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A comparative study on carbon footprint of rice production between household and aggregated farms from Jiangxi, China

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Abstract Quantifying the carbon footprint (CF) for crop production can help identify key options to mitigate greenhouse gas (GHG) emissions in agriculture. In the present study, both household and aggregated farm scales were surveyed to obtain the data of rice production and farming management practices in a typical rice cultivation area of Northern Jiangxi, China. The CFs of the different rice systems including early rice, late rice, and single rice under household and aggregated farm scale were calculated. In general, early rice had the lower CF in terms of land use and grain production being 4.54±0.44 t CO_2-eq./ha and 0.62±0.1 t CO_2-eq./t grain than single rice (6.84±0.79 t CO_2-eq./ha and 0.80±0.13 t CO_2-eq./t grain) and late rice (8.72±0.54 t CO_2-eq./ha and 1.1±0.17 t CO_2-eq./t grain). The emissions from nitrogen fertilizer use accounted for 33 % of the total CF on average and the direct CH_4 emissions for 57 %. The results indicated that the CF of double rice cropping under aggregated farm being 0.86±0.11 t CO_2-eq./t grain was lower by 25 % than that being 1.14±0.25 t CO_2-eq./t grain under household farm, mainly due to high nitrogen use efficiency and low methane emissions. Therefore, developing the aggregated farm scale with efficient use of agro-chemicals and farming operation for greater profitability could offer a strategy for reducing GHG emissions in China's agriculture.

Keywords Carbon footprint · Aggregated farm · Rice cropping system · Climate change mitigation · Greenhouse gas

Introduction

Global greenhouse gas (GHG) emissions, due to human activities, have grown rapidly since pre-industrialization (IPCC, 2007a), and agriculture made a significant contribution of 13 % to the global anthropogenic GHG emissions, which accounted for 52 and 84 % of the global anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions, respectively (IPCC, 2007b). Significant

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Ming Yan and Ting Luo made equal contribution. MY for carbon accounting analysis and TL for data collection via field surveys respectively.

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technical mitigation potential has been suggested for global agriculture mainly by improved crop production management (Smith et al. 2008). However, emissions from specific crop production sectors have not been thoroughly elucidated. Rice production, as a major cereals production sector under agricultural intensification, has been much concerned with the high environmental impacts (Tilman et al. 2002) and the potential to greatly increase CH_4 emission under the future climate change over the world (van Groenigen and Hungate 2013).

China is the most important rice-producing country in the world. Chinese rice production contributed nearly 30 % to the world total (IRRI, 2010). China committed to achieve the peaking of CO_2 emissions around 2030 and to increase the share of non-fossil fuels in primary energy consumption to around 20 % by 2030 (Xinhua net 2014). In order to achieve this goal, low carbon approaches have been incentivized under the national climate change mitigation strategy (NDRC, 2012a). Agriculture contributed about 11 % of the nation's total GHG emissions. In particular, rice fields contributed about 32 % to the agricultural CH_4 emissions in China (NDRC, 2012b). Meanwhile, environmental impacts of China's intensified agriculture have been much concerned with increasingly high fertilizer and pesticide inputs and limited use of a conservation tillage system (Jin et al. 2008). Rice production, as one of the most important staple crops in China, made up to 34 % (29.4 Mha) of the total grain croplands and 40 % (195.8 Mt) of the total grain production (DRSES-SBS, 2011). Thus, characterizing the GHG emissions of rice production remains one of the prior research foci to identify the key options for mitigating climate change in agriculture.

Carbon footprint (CF) has been widely employed for quantifying the impact of production sectors or human activities on climate change, which had been generally assessed with the full life stages of the GHG emissions directly and indirectly caused by an activity or a product using the life cycle assessment (LCA) methodology (Wiedmann and Minx 2008). The CF of crop production can be assessed through quantifying the total GHG emissions associated with the production of agrochemical inputs such as fertilizers and pesticides and with energy consumption from farm mechanical operations as well as irrigation using the LCA method up to the farm gate boundary (Dubey and Lal 2009; Hillier et al. 2009).

In previous studies, the work about the GHG emissions from farming practices provided the basic information for the quantification of CF in agriculture (Lal 2004; West and Marland 2002). Then, St. Clair et al. (2008) accessed the CFs of three bioenergy crops in the UK using the LCA method up to harvest. Using a similar methodology, Hillier et al. (2009) compared the CFs of stable crops among different farm types in the UK. This approach also allowed the comparison on the CFs of crop production among different cropping systems in Canada (Gan et al. 2011a) and among the different farming practices in the USA and India (Dubey and Lal 2009). Preliminary works on CF of rice production was reported in Japan (Yoshikawa et al. 2010) and in Madagascar (Bockel et al. 2010). While in China, a previous study by Cheng et al. (2011) estimated the overall CF of China's crop production using the national data from 1993 to 2007. A similar study by Xu et al. (2013) reported the CF for rice production in five rice districts of China. Using questionnaire survey data, the studies evaluated the CF of the rice production in Shanghai (Cao et al. 2014). More recently, Cheng et al. (2015) quantified the CF of China's overall rice production using the national statistical data. Household responsibility system is still the main farmland management pattern in China until now, which has led to small scale household farms with intense land fragmentation (Tan et al. 2006). However, big scale farms in China with intensive management have been developed in land consolidation programs. Constraints on land resource availability due to fragmented croplands and small household management systems impact on crop production (Tan et al. 2008; Feng et al. 2011). Schäfer and Blanke (2012) indicated that there were significant differences of CF among the different scales of farm business for pumpkin production. Sefeedpari et al. (2013) reported that wheat production under large farms in Iran had better energy ratio and less GHG emission in comparison with small farm size levels due to better management, yet the changes in CF of rice production with different farm scale in China have not addressed so far.

Therefore, the purpose of the present study is to compare the CFs of different rice cropping systems including early, late, and single rice between household and aggregated farm scale using the LCA method from farm survey data in a typical rice cultivation area of Northern Jiangxi, China. The contributions of individual inputs involved in farming practices to the overall CF were also characterized. The present study aims also to provide information for policy-maker to identify key options for reducing GHG emissions in China's agriculture.

Materials and methods

Carbon footprint accounting criteria

The CF of crop production was quantified through accounting the GHG emissions associated with agricultural inputs and farming practices using the LCA method (Hillier et al. 2009; Dubey and Lal 2009). In the present study, the total CF for rice production was estimated both of the direct and indirect GHG emissions within the farm gate (from sowing to harvest) in a single cropping system. Indirect emissions were those from manufacture of agrochemicals and electricity used in irrigation. Whereas direct emissions included the N_2O emissions from nitrogen (N) fertilizer application and the CH_4 emissions from rice cultivation as well as the emissions from farming mechanical operations with planting, tillage, and harvesting (Zou et al. 2007; Yan et al. 2003; IPCC, 2006). Soil carbon changes, hardly detectable over a crop season, were not considered in the CF assessment. Then, the GHG emissions from different inputs or sources were quantified using the methods described below.

Firstly, the GHG emissions from agricultural inputs including fertilizers, pesticides, energy cost for irrigation, and energy consumption for farm mechanical operation were estimated using:

$$CF_M = \sum (I_i \times EF_i) \tag{1}$$

Where, CF_M represents the sum of the GHG emissions induced by ith agricultural input (t CO_2-eq.), I_i is the amount of *ith agricultural input* (t for fertilizer and pesticide, L for diesel and petrol oil, and kw h for electricity), and EF_i is the GHG emission factor of the ith input when manufactured or generated (t CO_2-eq./t).

Secondly, the direct N_2O emissions due to N fertilizer application were estimated with:

$$CF_{N_2O} = I_N \times EF_{N_2O} \times \frac{44}{28} \times 298 \tag{2}$$

where CF_{N2O} represents the GHG emissions from the direct N_2O emissions due to N fertilizer use (t CO_2-eq.), I_N is quantity of N fertilizer applied (t N), and EF_{N2O} is the default emission factor for N_2O emission induced by N fertilizer application (t N_2O-N/t N fertilizer). Here, the specific EF_{N2O} under the different water regime during rice growing season was adopted from Zou et al. (2007). $\frac{44}{28}$ is the molecular conversion factor of N_2 to N_2O; *298* is the relative global warming potential (GWP) in a 100-year horizon (IPCC, 2007a).

Thirdly, the direct CH_4 emissions were estimated using:

$$CF_{CH_4} = EF_d \times t \times A \times 25 \tag{3}$$

where CF_{CH4} represents the methane emitted from rice paddy in a rice growth season (t CO_2-eq.), EF_d is a daily emission factor (t CH_4/ha/day), and t is rice growth period (days). Here, the growing length for early, late, and single rice crop was set as 90, 105, and 135 days, respectively; A is size of rice farm (ha); and *25* is the relative GWP of CH_4 in a 100-year horizon (IPCC, 2007a).

Here, EF_d was estimated with:

$$EF_d = EF_c \times SF_w \times SF_m \tag{4}$$

where EF_c, baseline emission factor for continuously flooded fields without organic amendments in a rice growth season (t CH_4/ha/day), which was adopted from Yan et al. (2003) in this study; SF_w, scaling factor to account for the differences in water regime during the rice growing period; and SF_m, scaling factor should vary for both type and amount of organic amendment applied. Here, SF_w and SF_m in submerged rice paddies were adopted from Yan et al. (2005).

In this study, the emission factors and scaling factors indicated above were given in Table 1.

Finally, the total CF (CF_t, t CO_2-eq.) for rice production was calculated summarizing the individual GHG emissions from the different inputs or sources using:

$$CF_t = CF_M + CF_{N_2O} + CF_{CH_4} \tag{5}$$

Carbon footprint in terms of land use and grain production

The CF in terms of land use (carbon cost) was estimated with:

$$CF_A = \frac{CF_t}{A} \tag{6}$$

where CF_A is the CF per unit of area under a given farming system (t CO_2-eq./ha) and A is the relevant cultivated area of rice paddy (ha).

Table 1 GHG emission factors of different inputs or sources used in the present study

Emission source	Abbreviation	Emission factor or scaling factor	Literature
N fertilizer	$EF_{fertilizer}$	6.38 t CO_2-eq./t N	Lu et al. (2008)
P fertilizer		0.605 t CO_2-eq./t P_2O_5	West and Marland (2002)
K fertilizer		0.44 t CO_2-eq./t K_2O	West and Marland (2002)
Pesticide	$EF_{pesticide}$	18.08 t CO_2-eq./t pesticide	West and Marland (2002)
Machinery	$EF_{machinery}$	2.63×10^{-3} t CO_2-eq./L diesel	BP China (2007)
		2.3×10^{-3} t CO_2-eq./L petrol	BP China (2007)
Electricity for irrigation	$EF_{irrigation}$	9.2×10^{-4} t CO_2-eq./kW/h	BP China (2007)
Direct N_2O emission from N fertilizer	EF_{N2O}	0.0042 t N_2O-N/t fertilizer-N under water regime of flooding-midseason drainage-reflooding (F-D-F);	Zou et al. (2007)
CH_4 emission from rice field		0.0073 t N_2O-N/ t fertilizer-N under flooding-midseason drainage-reflooding-moisture intermittent irrigation (F-D-F-M)	Zou et al. (2007)
	EF_c	1.5×10^{-3} t CH_4 /ha/ day for early rice;	Yan et al. (2003)
		2.1×10^{-3} t CH_4 /ha/ day for single rice;	Yan et al. (2003)
		4.2×10^{-3} t CH_4 /ha/ day for late rice	Yan et al. (2003)
	SF_w	0.60 under intermittently flooded – single aeration;	Yan et al. (2005)
		0.52 under intermittently flooded – multiple aeration	Yan et al. (2005)
	SF_m	1.1	Yan et al. (2005)

The CF in terms of grain production (carbon intensity) was evaluated with:

$$CF_Y = \frac{CF_A}{Y} \tag{7}$$

where CF_Y is the CF per unit of rice yield under a given farming system (t CO_2-eq. /t grain) and Y is the rice yield (t/ ha).

Data collection

As the second biggest rice production province of China, Jiangxi province owned 3.3 million hectares of rice cultivation, which accounted for 61 % of the total arable land areas in Jiangxi province under a predominantly double rice cropping system (SBJ, 2011). A field survey of rice crop production was conducted in 2011 in Gubu Township (28° 43′ N, 116° 48′ E), Yugan County, Jiangxi Province, China (Fig. 1). The area of the selected township is representative of a typical rural area of rice-based agriculture in the hill-terrace red soil region of northeastern Jiangxi (Kuiper et al. 2001). The local climate is governed by a subtropical monsoon, with a mean annual temperature of 17.3–19.1 °C and annual precipitation of 1500–2000 mm, with 0.7 of that occurring in March–early July for the last two decades. Derived from red soils in the land form of terraces, the rice paddy soil was classified as a hydro-agric Stagnic Anthrosol according to the Chinese Soil Taxonomy (Gong et al. 2007; JBLM, 1991) and as a typic Paleudult according to Soil Taxonomy (SSS-USDA 1999). The rice-cultivated area was about 110,000 hectares including 88 % for early and late rice and only 12 % for single rice in Yugan County, and the county produced nearly 560 Tg rice in 2010 (SBJ, 2011).

Small household farms with intense land fragmentation is still the main farmland management pattern in China now (Tan et al. 2006), but the aggregated farms with intensive management have been developed in land consolidation programs. In order to address the effect of the farm scale on CF of rice crop production, farms could be divided into two categories of small household (<3.33 ha, 50 Chinese mu) and aggregated farm scale (>3.33 ha) mainly according to the farm size (DFJP, 2008; Zhu et al. 2010).

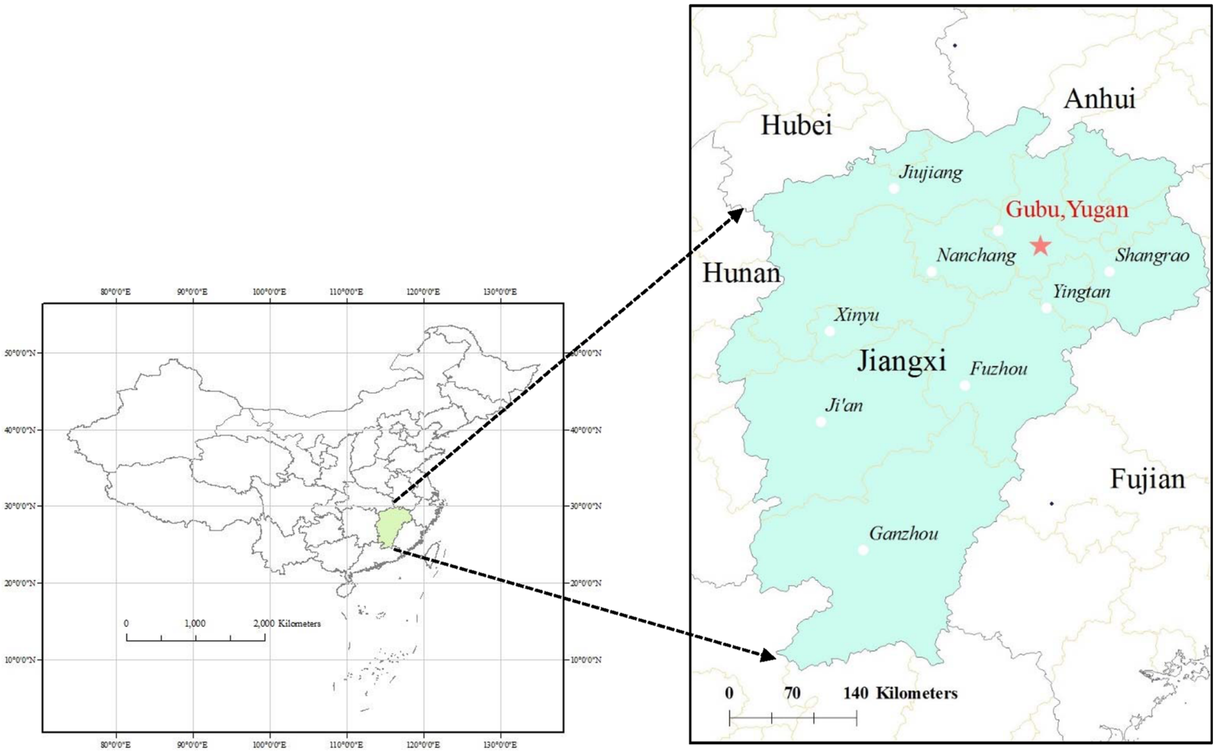

Fig. 1 The location of the surveyed region in Jiangxi province of China

Random sampling approach was employed to obtain the studied samples. First, the number of small household and aggregated farms including early rice, late rice, and single rice systems was surveyed from the official statistics of studied region, and the subgroups were built for sampling. In general, early rice was planted in late march and harvested in middle or late July, single rice were planted in middle or late May and harvested in middle or late September, and late rice was planted in middle or late June and harvested in middle or late October in the surveyed area. Then, ten farms under household and aggregated scale for each cropping systems were randomly selected from each sub-group. The farm size of samples ranged from 0.1 to 1.3 ha under household and from 5.3 to 46.7 ha under aggregated scale in the survey. As indicated above, there were less farmers planting single rice especially under household in Yugan County, so only seven farms under aggregated scale in single rice cropping system were randomly selected to determine the difference among the different cropping systems under aggregated management. At last, data collection was performed through face-to-face interview with the sampled farmers in 2011.

The data for a single rice cropping season inquired with the interview included the following: (a) amounts of agro-chemicals such as N, phosphate (P), and potassium (K) fertilizers and pesticides used; (b) energy consumption for farm mechanical operations such as spraying, tillage, transplantation, harvesting, and transportation; (c) energy cost in irrigation and water regime of irrigated rice (the pattern of flooding and drainage); and (d) farm size, rice cropping system including early rice, late rice, and single rice and rice yield. Then, data describing rice production and management in a single crop production cycle were recorded to create a database. The original data used in the present study was provided as Table S1 available online. A statistical summary of the data of the studied rice farming system was given in Table 2.

Data processing and statistical analysis

All the data were expressed as mean plus or minus standard deviation. Data processing was performed using Microsoft Office Excel 2010, and all statistical analyses were conducted using JMP Ver. 7.0. One-way ANOVA and the least significant difference test (LSD) were used

Table 2 General information of main agricultural inputs and rice yield from the surveyed farms

Rice yield	Farm type (number of sample)		Grain yield (t/ha)	N fertilizer (kg N/ha)	P fertilizer (kg P_2O_5/ha)	K fertilizer (kg K_2O/ha)	Pesticide (kg/ha)	Petrol for pesticide spraying (L/ha)
Early rice	Household (10)	Min.	3.4	130	15	8	0.8	0
		Max.	7.5	415	289	233	7.3	0
		Mean	5.8	255	132	103	2.9	0
		C.V.%	19	35	58	61	73	0
	Aggregated (10)	Min.	6.4	170	79	68	0.2	4.2
		Max.	9.8	284	190	149	5.1	9.0
		Mean	7.4	222	120	94	1.9	6.8
		C.V.%	13	18	27	29	85	33
Late rice	Household (10)	Min.	4.5	130	6	7	0.8	0
		Max.	9	465	249	213	8.3	0
		Mean	7.1	261	131	107	3.9	0
		C.V.%	16	44	54	57	62	0
	Aggregated (10)	Min.	6.4	141	34	34	2.5	12.5
		Max.	9.2	313	174	215	5.8	29.4
		Mean	8.0	221	114	110	4.3	21
		C.V.%	12	24	39	49	21	23
Single rice	Aggregated (7)	Min.	7.1	141	34	34	1.8	16.7
		Max.	10.5	400	174	215	5.8	29.4
		Mean	8.7	235	119	113	3.9	19.8
		C.V.%	13	34	38	52	32	24

Rice paddies were irrigated under the water regime of flooding-midseason drainage-reflooding (F-D-F) in household farms, of flooding-midseason drainage-intermittent flooding irrigation (F-D-IF) until a week before harvest in aggregated farms recorded in our survey

to check the differences between cropping systems and farm scale. A correlation analysis was employed to figure out the sources of CF variations among the farms. The level of significance was defined at $p<0.05$.

Results

Agricultural inputs and rice yield

Both agricultural inputs and grain yield varied among individual farms with different rice-growing seasons and farm scales (Table 2). Under small household, the range of N fertilizer application rates varied widely from 130 to 415 kg N/ha (coefficient of variation (CV) of 35 %) for early rice and from 130 to 465 kg N/ha (CV of 44 %) for late rice. However, N fertilizer application rates under aggregated farm scale were at the range of 170–284, 141–313, and 141–400 kg N/ha in the early rice, late rice, and single rice season; the CV of which was 18, 24, and 34 %, respectively. For pesticide application in household farms, the ranges were from 0.8 to 7.3 kg/ha and from 0.8 to 8.3 kg/ha in early rice and late rice season, respectively. Whereas pesticides were applied at the range of 1.8–5.8 kg/ha for single rice system in aggregated farms. In general, the inputs showed wider variations under small household than aggregated scale when comparing their CV (Table 2, Table S1).

Although less fertilizers were used under aggregated farm scale, the yields of early rice and late rice in aggregated farms were 7.4 and 8.0 t/ha on average compared to small household farms with the average yields of 5.8 t/ha for early rice and 7.1 t/ha for late rice. The CV of rice yield in household farms was 18.8 and 16.1 % for early and late rice, respectively, which was higher than that in aggregated farms (Table 2, Table S1).

Variation of carbon footprint with different farm scale

In general, early rice had the lowest CF being 4.54±0.44 t CO_2-eq./ha in terms of land use and 0.62±0.1 t CO_2-eq./t in terms of grain production, followed by single rice

Table 3 Carbon footprint of different rice cropping systems under aggregated farm scale (mean±SD)

Rice cropping system	Grain yield	Carbon footprint	
	(t /ha)	Land use (t CO_2-eq./ha)	Grain production (t CO_2-eq./t grain)
Early rice (10)	7.41±0.93b	4.54±0.44c	0.62±0.1c
Late rice (10)	8.04±0.97ab	8.72±0.54a	1.1±0.17a
Single rice (7)	8.68±1.11a	6.84±0.79b	0.8±0.13b

The number in parentheses is the number of the surveyed samples under different rice cropping systems. Different lower case letters indicate significant differences among the rice cropping systems at $p<0.05$

(6.84±0.79 t CO_2-eq./ha and 0.8±0.13 t CO_2-eq./t grain) and late rice (8.72±0.54 t CO_2-eq./ha and 1.1±0.17 t CO_2-eq./t grain; Table 3). The comparison of CFs for rice production between household and aggregated farm scale was shown in Fig. 2. It was found that the CFs of double rice cropping under aggregated farm scale being 13.26±0.8 t CO_2-eq./ha per year in terms of land use and 0.86±0.11 t CO_2-eq./t grain in terms of grain production were significantly lower (by 9 and 25 %, respectively) than small household farms (Fig. 2).

Specifically, the carbon cost of early rice under household was similar with aggregated farm scale. However, the carbon intensity of early rice under aggregated farm scale decreased by 28 % due to the higher

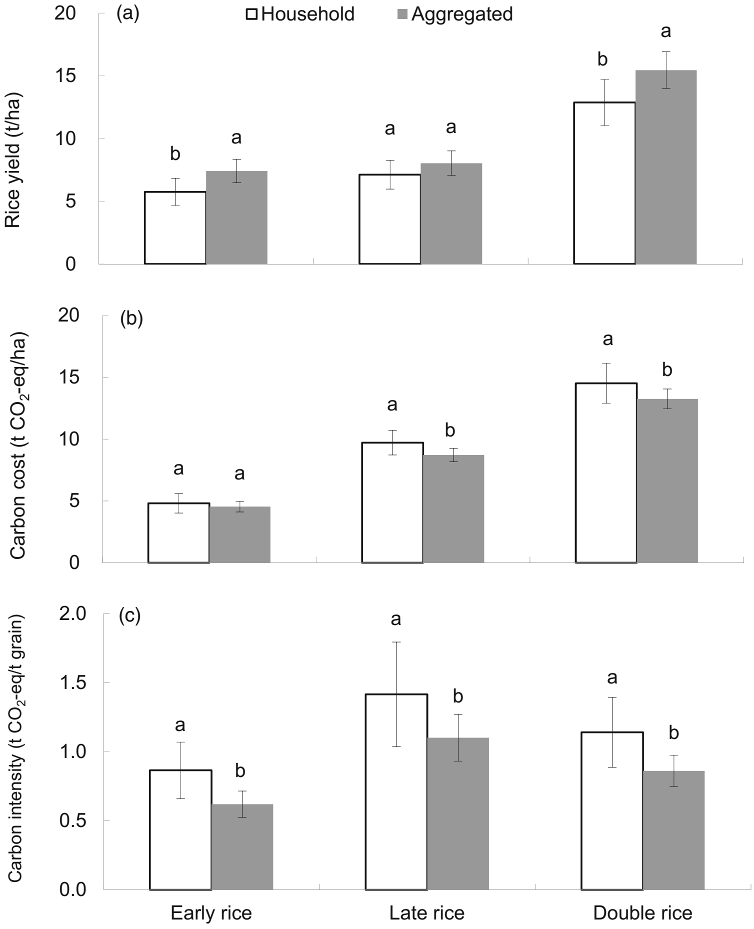

Fig. 2 Comparison of rice yield (**a**), carbon cost (**b**), and carbon intensity (**c**) between household and aggregated farm scale under double rice cropping systems (mean±SD). *Different letters* indicate significant differences between household and aggregated farm scale at $p<0.05$

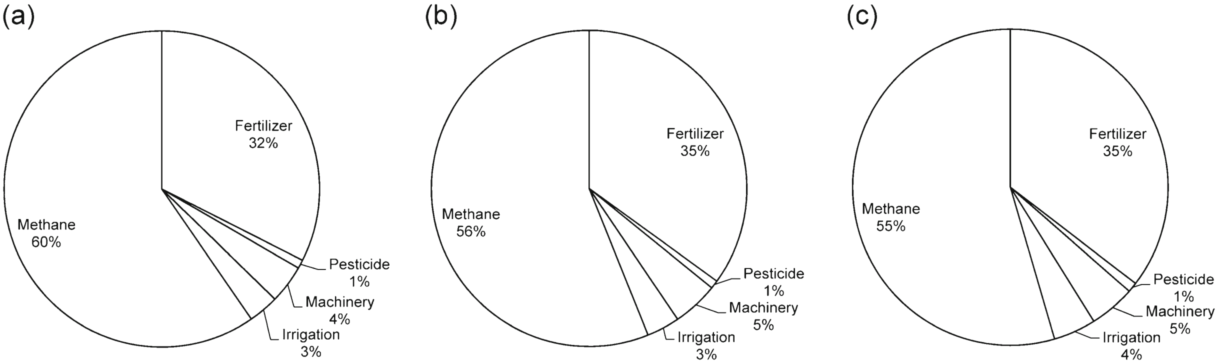

Fig. 3 Contribution of different agricultural inputs or emission sources to total carbon footprint for the household (**a**) and aggregated (**b**) double rice production, and aggregated single rice production (**c**)

yield of early rice compared to small household farms (0.86±0.2 t CO_2-eq./t grain). The CF of late rice under aggregated farm scale was lower by 10 and 22 % than small household being 8.72±0.54 t CO_2-eq./ha and 1.1 ±0.17 t CO_2-eq./t grain, respectively (Fig. 2).

Contributions of individual inputs

The proportions of various GHG emission sources to the total CFs were calculated to analyze the contributions of different agricultural inputs (Fig. 3). There was no significant difference in the proportion of each input between different cropping systems and farm scales. Obviously, the direct CH_4 emission was the biggest contributor to the total CF, which accounted for 55–60 % (Fig. 3). Then, the emissions from fertilizer input contributed by 32–35 % to the total CF in which almost 95 % was induced by N fertilizer application. However, farm mechanical operation, irrigation, and pesticide (3, 5, and 1 %, respectively) made up a minor proportion of the total emissions. Therefore, it was clear that emissions from direct CH_4 emissions and N fertilizer application were the major contributors for the total CF of rice production.

Nevertheless, there were some differences in carbon intensities from individual inputs between the household and aggregated farm scale (Table 4). Carbon intensity from fertilizer use and direct methane emissions under aggregated farm scale was shown to be significantly lower by about 20 and 30 %, respectively, than household mainly due to the higher nitrogen use efficiency and more aeration events under aggregated management (Table 2 and S1).

Discussions

Comparison with similar studies and other crops

The mean CF of rice production was calculated as 4.54–8.72 t CO_2-eq./ha and 0.62–1.1 t CO_2-eq./t in Jiangxi province of China, according to the current results

Table 4 Carbon intensity of different agricultural inputs or sources under household and aggregated farm scale (mean±SD)

Rice type	Farm scale	Carbon intensity of individual inputs (kg CO_2-eq./t grain)				
		Fertilizer	Pesticide	Machinery	Irrigation	CH_4 emission
Early rice	Household (10)	399.7±127.7a	10.1±8.7a	49.9±11.9a	32.4±7.7a	372.8±102.7a
	Aggregated (10)	312.8±69.3b	4.9±4.5a	39.9±4.7b	24.5±2.7b	237.9±26.2b
Late rice	Household (10)	340.1±171.5a	9.9±6.1a	39.9±8.2a	38.7±7.9a	986.3±241.3a
	Aggregated (10)	289.1±83.7a	9.7±2.2a	40.9±5.1a	33.8±4.3a	727.5±92b
Double rice	Household (10)	369.9±136.1a	10±6.5a	44.9±7.5a	35.6±5.8a	679.5±435.9a
	Aggregated (10)	301±63.3a	7.3±2.7a	40.4±4a	29.1±2.9b	482.7±51.7b

The number in parentheses is the number of the surveyed samples. Different lower case letters indicate significant differences between household and aggregated farm scale at $p<0.05$

(Table 3), which are comparable to the CF values found by some previous studies (Cheng et al. 2015; Xu et al. 2013; Cao et al. 2014). Cheng et al. (2015) estimated the area-weighted mean CF of rice production as 1.36 t CO_2-eq./t grain in China. CF of rice production was shown ranging from 1.34 to 2.5 t CO_2-eq./t grain in five typical rice-cultivating provinces of China (Xu et al. 2013), which showed the regional variation in CF, and the rice production CF of 1.23 t CO_2-eq./t in Shanghai quantified by Cao et al. (2014) was close to that in Jiangxi estimated by this study. The mean CF of polished rice in Japan was 1.93 t CO_2-eq./t higher than the present estimation because the emissions by rice polishing, distribution, and retailing, rice cooking, and waste treatment were also included in the calculation.

A recent study quantified a specific CF of 2.91 and 2.86 t CO_2-eq./ha, respectively, for China's wheat and maize production using the national statistical data in 2011 (Cheng et al. 2015). The CFs of wheat and maize crop production were estimated as 4.03 and 2.33 t CO_2-eq./ha in Hebei province, China (Shi et al. 2011). A study in the UK showed that the mean CF for staple dry crops in conventional farms was 1.6 t CO_2-eq./ha (Hillier et al. 2009). In Canada, the CF of durum wheat was only 0.7–0.9 t CO_2-eq./ha (Gan et al. 2011a, b). Apparently, rice production in this typical rice production area of China had the much higher CF not only than that of the dry crop production in China but also that of crop production in Western countries that was mainly due to the significant contribution of CH_4 emissions to the total CF for rice production (Fig. 3). Thus, rice production could be considered as a high carbon grain production sector in China, although comparison with rice production from other countries was not possible due to lack of available data.

Role of CH_4 emissions and N fertilizer in carbon footprint of rice production

The CH_4 emission was the biggest contributor to the total CF in rice production. Similarly, the proportion of 69 % was also reported by Cheng et al. (2015) using the national statistical data. CH_4 is produced under anaerobic conditions by methanogens (Schimel 2000). Rice paddies, which are characterized by high moisture content and relatively high organic carbon levels, and prolonged anaerobic conditions during rice growth are one of the major anthropogenic sources of CH_4 accounting for almost one fifth of agricultural CH_4 emission (Schimel 2000; Linquist et al. 2012). There are many studies indicated that CH_4 flux had a steadily increase during the continuous flooding period, and less frequent water logging could reduce CH_4 emissions from rice field (Cai 2000; Huang et al. 2004; Li et al. 2005; Zou et al. 2005). Hence, the irrigation patterns could largely affect the amount of CH_4 emissions in rice paddies. For example, Lu et al. (2000) indicated CH_4 emissions had a 30 % reduction by intermittent irrigation compared with midseason drainage of the local practices (longer waterlogging lengths) from irrigated rice fields. As indicated above, rice was irrigated under the water regime of flooding-midseason drainage-reflooding (F-D-F) in household farms and of flooding-drainage-intermittent flooding (F-D-IF) in aggregated farms in this survey.

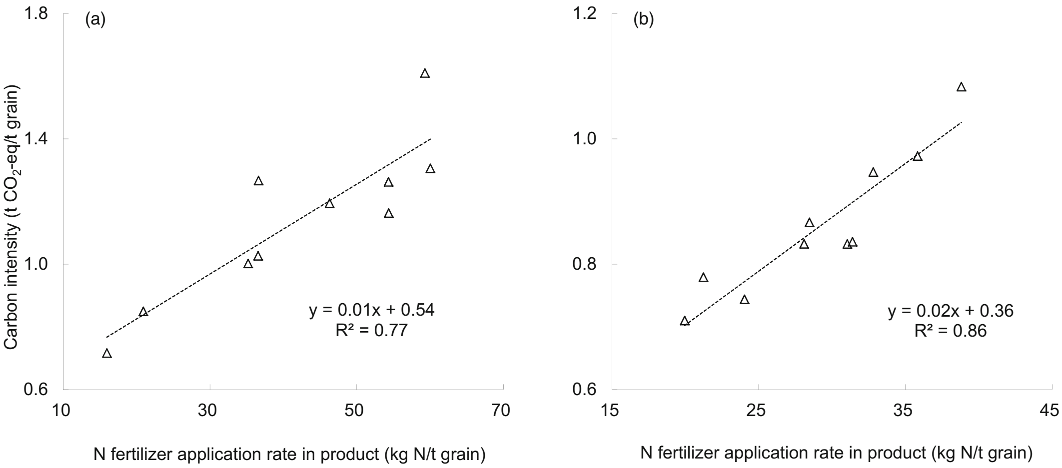

Fig. 4 Correlation of N fertilizer application rate with the total carbon cost for double rice production under household (**a**) and aggregated farm scale (**b**)

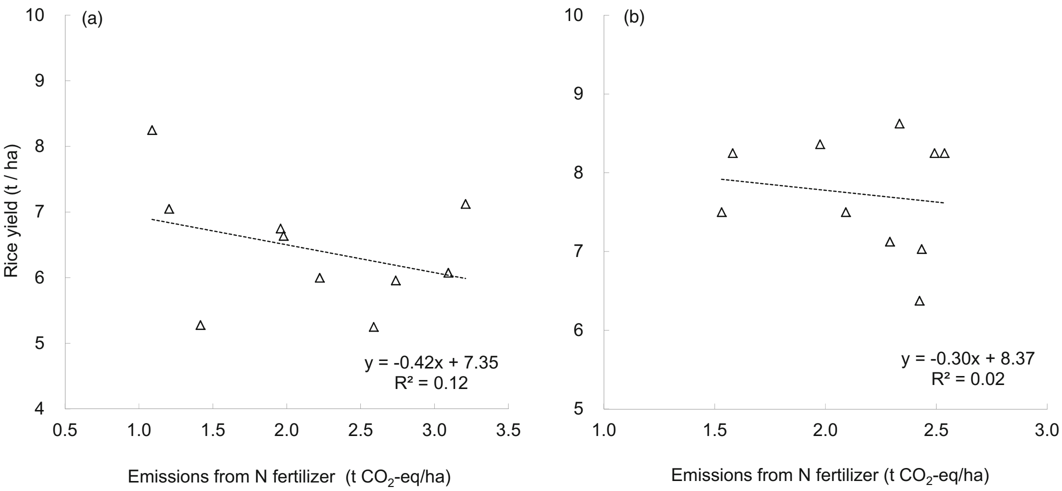

Fig. 5 Relation of N fertilizer induced GHG emissions with rice yield for double rice production under household (**a**) and aggregated farm scale (**b**)

Therefore, the carbon intensity from CH_4 emissions decreased by 26–35 % under aggregated farm scale than household mainly due to shorter waterlogging lengths.

Synthetic N fertilizer application was the second largest contributor accounted for 31–34 % to the total CF in rice production. Synthetic N fertilizer consumption in China accounted for nearly 30 % of the global total since 2007. A large amount of excessive N fertilizer was used in excess of crop requirement (Ju et al. 2009), resulting in a negative environmental impact, such as soil acidification (Guo et al. 2010) and water quality deterioration. Kahrl et al. (2010) gave a general estimation of 400–840 Mt CO_2-eq. per year for China's N fertilizer production and application in agriculture, which was equivalent to 8–16 % of China's energy-related CO_2 emissions in 2005. Hence, avoiding overuse of synthetic N fertilizer may be a potential pathway to reduce CF in rice production. As shown in Fig. 4, 77 and 86 % of the variation in the CF across farms could be explained by N fertilizer application. However, the increase of N fertilizer induced emissions did not bring the increase of rice yield, and even the rice yield in small household farms slightly decreased (Fig. 5). Furthermore, aggregated farms decreased by 15–22 % of emissions induced by N fertilizer use compared to small household farms (Table 4). The aggregated farms gained more rice yield but input lower N fertilizer than household farms. Generally, about 80 kg CO_2-eq./t from N fertilizer was saved, but the rice yield of 1.3 t /

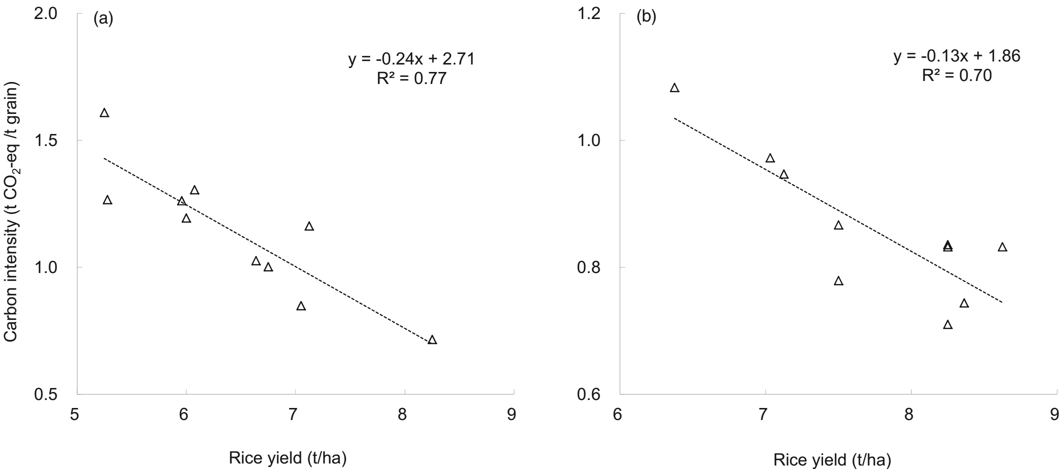

Fig. 6 Relation of rice yield with carbon intensity for double rice production under household (**a**) and aggregated farm scale (**b**)

ha increased in line with a reduction of 0.3 t CO_2-eq./t grain yield in CF under aggregated farm scale in comparison with small household farms.

Opportunity for GHG emission mitigation in China's rice production

A negative correlation was observed between rice yield and carbon intensity (Fig. 6), which indicated GHG emissions could be reduced with the increase of grain yield. Denier van der Gon et al. (2002) and Burney et al. (2010) also indicated that optimizing grain yields could mitigate GHG emissions with the best management practices application. As indicated in this study, the CF of rice production was very different between household and aggregated farm scale. With the increased yield (20 % on average), aggregated farms had a large decreased by 25 % on average in the rice carbon intensity in comparison with small household. Similarly, Tan et al. (2008) examined the impact of land fragmentation on the production costs of rice farm in Jiangxi and found an increase in farm size decreased the total production cost. Feng et al. (2011) reported that topsoil SOC storage could be higher over 30 % in larger sized farms (>0.7 ha, 10 Chinese *mu*) than in smaller ones (<0.7 ha) from survey work in a similar region as this study. In a comparable study using questionnaire data, Sefeedpari et al. (2013) reported that farms less than 1 ha had a higher total energy input by 17, 21, and 34 % respectively than those of 1–4, 4–10, and >10 ha for rain-fed wheat production from central Iran. The improved management patterns under aggregated farm scale make the major contributions to the low GHG emissions in the life cycle of crop production.

There had been a study reported that China's major crop production has been already carbon intensive (Kitzes et al. 2008). Cheng et al. (2011) also indicated that carbon use efficiency had been decreased recently in China's agriculture. Rice production would become increasingly carbon intensive due to more inputs of chemicals and CH_4 emissions with the purpose of rice yield increase. Consequently, it would be critical for China's rice production, and better managing rice production will be urgently needed. The present study highlighted the role of farming management characterized by farm size scales in the CF of rice production and stated the higher and more consistency of grain yield in line with management improvement under farm aggregation would open a great opportunity to obtain the sustainable climate change mitigation.

Conclusions

Carbon footprint of rice production was quantified in a typical rice cultivation area of China. Early rice had the lowest CF being 4.54±0.44 t CO_2-eq./ha in terms of land use and 0.62±0.10 t CO_2-eq./t in terms of grain production following single rice (6.84±0.79 t CO_2-eq./ha and 0.8±0.13 t CO_2-eq./t grain) and late rice (8.72±0.54 t CO_2-eq./ha and 1.1±0.17 t CO_2-eq./t grain). It was concluded that the most contributors to the total CF in rice production were CH_4 emissions (55–60 %) and N fertilizer application (31–34 %). The carbon intensity of double rice production under aggregated farm scale was significantly higher by about 25 % than that under small household farm scale, mainly due to low N fertilizer use and CH_4 emissions but high grain yield under aggregated farm scale. Developing aggregated farm scale with intensive management could be an important strategy to mitigate climate change in the future of China's agriculture.

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