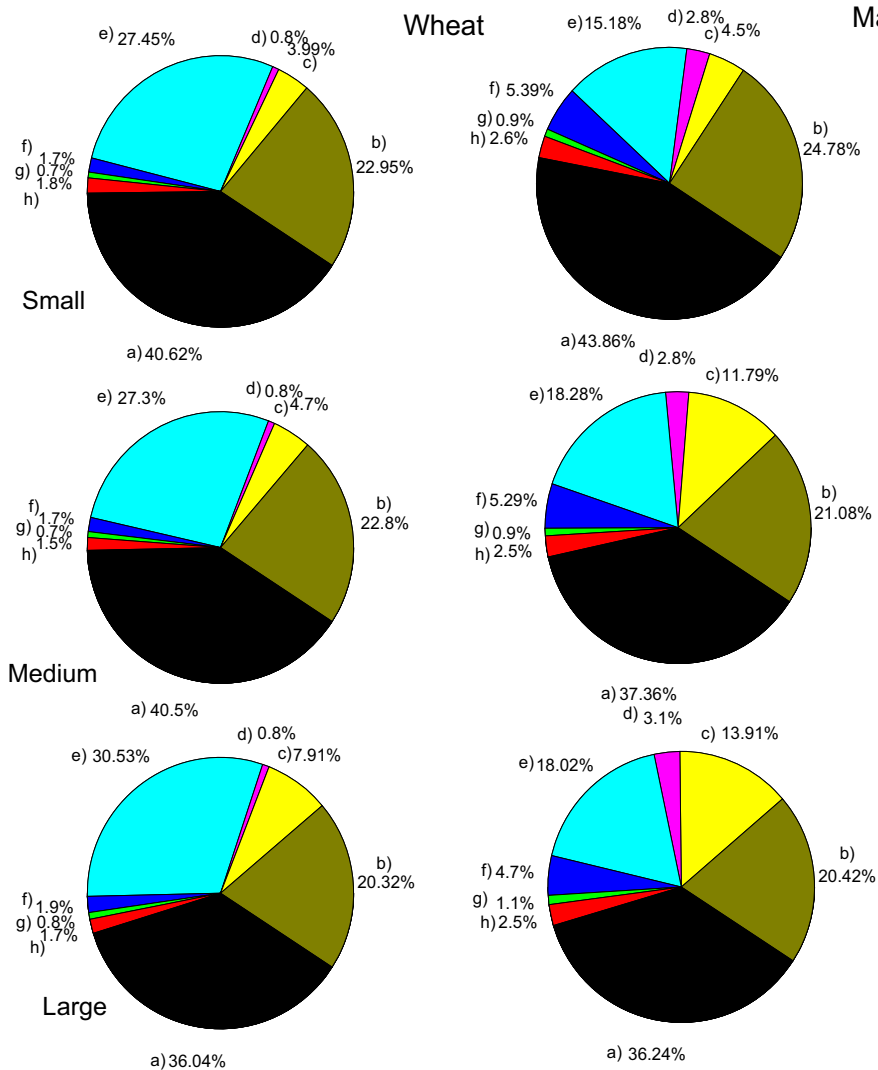
- locations and sizes of fields;
- crop types and corresponding yields;
- agricultural inputs (amounts of seed, fertilizers and pesticides);
- machinery use (quantified as diesel oil used for tillage, seeding, cultivation and transportation); and
- electricity used for irrigation.

To ensure the credibility of the surveyed data, informal interviews with selected informants were conducted at the same time. Based on this campaign, the authors sent out 350 questionnaires and 266 questionnaires were received. The invalid questionnaires were then removed out in further analysis, the values of which were threefold standard deviations more than the mean of the data set. Lastly, a total of 236 validated questionnaires were gathered (Figure S1).

Through linear correlation, it was found that CFs for wheat and maize were both reduced with the increase of farm area, but the response for wheat appeared to be more susceptible than maize because the regression slope was more cliffy (Figure S2). To illustrate and compare the results more clearly, the raw data were then clustered into three groups according to farm size (small, < 3.3 ha; medium, 3.3–16.7 ha; large, > 16.7 ha). This clustered method was based on the distribution of our data set (Figure S1) and classification standard in China (Yun, 2016). More detailed information was showed in the Supplementary material.

### 2.4 Data processing and statistical analysis

Microsoft Office Excel 2003 was used to calculate CF; further statistical analyses were conducted by SPSS (Ver. 10). One-way ANOVA and the least significant difference test



**Notes:** (a) CO<sub>2</sub> emissions from N fertilizer production; (b) direct N<sub>2</sub>O emissions from N fertilizer application; (c) CO<sub>2</sub> emissions from diesel combustion; (d) CO<sub>2</sub> emissions from pesticide production; (e) CO<sub>2</sub> emissions from electricity used for irrigation; (f) CO<sub>2</sub> emissions from seed production; (g) CO<sub>2</sub> emissions from K fertilizer production; and (h) CO<sub>2</sub> emissions from P fertilizer production

**Figure 2.** Contribution of different GHG emission sources to the total carbon footprint of wheat and maize production by farm size

(LSD) were adopted to determine parameter differences between the size classes at a significance level at  $p < 0.05$ . Linear regressions were used to figure out the dependence of total CF and each emission source on increase of the farm area.

### 3. Results

Small farms made up ~56% of the total farms surveyed (Table 2 and Figure S1). Generally, these farms managed multiple separate parcels of land, while medium and large farms were usually contiguous, showing the continued fragmentation of China's croplands and demonstrating that farm households remain the dominant production unit in rural areas (Yun, 2016).

Agricultural input levels varied significantly at different farm scales. For example, small farms applied far more fertilizer than medium and large farms, especially for N fertilizer (Table 2). The input of electricity and pesticides was also in the order of small farms > medium farms > large farms, while the cost of diesel oil followed a contrary trend (Table 2). In Figure 2, proportion of different GHG emission sources was illustrated. GHG emissions from N fertilizer production and use were the single biggest contributor to the total CF (more than 50%), followed by electricity used for irrigation (15–30%). Machinery use (diesel oil cost) clearly rose with farm size (4–14%), while other fertilizers, seed production and pesticide production comprised only a small portion of total emissions (4–8%) and generally showed less dependency on farm size (Figure S3). These results suggest that reducing or controlling the use of N fertilizer and irrigation would be the most effective approach to achieve lower-carbon crop production in the NCP.

The CFs of maize were 3325, 2724 and 2473 kg CO<sub>2</sub> eq ha<sup>-1</sup> in small-, medium- and large-scale farms, respectively, which were dramatically lower than the corresponding group of wheat (5350, 5235 and 4169 kg CO<sub>2</sub> eq ha<sup>-1</sup>) [Figure 3(a)]. On the other hand, gain yield of two crops (especially for maize) showed an increased trend as the enlargement of farm scale, with the magnitude of 7328, 7541 and 7532 kg ha<sup>-1</sup> in small-, medium- and large-scale farms for wheat and with the corresponding values of 8255, 9042 and 9276 kg ha<sup>-1</sup> for maize [Figure 3(b)]. These results lead to much smaller yield-scale CFs of maize (varied from 0.40 to 0.27 kg CO<sub>2</sub>eq kg<sup>-1</sup> grain) than that of wheat (in the range of 0.73 to 0.55 kg CO<sub>2</sub>eq kg<sup>-1</sup> grain) [Figure 3(c)]. Based on our data set and the literature reports, the comparisons of carbon footprint and contribution of N fertilizer for wheat and maize production with the outcomes in China and around the world was present in Table 3.

### 4. Discussion

#### 4.1 Variations of yield, agricultural inputs and carbon footprint as affected by farm size

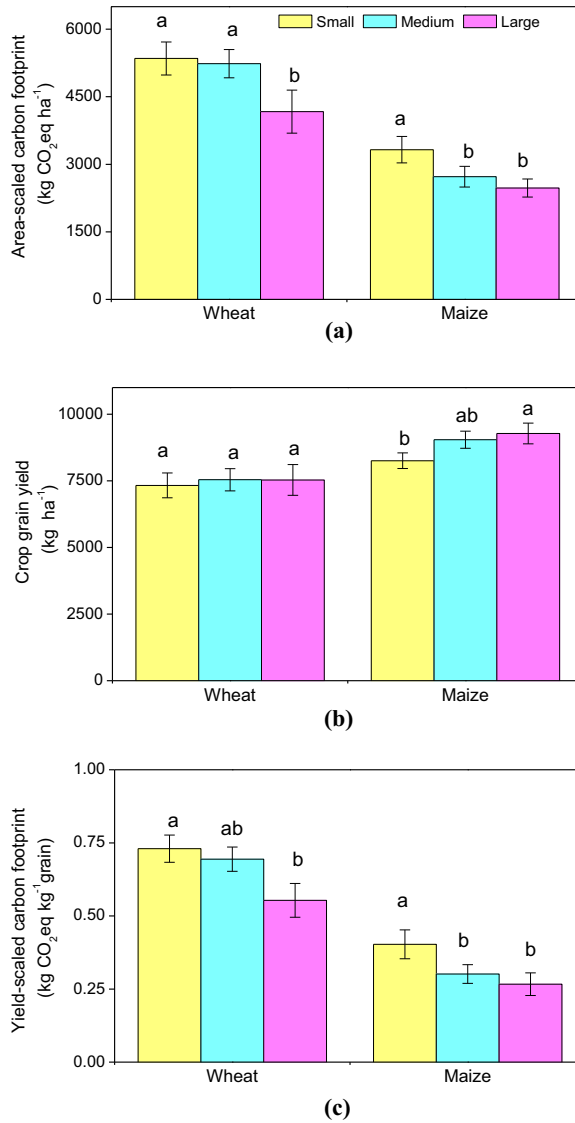
Maize yield seemed more responsive to farm size, as this increased significantly ( $p < 0.05$ ) from small to large farms (by 12.4%), whereas wheat yield increased only slightly with no significant difference ( $p > 0.05$ ). Although the underlying mechanisms may relate to agronomic factors beyond the scope of this study, the different responses of wheat and maize to farm size implies that maize's yield potential has not been fully exploited on smaller farms. Similarly, Yan *et al.* (2015b) showed that rice yield in South China increased with farm size, attributing this to the excessive N fertilizer used on small farms that actually inhibited yield. One possible reason for such fertilizer overuse is a desire among small farmers to replace natural fertilizer with chemical fertilizer to compensate for labor shortages (Cheng *et al.*, 2011). In addition, large farms are usually profit-oriented commercial enterprises that are more likely to adopt modern agricultural techniques to maintain high crop yields while judiciously reducing investment in chemical fertilizers (Cui *et al.*, 2010).

Farm type <sup>a</sup>	Farm area <sup>b</sup> (ha)	Crop type	N fertilizer (kg)	P fertilizer (kg P2O5)	K fertilizer (kg K2O)	Wheat seed (kg)	Maize seed (kg)	Electricity cost (kW h)	Pesticides (kg)	Diesel oil (L)
Small (132)	<3.3 (0.4)	Wheat	262.3	155.2	80.2	221.3	—	1836.6	2.5	80.4
		Maize	175.8	139.8	64.3	—	46.6	633.3	5.1	57.4
Medium (73)	3.3–16.7 (7.3)	Wheat	255.4	131.7	77.4	223.7	—	1783.4	2.3	93.8
		Maize	122.6	112.4	58.4	—	37.2	621.8	4.2	122.5
Large (31)	>16.7 (21.8)	Wheat	180.6	118.6	79.9	197.6	—	1590.2	1.9	125.9
		Maize	107.9	103.3	60.5	—	30.5	557.4	4.2	130.6

**Notes:** <sup>a</sup>Parenteses show farm number. <sup>b</sup>Parenteses show average area

**Table 2.** Characteristics and agricultural inputs for three farm-scale groups in NCP (ha<sup>1</sup> year<sup>1</sup>)





**Figure 3.** Comparison for wheat and maize of (a) area-scaled carbon footprint, (b) crop yield, and (c) yield-scaled carbon footprint by farm size

**Note:** Error bars denote standard deviation and letters indicate significant differences ( $p < 0.05$ ). The number of sample size for large, medium and small farms was 16, 35 and 62 for wheat and 15, 38 and 70 for maize

Small farms also consumed more electricity for irrigation, but used less diesel oil, as modern machinery is more likely to be used on medium and large farms (Wang *et al.*, 2015a).

The carbon footprint and contribution of N fertilizer for wheat and maize in our studies were compared with the outcomes around the world (Table 3). Gan *et al.* (2011) reported that the use of N fertilizer for Canadian wheat production contributed 30–40% of the total CF, considerably lower than the 53–57% for all Chinese crop production (Cheng *et al.*, 2015) and for wheat and maize in our study area, which were high even for China. At present, China is the largest consumer of N fertilizers in the world, using more than 30% of the total. In some intensive agricultural areas of China (such as the NCP), the applied levels of N fertilizer actually exceed crop needs even after maximum yield has been achieved (Ju *et al.*, 2009). The unused N is eventually released to the atmosphere or leached into water, creating serious environmental problems. Such over-fertilization originated through the belief of Chinese farmers that using more N fertilizer were served as insurance to guarantee high and stable yields, rather than matching fertilizer use to crop requirements. In addition, heavy N pollution in the NCP has caused total environmental N inputs (derived from atmospheric deposition and irrigation water) to reached up to 104 kg of N ha<sup>-1</sup> at present as compared to 29 kg of N ha<sup>-1</sup> in the 1980s (Liu *et al.*, 2019). Thus, lower levels of inorganic N fertilizer currently need to be applied than previous experience had suggested. Field tests in the NCP have shown that current N application rates for double-cropping systems should be reduced by 30–60% (Ju *et al.*, 2009), enough to maintain crop yields while dramatically lowering the environmental risks of N loss (optimum N fertilization rates are 128 kg N ha<sup>-1</sup> for wheat and 158 kg N ha<sup>-1</sup> for maize.). N fertilizer use in our data set exceeded critical values for wheat production at all farm sizes and maize production on small farms. If N fertilizer use were reduced to the above suggested value, the total CF (including the total input for maize and wheat) of small farms would be cut by 14.5% (equivalent to 1262 kg CO<sub>2</sub> eq ha<sup>-1</sup>).

Overall, our results show that farms should pay more attention to the appropriate use of N fertilizer (especially small farms and wheat producers) to better control GHG emissions from crop production in the NCP. Furthermore, larger farms should adopt proper water-saving agricultural techniques as its relative contribution to CF increases with farm size (Figure 2).

The CFs of wheat and maize production had been intensively studied across China and globally. In a similar study of the North China Plain, Shi *et al.* (2011) found CFs for wheat and maize production in Hebei Province of 4030 and 2330 CO<sub>2</sub> eq ha<sup>-1</sup>, respectively, within

Country	Crop type	Carbon footprint (kg CO <sub>2</sub> eq ha <sup>-1</sup> )	Contribution of N fertilizer (%)	Source
Canada	Wheat	–	30–40	(Gan <i>et al.</i> , 2011)
USA	Maize under best management practices	1980	–	(Gan <i>et al.</i> , 2011)
Global crop	Wheat	2165	–	(Nemecek <i>et al.</i> , 2012)
	Maize	2950	–	
Across China	Wheat	502–7513	–	(Zhang <i>et al.</i> , 2017)
	Maize	1192–9282	–	
	All crop	–	53–57	(Cheng <i>et al.</i> , 2011)
NCP	Wheat	4169–5350	54–64	This study
	Maize	2473–3325	57–69	This study

Note: – indicates unavailable data

**Table 3.** Comparison of carbon footprint (CF) and the contribution of N fertilizer between this study and other global research

the same range as our results. Chen *et al.* (2015) used national statistical data to estimate the average CFs for Chinese wheat and maize as 2910 and 2860 kg CO<sub>2</sub> eq ha<sup>-1</sup>, respectively. Zhang *et al.* (2017) showed that CFs were highly variable by region in China, ranging from 502 to 7513 kg CO<sub>2</sub> eq ha<sup>-1</sup> for wheat and 1192–9282 CO<sub>2</sub> eq ha<sup>-1</sup> for maize. In the NCP, wheat had a greater CF than maize because the former used more electricity due to a higher reliance on irrigation from deep groundwater and higher rates of N fertilizer application as suggested by Zhang *et al.* (2017). The higher yield accompanied with much lower CFs for maize production suggests that its cultivation should be expanded to satisfy growing grain demand and simultaneously reduce GHG emissions in the NCP. Our CFs for wheat and maize in the NCP were much higher than global mean values (especially for wheat) and those of other countries (Table 3), demonstrating that crop production in the NCP has clear potential for optimization with regard to reduced GHG emissions. The decrease in CF with increased farm size for both wheat and maize (Figure 3) was consistent with Sefeedpari *et al.* (2013), who conducted a questionnaire survey for wheat production in Iran and found that the energy input (comparable to CF) of small farms (< 1 ha) was 17, 21 and 34% greater than farms of 1–4 ha, 4–10 ha and > 10 ha, respectively. This phenomenon could be attributed to the reasons that larger farms are more willing to adopt advanced agricultural techniques, apply moderate levels of chemical fertilizer and uses labor and other inputs more efficiently (Niroula and Thapa, 2007; Tan *et al.*, 2010). For instance, it is often inconvenient to use agricultural machinery on smaller farms, as the frequently altered directions involved in traversing small plot or the increased travel time between unconnected fields costs excess time and consumes unnecessary fuel. Consequently, less agricultural machinery was employed in smaller, which might in turn lead to lower N use efficiency even under same N addition rate (Wang *et al.*, 2015a). As N is the biggest contributor to the total CF, this further increases GHG emissions and decreases resource-use efficiency (Manjunatha *et al.*, 2013). This might partly explain why small farm acquired smaller grain yield even though inputting more N fertilizer. Moreover, it can also be more difficult for small farms to irrigate or control pests and weeds because specific conditions vary between scattered plots (Zhu *et al.*, 2018). Thus, to avoid production losses, small farms often apply identical irrigation and pesticide levels regardless of conditions, due in part to poor educational infrastructure that blocks the transfer of modern agricultural knowledge to such farmers (Tan *et al.*, 2010). Overall, the above possible reasons resulted in the fact that some inputs far exceed crop requirements on small farms, causing resource waste.

Notably, our results indicated that the optimal farm size for wheat production should better be larger than for maize as no significant difference in area-scaled and yield-scaled CF was identified between small and medium wheat farms ( $p > 0.05$ ), unlike for maize (Figure 3). The next research step should focus on integrating questionnaire investigation with field experiments to explore optimal field scales for different crops, which would coordinate food security with the environmental risk.

#### 4.2 Reducing agricultural greenhouse gas emissions

Various approaches could be used to reduce the CFs of wheat and maize cultivation in the NCP. As N fertilizer and electricity for irrigation were the major sources of GHG emissions, improved management practices could include improving fertilization methods (such as through controlled-release fertilization and using nitrification inhibitors) and replacing flood irrigation with drip irrigation (Mutegi *et al.*, 2010; Wang *et al.*, 2015b). Straw return along with inorganic fertilizer has also been strongly recommended as this practice could increase grain yield and enhance nitrogen use efficiency simultaneously (Menendez *et al.*, 2012). The added straw would synchronize the soil's inorganic N supply and crop N uptake, lowering

the environmental risk of N losses (Chen *et al.*, 2014a). Additionally, the use of straw mulch can effectively suppress weed growth, reducing herbicide use and energy costs (Ramakrishna *et al.*, 2006).

From the social support, the government should promote the importance of low-carbon agriculture through media (including newspapers, broadcasting, television and the internet), and offer more agricultural training and direct field guidance by agricultural technicians (Liu *et al.*, 2011). As small, household-based farms will remain the dominant organized unit for agricultural production in China in the foreseeable future (Yun, 2016), the government should pay more attention to assisting these farmers in modernizing and improving their methods. For example, Hou and Hou (2019) argued that training focused on small farmers could more effectively lower GHG emissions than approaches aimed at larger farmers. This would provide a more efficient method for quickly lowering agricultural GHG emissions across China at present.

#### 4.3 Possible uncertainties and future research needs

This research leaves some uncertainties in calculating the CF value and assessing farm-size effects. The wide differences in CF values for different studies can be attributed, not only to material and energy inputs as assessed here but also to different life-cycle definitions and the values of emission factors employed during estimations (Table 1). As GHG emissions associated with N fertilizer comprised the largest proportion of CF, the main uncertainties originated from CO<sub>2</sub> emissions during N fertilizer manufacturing and field N<sub>2</sub>O efflux caused by fertilization. The CO<sub>2</sub> emissions factor for N fertilizer manufacturing in present study was much larger than that for developed countries because coal, rather than natural gas, is the primary feedstock and energy source used for N fertilizer production in China (Zhang *et al.*, 2013). Moreover, China's ammonia-fertilizer producers are mostly small-medium sized, using more energy per production unit than larger facilities. Even so, Zhang *et al.* (2013) suggested that the emissions factor could be decreased to 4.7 if more advanced technologies were introduced through encouragement or enforcement by the government.

The default value (0.01) provided by the IPCC (IPCC, 2006) was used to estimate the direct N<sub>2</sub>O emissions (Table 1). Previous *in situ* experiments have shown that the emission factor of N<sub>2</sub>O exhibited high variability, as jointly determined by climate (especially precipitation), N fertilizer type, soil conditions and agricultural management (Wang *et al.*, 2017b; Jiang and Yu, 2019a). Using a fixed emission factor masked the actual differences and lowered the estimation accuracy. Developing and using a process-oriented model is an alternative way to improve the estimation, though it depends on more auxiliary parameters that need to be determined simultaneously (Zheng and Han, 2017; Jiang and Yu, 2019b).

Due to time limitations, the authors did not take soil samples and analyze the impact of soil carbon sequestration on offsetting the GHG emissions within agro-ecosystem carbon budget. Recent studies have argued that the soil organic carbon (SOC) stock on large farms tends to be greater than on small farms as the former prefer to use conservation agriculture practices (e.g. incorporation of crop residues into soil) based on specialized agricultural machinery (Zhu *et al.*, 2018). The added crop residue not only promotes higher and more stable crop yield and increases SOC stock but also partly replaces synthetic fertilizer. Thus, the magnitude of benefits with regard to CF by large farms in this study might be substantially undervalued. Future work should use broader datasets and adopt more complex calculation methods to constrain such uncertainty to more accurately evaluate the impact of farm scale on agriculture GHG emissions in the NCP. In spite of above uncertainties, the basic estimations presented here provide fundamentally useful

information clarifying the connection between agricultural GHG emissions and farm size in the NCP, one of the most important grain production regions in China.

## 5. Conclusions

To clarify and optimize the environmental-friendly strategy for crop production, a comprehensive survey in three provinces of NCP was conducted. Our results confirmed that GHG emissions derived from N fertilizer production and use made up ~60% of the total CF for wheat and maize production in the NCP, with electricity used for irrigation as the second-highest contributor (~20%). The CF for wheat and maize production in our study area were at the high end of the outcomes around the world or even in China. Maize possessed higher grain yields, but much smaller CFs than wheat. On the other hand, the two crops displayed similar trends with increase of farm size, for which the contribution of N fertilizer production and use to total CF was clearly reduced, the magnitude of total CF declined while the crop yield rose. This was probably because more modern agricultural management adopted by larger farms made better use of resources. More importantly, the suitable farm size for maize appeared to be smaller than for wheat as the CF and yield of maize were more susceptible to the farm-size effect. Overall, as GHGs derived from crop production is one of the largest emission sources in China, selecting the reasonable field scales for different crops would greatly mitigate the risk of environmental cost on the premise of grain security. Although more works were needed to lower the uncertainty in present research, this preliminary analysis could be helpful for farm operators and policy-makers to optimize field management of a multi-crop system to make full use of inputted resources and simultaneously minimize negative impacts on climate change.

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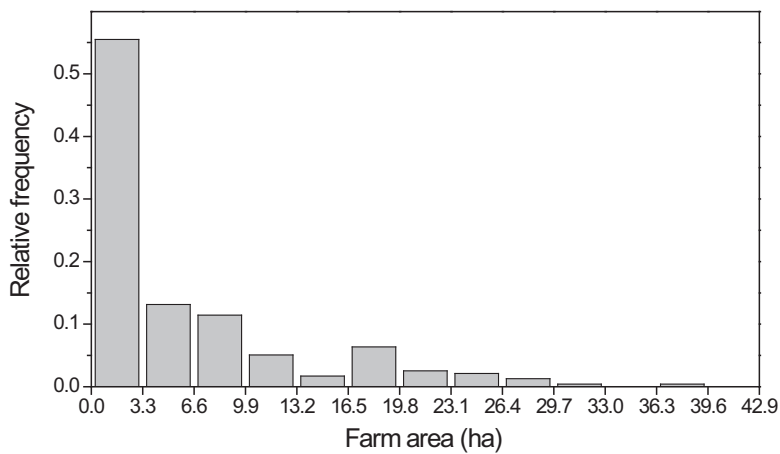
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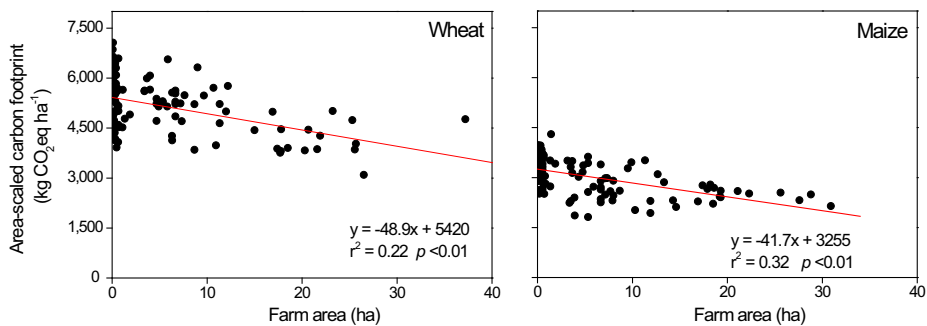
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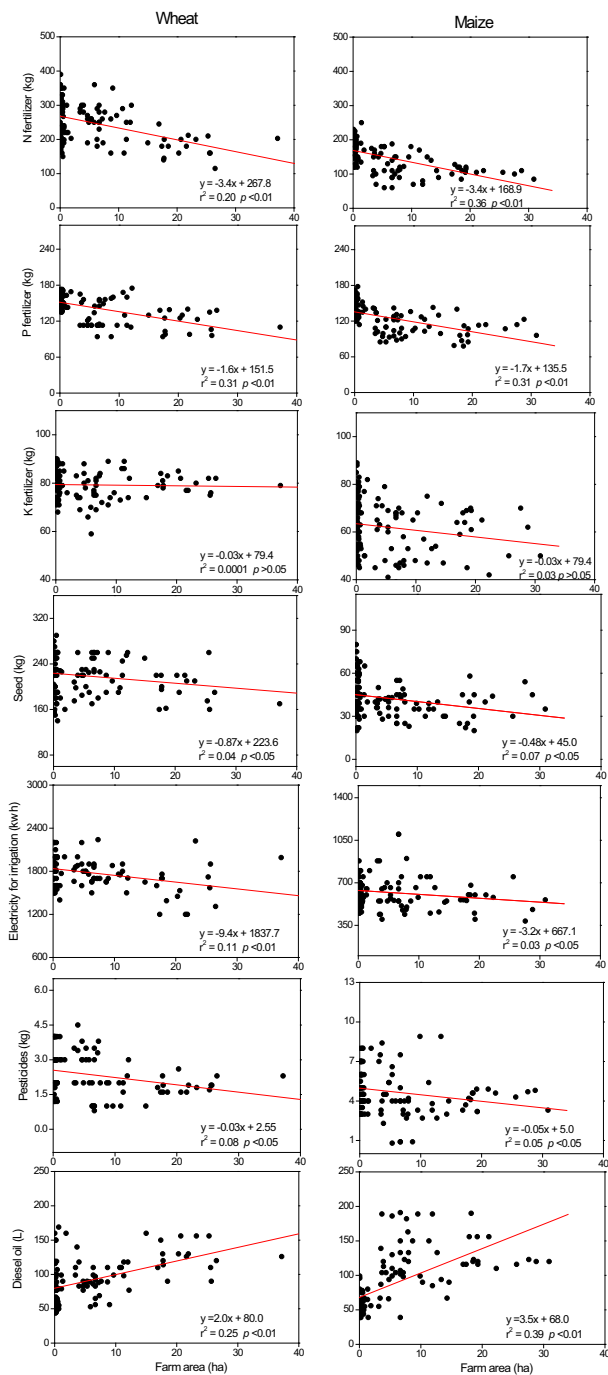


**Figure S1.**  
Frequency histogram  
of farm area in the  
surveyed data set



**Figure S2.**  
Relationships  
between farm area  
and area-scaled  
carbon footprint for  
wheat and maize,  
separately





**Figure S3.** Relationships between farm area and different emission sources ( $\text{ha}^{-1} \text{year}^{-1}$ ) for wheat and maize, separately