Carbon Footprint of Crop Production and the Significance for Greenhouse Gas Reduction in the Agriculture Sector of China

Ming Yan, Kun Cheng, Ting Luo and Genxing Pan

Abstract World agriculture is facing a great joint challenge of ensuring food security and mitigating greenhouse gas emissions under climate change. Characterizing the carbon footprints of crop production by life cycle analysis is be critical for identifying the key measures to mitigate greenhouse gas emission while sustaining crop productivity in the near future. In this chapter, the carbon footprints of bulk crop production; individual staple crops of rice, wheat, and maize; as well as vegetable crops from China were analyzed using data from either statistical archive or of questionnaire survey for quantification of all carbon costs in a whole life cycle. Although the overall carbon footprint of crop production sector of China is much higher than that of the UK and USA, rice and wheat have significantly higher carbon footprints than maize. The nitrogen- fertilizer-induced footprint was shown to be the biggest contributor to the total carbon footprint for all the crops (more than 60 %), leaving a big space for mitigation of luxury emissions of N_2O with nitrogen use in excess. Although the carbon footprint has quickly increased since 1970s, crop production did not show a positive response to increasing carbon cost. While reducing nitrogen chemical fertilizer use is apparently a key option to cut down the highly carbon- intensive agriculture, substitution of rice or wheat with maize would offer a final option to ensure both high cereal production and low carbon cost in China's crop production sector. There is an urgent need to depict the variation of carbon footprints for different cropping and farming systems, climate conditions, and the threshold of nitrogen luxury emissions for a certain crop.

Keywords Carbon footprint · C cost · Crop production · Vegetables · Carbon management · Fertilizer · GHGs emission · Life cycle analysis

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1 Introduction: General Issues of China's Crop Production

Agriculture is a key sector in the global economy, which is critical for providing the food and fiber demanded by the huge population of 7 billion people in 2010. However, the agriculture sector contributes significantly to global warming from direct and indirect carbon emissions associated with crop production. To ensure food safety for the still fast-increasing population, world agriculture has been tackling the trilemma of high productivity, low greenhouse gas (GHG) emission, and adaptation to climate change (Smith et al. 2013). World agriculture emitted 5,100–6,100 Mt CO_2-eq year^{-1} and contributed approximately 30 % to the global total anthropogenic emissions, being the second greatest emitter after fossil fuel consumption (Smith et al. 2008). With the joint challenges of food security and climate change faced by the global society in the coming decades, world agriculture has been increasingly concerned with global solutions to mitigate climate change (FAO 2010).

The trilemma is even more critical for China, which has long struggled with a safe solution to adequate food supplies (Brown 1994). China preserved a total cropland of approximately 130 Ma and produced 0.59 billion tons of cereals in 2012. Rice, wheat, and maize were cultivated in an area of croplands of 29.8 Mha, 24.2 Mha, and 32.5 Mha, respectively, in 2010, overall making up 68.4 % of the total harvest area (160.7 Mha) and 80 % of the total arable land (109.9 Mha) in China. The yield for rice, wheat, and maize crop production were 195.8 M tons, 115.2 M tons, and 177.2 M tons, respectively, in 2010 (DRSES-SBSC 2011). Vegetables, melons, and fruits were planted in areas of 19.0 and 2.4 Mha, respectively, in 2010, accounting for 11.8 and 1.5 % of the total harvest area (160.7 Mha) in China. The yields for vegetable, melon, and fruit production were 65.1 M tons and 8.5 M tons, respectively, in 2010 (DRSES-SBSC 2011). However, the sustainability of China's agriculture is increasingly of concern in the light of excess use of nitrogen (N) fertilizer, soil degradation and pollution, and the vulnerability to climate change (Guo et al. 2010; Ju et al. 2009; Liu et al. 2010; Ye and Van Ranst 2009; Pan et al. 2011a). The high yield on the cost of high inputs for food production would certainly impact the greenhouse gas emissions from agriculture; the use of synthetic N fertilizers, for example, could cause a potential yearly emission of 400–840 Mt CO_2-eq, equivalent to 8–16 % of China's energy-related CO_2 emissions in 2005 (Kahrl et al. 2010). Contributing 9.2 % to the national total anthropogenic GHG emissions, China's agriculture emitted 686 Mt CO_2-eq in 2007 (Chen and Zhang 2010). China has committed to reduce GHG emissions by 40–45 % per unit of gross domestic product (GDP) until 2020 on the baseline of 2005 (Xinhua Net 2009). Mitigation in agriculture could offer a significant reduction in national total GHG emissions as well as cobenefits for crop production and ecosystem functioning. Recently, low carbon approaches have been encouraged by incentives under the national climate change mitigation strategy (Anonymous 2009; Anonymous 2012; NDRC 2012).

In this chapter, to offer basic formation on greenhouse gas emission intensity and the factors in China's agriculture, the carbon footprint will be characterized for staple and vegetable crops, along with a description of the methodology. Finally, a discussion is provided on policies and perspectives on future trends.

2 Methods for Quantifying Carbon Footprint in Agriculture

2.1 Rational of Accounting Approach

There have been many studies on the carbon footprint of agriculture since 2005. To characterize the GHG emissions of human activities in the production sector of industry, transportation, and human lifestyle as well as social activities, the concept of carbon footprint (CF) has been generally based on the accounting of all greenhouse gas emissions directly and indirectly caused in the whole life cycle of a product or an activity (BP 2005; POST-UK 2006; ETAP 2007; Wiedema et al. 2008; Finkbeiner 2009). Subsequently, the carbon intensity of overall greenhouse gas emissions could be assessed on the CO_2 equivalent of a product over the whole course of production (Woolf et al. 2010). Generally, the CF of crop production accounts for all carbon costs through individual inputs for crop production up to the farm gate (harvest) together with the emission factors for these inputs (St Clair et al. 2008; Hillier et al. 2009).

2.2 Procedure of Carbon Emission Accounting

In our studies, carbon footprint accounting was performed by basically following the protocol described by Hillier et al. (2009), in which the total carbon cost (CO_2-eq) was assumed to be the sum of emissions due to the energy consumption associated with chemical input and mechanical operations for spraying and tillage, harvesting, strapping, transportation, and irrigation, and the direct emissions of N_2O emissions from cropland due to N fertilizer application and CH_4 emissions from rice cultivation. Individual carbon cost of management activities or of agrochemical inputs can be calculated separately using the following formula:

$$CF_i = AI_i \times EF_i \qquad (1)$$

where, CF_i is the GHG emissions induced by an agricultural input (in CO_2-eq); AI_i is the amount of agricultural input applied (in kilograms for fertilizer, pesticide, and plastic film, in liters for diesel oil due to machinery operation, or in kilowatt-

Table 1 Emission factors used for carbon footprinting

Emission source	Abbreviations	Emission factor or scaling factor	Literature
N fertilizer	$EF_{fertilizer}$	6.38 t CO_2-eq t^{-1} N	Lu et al. (2008)
P fertilizer		605.33 kg CO_2-eq t^{-1} P_2O_5	West and Marland
K fertilizer		441.03 kg CO_2-eq t^{-1} K_2O	(2002)
Pesticide	$EF_{pesticide}$	18.08 t CO_2-eq t^{-1} pesticide	West and Marland (2002)
Insecticide		1.32 t CO_2-eq t^{-1} insecticide	Hillier et al. (2009)
Herbicide		23.10 t CO_2-eq t^{-1} herbicide	
Fungicide		11.59 t CO_2-eq t^{-1} fungicide	
Plastic film	EF_{film}	2.5 t CO_2-eq t^{-1} film	Energy Source, China (2009)
Diesel oil for machinery	$EF_{machinery}$	2.63 kg CO_2-eq L^{-1}	BP China (2007)
Electricity for irrigation	$EF_{irrigation}$	0.92 kg CO_2-eq kw^{-1} h^{-1}	
Labor	EF_{labor}	0.9 kg CO_2-eq day^{-1} $person^{-1}$	Yang (1996)
Direct N_2O emission from N fertilizer	EF_{N_2O}	Dry cropland, 0.01 t N_2O-N t^{-1} fertilizer-N	IPCC (2006)
		Rice paddy, 0.0073 t N_2O-N t^{-1} fertilizer-N	Zou et al. (2007)
CH_4 emission from rice land	EF_c	1.30 kg CH_4 ha^{-1} day^{-1}	Yan et al. (2005)
	SF_w	0.52	
	SF_p	0.68	
	SF_m	1.0	

hours for electricity due to irrigation); i is the agricultural input, such as, fertilizer, pesticide, machinery operation, or irrigation, etc; and EF_i is the individual carbon intensity (in CO_2-eq per unit volume or mass) when manufactured and/or applied of individual agricultural input. The reference emission factors used in the estimation are listed in Table 1.

Direct N_2O emissions from N fertilizer can be estimated using Eq. 2:

$$CF_N = F_N \times \delta_N \times \frac{44}{28} \times 298 \qquad (2)$$

where, CF_N represents the carbon footprint due to direct N_2O emissions from application of synthetic N fertilizer (in CO_2-eq ha^{-1}); F_N and δ_N is respectively the quantity (in kg ha^{-1}) of N fertilizer applied for crop production and the default emission factor of N_2O emission per unit of N fertilizer applied (in kg N_2O-N kg^{-1} N fertilizer); $44/28$ is the molecular weight of N_2 in relation to N_2O; and 298 is net global warming potential (GWP) in a 100-year horizon (IPCC 2006).

For rice production, methane is produced with waterlogging in paddies, which could be estimated using the equation

$$CF_{CH_4 rice} = EF_d \times t \times A \times 25 \qquad (3)$$

where, $CFCF_{CH_4 rice}$ represents the annual methane emissions from rice cultivation (in CO_2-eq); EF_d is a daily emission factor, (in kg CH_4 ha^{-1} day^{-1}); t is cultivation period of rice (in days); A is the size of rice farm (in ha); and 25 is the relative molecular warming forcing of CH_4 in a 100-year horizon (IPCC 2006). The factor of EF_d can be estimated using data from literature:

$$EF_d = EF_c \times SF_w \times SF_p \times SF_m \times SF_{s,r} \tag{4}$$

where EF_d is the adjusted daily emission factor for a particular rice area; EF_c is the baseline emission factor for continuously flooded fields without organic amendments; SF_w is the scaling factor to account for the differences in water regimen during the cultivation period; SF_p is the scaling factor to account for the differences in water regimen in the pre-season before the cultivation period; SF_m is the scaling factor, which should vary for both type and amount of organic amendment applied; $SF_{s,r}$ is the scaling factor for soil type, rice cultivar, etc., if available.

In particular, labor was taken into account in the counting to avoid bias from machinery operation in China for operations of fertilizing, tillage, and harvesting performed with labor in many cases. This is estimated with the following equation:

$$CF_{labor} = N \times EF_{labor} \tag{5}$$

where N is the total number of days for labor input and EF_{labor} (in CO_2-eq day^{-1} $person^{-1}$) is the carbon dioxide respired by an adult per day.

As generally accepted, the GHG emissions with disposal or treatment of crop residues were not considered in this study. In addition, CO_2 emission due to soil respiration, being a very small contribution to global CO_2 emission (Bellarby et al. 2008), was not considered in the CF analysis.

2.3 Data Used for CF Accounting

2.3.1 Statistical Data

Data from retrieved from China Rural Statistical Yearbook series of 1993–2007 was used. This data included cropland area, total production, and the various inputs of fertilizers, pesticides, diesel, plastic films, and electricity involved in crop production, which were recorded annually. Because the crops in this data set covered all the crops cultivated and the production was represented as a bulk sum of rice, wheat, corn, beans, potato, vegetable, fruits, cotton, oil, and sugar crops, an overall carbon footprint of the crop production sector of China was determined (Cheng et al. 2011).

2.3.2 Farm Survey Data

For assessing the footprint of different crops under different management practices and different cropping/farming systems, data can be obtained via surveys to farmers about the input for their production of a single crop growing season under local conditions. This is usually done with a questionnaire sheet (Table 2) for data input via face-to-face interview with the farmers who manage the crop production (Chen et al. 2011; Yan et al. 2013). A dataset (Table 3) was then established for further quantification processes and statistics with carbon footprinting software.

Table 2 A data input sheet used in questionnaire survey to farmers

___ Province ___ City (GPA position) Investigator: ___ Date: ___

Crop: ___	Farm size: ___	Yield: ___ (kg)	Location: ___	Interviewee: ___
Agro-chemical inputs	Fertilizer type	N %, P_2O_5 %, K_2O %	Amount (kg) and times	Expense
	Pesticide type	Amount (g or mL) and times		
	Others			
	Film			
	……			
Machinery operation	Please choose $\sqrt{}$	Power (kw/h) or diesel oil (L)	Work hours and times	
	☐ Seeding			
	☐ Tilling			
	☐ Spraying agricultural chemicals			
	☐ Harvest			
	☐ threshing			
	☐ Transport			
	☐ Others			
	….			
Irrigation	☐ Pumping			
	☐ Well irrigation			
	☐ Others			
Labor		Persons	Days or hours	
	☐ Seeding			
	☐ Weeding			
	☐ Fertilizing			
	☐ Spray pesticide			
	☐ Harvest			
	☐ Others			
Dispose of straw: ☐ Burning ☐ Returning straw to field ☐ Others				

Table 3 Examples of data coding in a dataset for quantification calculation

Code of region	Code of farm surveyed	Code of crop	Code of cropping system	Code of input	Code of grain yield
1: Humid	1: Single household	1: Rice	1: Rice-wheat rotation	1: Fertilizer	1: Rice
2: Semiarid		2: Wheat		2: Pesticides	2: Wheat
3: Arid	2: Aggregated	3: Maize	2: Double-rice rotation	3: Plastic film	3: Maize
4: Boreal	3: Company owned		3: Wheat-maize rotation	4: Farm operation	
				5: Irrigation	

3 Overall Carbon Footprints of China's Crop Production

3.1 General Feature of Carbon Footprint

Using the statistical data retrieved from the China Rural Statistical Yearbook series throughout the period of 1993–2007 (DRSES-SBSC 2008), Cheng et al. (2011) conducted a basic estimate of the overall CF of crop production in China. The study showed an overall carbon cost of 0.44 Pg CO_2-eq on average annually for production of all crops, including rice, wheat, corn, beans, potato, vegetables, fruits, cotton, oil, and sugar crops in the time span. The work indicated an overall carbon intensity of 2.3–3.4 t CO_2-eq ha^{-1} yr^{-1} for cultivated lands and of 0.5–0.4 t CO_2-eq for per ton crop harvested on average of the whole time period of 1993–2007 (Cheng et al. 2011). China's total emissions from energy consumption were estimated to be 7.5 Pg CO_2-eq in 2005 (Anonymous 2012) and 8.4 Pg CO_2-eq in 2007 (Chen and Zhang 2010). The overall carbon emissions from CF of crop production estimated here corresponded to approximately 8 % to the nation's total emissions. Because agriculture (including livestock production) contributed 14 % to the total GHG emissions of the nation, crop production made up more than half of the overall sector.

3.2 Change in CF with Agricultural Development

This work also traced the dynamics of CF during the time period of 1993–2007. Although the total CF showed a linearly increasing trend with increasing crop productivity, mainly with the green revolution using new varieties and chemicals, the carbon intensity from croplands exerted a linear increasing but an exponential decrease from per ton of harvest since 1993. In a consistently upward trend, total CF of China's crop production increased from 346.1 Mt CO_2-eq in 1993 to 516.3 Mt CO_2-eq in 2007, by 49 % over the time span of 1993–2007.

Looking at the contribution of different inputs to the overall CF, on average, two-thirds of the total CF was from agrochemical inputs (Cheng et al. 2011). In

particular, N fertilization averaged 55 % of the total CF, which was very closely linearly correlated with the overall carbon intensity both in terms of lands culti-vated (see Fig. 5 in Cheng et al. 2011). Kahrl et al.(2010) developed a specific emission factor for China's N fertilizer manufacturing and application (5–31 t CO_2-eq t^{-1} N), and argued that large use of synthesized N fertilizers could led to total emissions of 400–840 Mt CO_2-eq in 2005, equivalent to 8–16 % of China's energy-related CO_2 emissions in that year. In their work, sales of all N fertilizers were taken into account for the higher estimation. In general agreement with their findings, the figures of N fertilizer-induced emission here also suggest that a reduction in N fertilizer use in China's crop production will offer a great option to reduce the national total GHG emissions. A reduction in N fertilizer use by 10 % could bring about a reduction in total carbon emission by 5 %, both in terms of land cultivated and mass produced.

Another big proportion was by irrigation energy consumption, which made a mean contribution of 22 % on average. The other inputs such as plastic film use and crop management performance by machinery use were less than 10 % of the total CF for crop production, although they also showed a significantly increasing trend. This first work demonstrated the high CF of China's bulk crop production, which has been characterized by high N fertilization and with an increasing carbon cost for increasing crop production. The high proportion of energy cost for irri-gation highlighted the drought impact on China's crop production, which is increasingly critical due to an increasing drought frequency under the climate change conditions (Pan et al. 2011a; Lv et al. 2011).

Our work (Cheng et al. 2011) also showed that carbon cost or CF was greatly reduced with increasing gross harvest yield per hectare [C intensity (t CO_2-eq t^{-1}) = 0.21 × Yield (t ha^{-1}) − 0.40, R^2 = 0.84, $p < 0.01$]. Gross crop produc-tion was shown in a logarithm increasing function with total carbon cost [Harvest yield (t ha^{-1}) = 11.38 × ln CF (t CO_2-eq ha^{-1}) + 9.83, R^2 = 0.96, $p < 0.01$]. Also, crop production failed to increase beyond a high CF over 0.8 t CO_2-eq ha^{-1} (Fig. 1), indicating a problem of luxury carbon cost of approximately 0.2 t CO_2-eq ha^{-1} with the effort to keep up crop yield with continuously increasing inputs. In other words, increasing inputs is not a practical option to sustaining high yield over a given production capacity threshold. Similarly, Burney et al. (2010) argued that approaches for yield improvements should be cautious for climate change mitigation, as all efforts would not reduce GHG emissions.

4 Carbon Footprint of Staple Crop Production in China

Assessment of the carbon footprint of different staple crop production was done using farm survey data because there were no data in the statistical bureau spe-cifically for different crop production. Questionnaire surveys were conducted to obtain data for the individual inputs used for crop production in representative regions of China's crop production during 2010–2012. A dataset was established
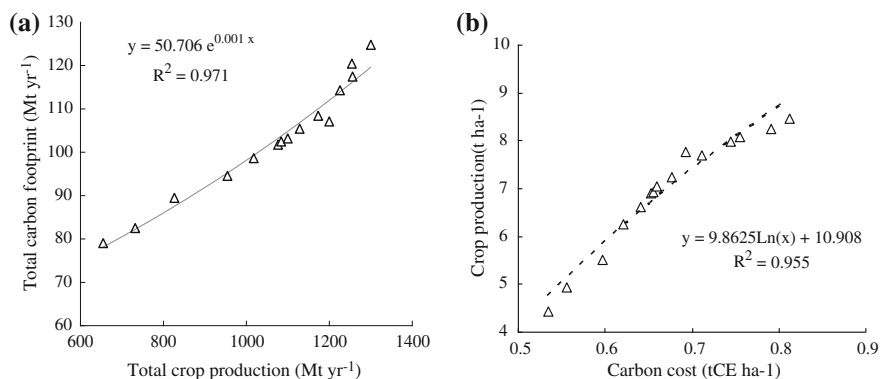
Fig. 1 Total CF in correlation with total harvested crop yield (**a**) and crop yield in correlation to CF (**b**) of China's crop production using agro-statistics data for 1993–2007 (Cheng et al. 2011)

of inputs of chemicals for fertilizers and pesticides and machinery operation for staple crops of rice, wheat, and maize crop from more than 130 household-managed farms over the representative crop production regions; it was used for quantification using the above-mentioned methodology.

4.1 CF of Staple Crop Production

Quantization using the farm survey data allowed a basic estimation of CFs for different crop production for the past years by the individual household farms, with varying size and crop productivity under different management practices.

The estimated mean total carbon emissions for crop production studied here ranged from $2,240.7 \pm 131.9$ kg CO_2-eq ha^{-1} and 326.9 ± 18.3 kg CO_2-eq t^{-1} for maize to $5,795.8 \pm 117.6$ kg CO_2-eq ha^{-1} and 769.0 ± 20.2 kg CO_2-eq t^{-1} for rice production in 2010. For rice, wheat, and maize; total cultivated croplands were 29.8 Mha, 24.2 Mha, and 32.5 Mha, respectively, in 2010 (DRSES-SBSC 2011), possessing 68.4 % of the total harvest area (160.7 Mha) and 80 % of the total grain cropland (109.9 Mha) in China. The yields of rice, wheat, and maize crop production were 195.8 M tons, 115.2 M tons, and 177.2 M tons, respectively, in 2010 (DRSES-SBSC 2011). Accordingly, the mean carbon intensity could be predicted on averaged as 3.7 t CO_2-eq ha^{-1} for overall croplands and 0.58 t CO_2-eq for grain production per metric ton in 2010, respectively. This result corresponded to the high values in the estimated range for bulk crop production reported by Cheng et al. (2011) during 1973–2007. This could be explained by the higher yield and the high input, shown in increasing trend of China's agriculture (Cheng et al. 2011). Hillier et al. (2009) reported a mean CF of 1.6 t CO_2-eq ha^{-1} yr^{-1} for crops in conventional farms in the UK based on survey data collected in 2006. The

CF of these three crop productions seemed much higher than the reported CF of 0.7–0.9 t CO_2-eq ha^{-1} and 0.27–0.42 kg CO_2-eq kg^{-1} of durum wheat grown under various cropping systems in southwest Saskatchewan, Canada (Gan et al. 2011). The higher carbon (C) intensity here demonstrated a high C cost of China's agriculture for achieving a high yield for food security of the nation (Liu and Zhang 2011). This could again be challenged by climate change with the increasing C cost during the period of 1993–2007, as shown in the work by Cheng et al. (2011).

4.2 Difference in CF Between Major Crops

For the three major staple crops surveyed, the CF was averaged (mean ± standard error) of 5,795.8 ± 117.6 kg CO_2-eq ha^{-1}, 3,000.4 ± 185.8 kg CO_2-eq ha^{-1}, and 2,240.7 ± 131.9 kg CO_2-eq ha^{-1}, with carbon intensity in the range of 769.0 ± 20.2 kg CO_2-eq t^{-1}, and 645.6 ± 32.6 kg CO_2-eq t^{-1}, and 326.9 ± 18.3 kg CO_2-eq t^{-1} for rice, wheat, and maize, respectively (Table 4). Clearly, rice production showed the highest C intensity, whereas maize showed the lowest in terms both of land use and grain production. Using the total cultivated croplands and the total year of grain produced, a yearly total C emission from cultivation and production could be estimated approximately as 150–172 Tg CO_2-eq of rice, 73–73 Tg CO_2-eq of wheat, and 58–73 Tg CO_2-eq of maize in 2010, with the rice production being the biggest carbon emitter in the sector of crop production.

Overall, N fertilizer contributed to the total CF by 46 %, 80 %, and 75 %, respectively, for rice, wheat, and maize production and a big portion of energy cost for irrigation and methane emission for rice (Fig. 2). Meanwhile, mechanical operation made up 8 %, 15 %, and 14 %, respectively, for rice, wheat, and maize production. However, a marginal proportion (2–6 %) was occupied by the inputs with pesticides, phosphorus fertilizer, and labor operations for all three crops.

In our analysis, there were relatively small changes in the proportion of individual inputs with the different crops, except for irrigation. For maize crops particularly, input of plastic films contributed 3 % to the total CF. The mean N use rates in the survey data was (mean ± SE) 269.1 ± 9.6 kg N ha^{-1},

Table 4 Carbon footprint (CF) of crop production of rice, wheat, and maize estimated using survey data from 123 household farms over China (mean ± standard error)

| Crop	Farms surveyed	Farm size (ha)	Mean yield (t ha^{-1})	CF in cropland (kg CO_2-eq ha^{-1})	CF in production (kg CO_2-eq t^{-1})
Rice	17	0.1–12	7.6	5,795.8 ± 117.6 [a]	769.0 ± 20.2 [a]
Wheat	48	0.1–12	4.8	3,000.4 ± 185.8 [b]	645.6 ± 32.6 [b]
Maize	58	0.1–2	7.0	2,240.7 ± 131.9 [c]	326.9 ± 18.3 [c]

Different letters indicate significant differences between crops at $p < 0.05$
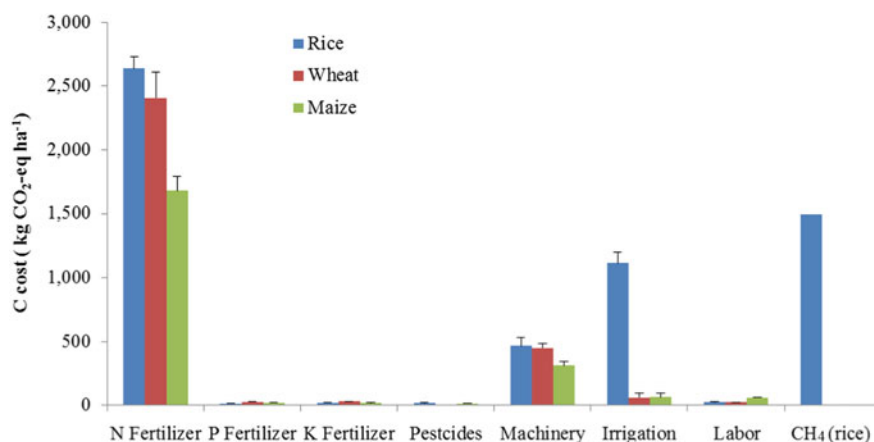
Fig. 2 Carbon cost of individual inputs for rice, wheat, and maize crop production. Data from questionnaire farm survey conducted during 2010–2011

217.5 ± 18.1 kg N ha^{-1}, and 152.0 ± 9.9 kg N ha^{-1}, respectively, for rice, wheat, and maize. CF was shown to be very significantly linearly correlated to N fertilizer use rate for both wheat and maize, but less significantly for rice due to the significant contribution by methane and irrigation-induced emission. However, yield was not observed in a linear positive response to N fertilization in these household-managed farms, reflecting a problem of N in excess. According to the survey data, a high yield (5,000–9,000 kg ha^{-1}) was achieved with N fertilizer use at rates of 200–300 kg N ha^{-1}, although >300 N ha^{-1} inputs did not statistically increase yield when a local conventional yield was approximately 6,000 kg ha^{-1} (Fig. 3). This had been a common problem in China's crop production with the household management system and thus is also a problem for luxury emissions from agriculture.

The total annual N fertilizer-induced direct emissions from the staple crop production could be estimated as 92, 60, and 45 Tg CO_2-eq, giving an overall value of approximately 200 Tg CO_2-eq for the major staple crop production. This value was much less than the estimate by Gao et al. (2011) of 313 Gg N_2O-N in 2007 and by Liu and Zhang (2011) of 403 Tg CO_2-eq for the overall cropland. Therefore, the carbon footprint of China's crop production is largely N-dependent, so reducing N overuse could be a key measure to lower the CF of major crop production in China.
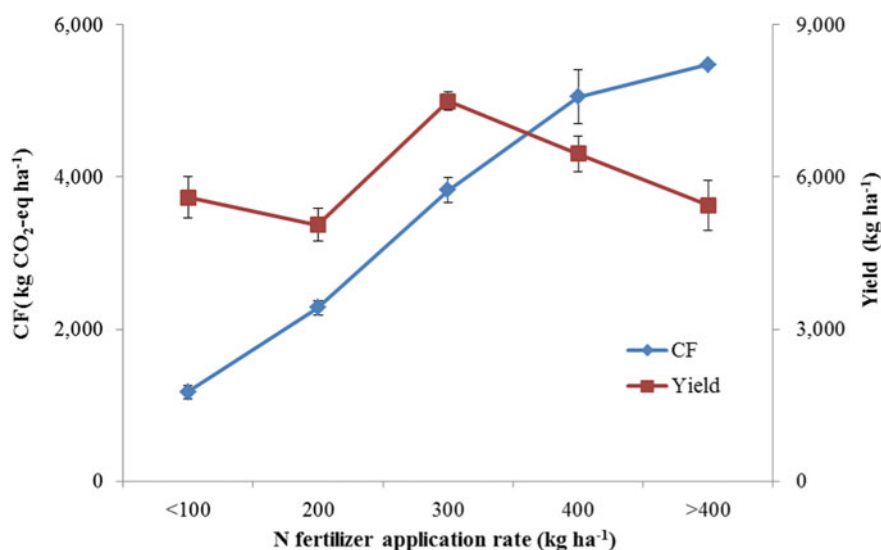
Fig. 3 Variation of carbon cost and yield with nitrogen (N) fertilization of all the farms surveyed. CF, carbon footprint.

5 Carbon Footprint of Vegetable Production

5.1 General Feature of the Carbon Footprint of Vegetable Crops

For assessing the carbon footprint of vegetable crop production in China, a provincial-wide farm survey by questionnaire were done across Jiangsu, China in 2010 following a similar procedure as that for staple crop production. Farmers were individually visited and input data were recorded for individual vegetable crops, including Chinese cabbage (*Brassica chinensis* L.), tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus* Linn), water spinach (*Ipomoea aquatica*), and amaranth (*Amaranthus spinosus* L.). A similar dataset was thus established for accounting use. The yield of the biomass or harvested fruit was much higher for vegetable production than for crops in terms of unit of land used, and inputs were much higher here (Chen et al. 2011; Yan et al. 2013). The estimated carbon cost on average for vegetables ranged from 3,880.4 $\pm$ 3,063.5 to 6,032.4 $\pm$ 366.3 kg CO_2-eq ha^{-1}. However, there was no significant difference in CF between the five types of the vegetable crops in terms of per hectare (Table 5).

As shown in Table 5, the carbon intensity showed a more divergent pattern. Chinese cabbage (496.6 $\pm$ 274.7 kg CO_2-eq t^{-1}) had the highest carbon intensity, whereas water spinach (51.1 $\pm$ 41.5 kg CO_2-eq t^{-1}) had the lowest. However, there was no significant difference in carbon intensity among amaranth

**Table 5** Carbon (C) footprint on average (mean plus standard deviation) for the vegetable crops surveyed

Vegetable	C cost (kg CO_2-eq ha^{-1})	C intensity (kg CO_2-eq t^{-1})
Tomato	6,032.4 ± 366.3 a	168.5 ± 96.7 bc
Chinese cabbage	4,719.0 ± 2,135.8 a	496.6 ± 274.7 a
Cucumber	4,667.3 ± 2,356.2 a	159.0 ± 136.9 bc
Water spinach	3,880.4 ± 3,063.5 a	51.1 ± 41.5 c
Amaranth	5,668.7 ± 3,174.2 a	385.9 ± 249.9 ab

Different letters indicate significant difference between crops at $P < 0.05$

(385.9 ± 249.9 CO_2-eq t^{-1}), tomato (168.5 ± 96.7 CO_2-eq t^{-1}), and cucumber (159.0 ± 136.9 kg CO_2-eq t^{-1}). Clearly, for the carbon intensity of the harvest, vegetable production seemed to have a lower carbon footprint than crop production.

5.2 Proportion of Different Inputs to Total Carbon Cost

Statistics of the input data demonstrated a somewhat different figure of the contribution of different sources to the total CF for the vegetable crops compared to the grain crops as in the above sections. On average of the all vegetables surveyed, 76 % of the total C cost was allocated to nitrogen fertilizer use of inorganic and organic forms (Fig. 4). This is particularly due to high direct emissions of N_2O from N fertilizer, which was estimated using the default factor of 1 % (IPCC 2006). This figure was similar to the estimate of 76 % for food crop production in the UK (Hillier et al. 2009). However, the proportion of 76 % estimated here seems much higher than our previous estimate of 57 % for the overall CF of bulk crop production (Cheng et al. 2011). Among the others, the ground preparation, crop protection, P and K fertilizers, and machinery operations contributed less than 5 % on average to the total carbon footprint (Fig. 4), although this value varied for
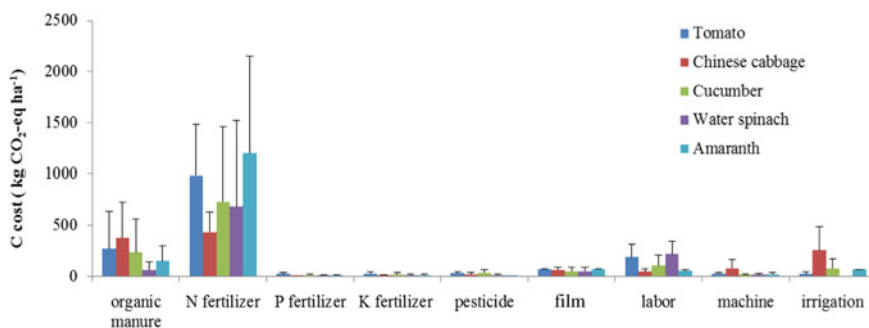
Fig. 4 Carbon cost of individual inputs for vegetable crop production in Jiangsu, China

different vegetable crops. This finding may suggest that mitigation of greenhouse gases emissions from vegetable production may be focused on reducing N fertilizer, although N fertilization in much excess had been already in debt (Zhang et al. 2010). While N fertilizer occupied a dominant proportion, farm operations with labor inputs made a bigger contribution for tomato and water spinach and irrigation made a bigger contribution for Chinese cabbage to their total C cost. In particular, crop management or maintenance may influence not only the total C cost but also the proportion of the different inputs to the overall C cost.

6 From Carbon Footprint to Carbon Management: Future of China's Crop Production

China is experiencing an economic transition from high carbon cost to low carbon for the commitment to reduce GHG emissions per unit of GDP by 2025 on the baseline of 2005 (CCSNARCC 2011), which is a global challenge. Increasing crop productivity will be still a general demand in agriculture development. However, this transition will be further challenged in a trilemma of sustaining high productivity, reducing carbon emissions, and adapting to climate change (Smith et al. 2013). China's ambition to keep stable the production of 0.4 billion ton of grain may have unforeseen difficulty, especially under the vast deterioration of soil fertility due to pollution and soil degradation under intensified cultivation, and especially under the impact of climate change.

The study of CF demonstrated a decreasing trend of intensity with crop productivity, which was not further increased when inputs (carbon costs hereby) were intensified at a background yield of 9 tons after 2003. Rice, a high yield grain crop and of key importance for grain production in China, was already very high in carbon intensity due to irrigation, methane, and N_2O emission. Water stress due to the increasing drought frequency in Northeast and South China (Pan et al. 2011a; Lv et al. 2011) could limit the rice productivity. However, maize was shown to have the lowest carbon intensity, which could be suitable to produce increasing areas of mainland China due to the climate change (Yang et al. 2011). With the help of new verities, crop management practices, and conservation tillage, maize cultivation could reach a high grain yield of over 10–12 ton per hectare. Therefore, to purse a safe and high productivity of China's crops, improving the cropping regionalization and extending maize to potentially suitable lands offers an option to sustain high grain production while stabilizing GHG emissions.

All the different case studies in this chapter revealed that N was the biggest GHG emission contributor in China's agriculture (Table 6). The negative impacts of N fertilizer overuse have been very well addressed. Particularly for GHG mitigation in agriculture, optimum management of N fertilization is urgently required to avoid luxury emissions.

Table 6 A comparison of approximate carbon footprint (CF) of China's crop production (2007–2010)

Sector	Total land used (Mha)	Carbon intensity in land use (tCO$_2$-eq ha^{-1})	Carbon intensity in harvested product (kgCO$_2$-eq t^{-1})	N fertilizer proportion to total CF (%)
Overall crop production	160	2.9	403	55
Staple crop production	110	2.2–5.6	327–769	46–80
Vegetable crop production	20	3.9–6.0	51–497	59

This study also indicated that changes in food consumption could help to establish a lower carbon intensity of crop that is production in China. First, if all rice were replaced by maize, then a total of almost 90 Tg CO$_2$-eq could be avoided without tradeoffs. In addition, consumption of water spinach instead of Chinese cabbage, a vegetable crop not commonly high in nutrition quality but requires a large amount of water from irrigation, would give a reduction in carbon intensity by more than 90 %. Thus, improving diet structure would offer a key option to reduce the carbon footprint of crop production in the future.

In addition, the carbon intensity of crop production could also vary greatly with farm management conditions. Crop yield was lower but carbon intensity was much higher in fragmented farms than in scaled-up farms (Yan et al. 2013). Scaling-up household farms will be another way to sustain high crop productivity with the benefits of reductions in carbon emissions.

Finally, are there any technical measures to sustain crop productivity but reduce GHG emissions in the field? Our studies on biochar soil amendment and biochar fertilizer have indicated a positive answer. Biochar soil amendment could help to increase crop yield in rice paddies by 0–5 % but in dry croplands by 5–25 %, while reducing GHGs emissions by 25–45 % under biochar amendment of 20–40 t ha^{-1} (Zhang et al. 2010, 2012a, b; Joseph et al. 2013). Fortunately, the positive effects by biochar could be sustained for a number of years (Zhang et al. 2012a, c). Because biochar from pyrolysis of crop residue is incentivized by the state to avoid in field burning, production and application of biochar is under development in China (Pan et al. 2011b). This new technology and product input to croplands could be a "new green from black" revolution (Lehmann et al. 2006); thus, it is a priority measure to cut the high carbon footprint of China's crop production.

A number of research opportunities have emerged for carbon management in agriculture. Among these could be the variation of carbon footprint with different cropping and farming systems, with climate conditions and the threshold of N luxury emission for a certain crop. Also, the characterization of carbon intensity in terms of vegetable nutrition value is critical for the assessment of vegetable crops.

It is anticipated that carbon footprinting and carbon management will be further supported in China to better address the carbon cost and improve carbon use for sustainable agriculture and quality of life.

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