Farm and product carbon footprints of China's fruit production - life cycle inventory of representative orchards of five major fruits

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Title: Farm and product carbon footprints of China's fruit production – Life cycle inventory of representative orchards of five major fruits

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Running title: Carbon footprint of China's fruit production

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Abstract

Understanding the environmental impacts of fruit production will provide fundamental information for policy making of fruit consumption and marketing. This study is to characterize the carbon footprints of China's fruit production and to explore the key greenhouse gas emissions to cut with improved orchard management. Yearly input data of materials and energy in a full life cycle from material production to fruit harvest were obtained via field visits to orchards of 5 typical fruit types from selected areas of China. Carbon footprint (CF) was assessed with quantifying the greenhouse gas emissions associated with the individual inputs. Farm and product CFs were respectively predicted in terms of land use and of fresh fruit yield. Additionally, product CFs scaled by fruit nutrition value (*Vc* content) and by the economic benefit from fruit production were also evaluated. The estimated farm CF ranged from 2.9 t CO_2-eq ha^{-1} to 12.8 t CO_2-eq ha^{-1} across the surveyed orchards. Whereas, the product CF ranged from 0.07 kg CO_2-eq kg^{-1} to 0.7 kg CO_2-eq kg^{-1} fruit. While the mean product CFs of orange and pear were significantly lower than of apple, banana and peach, the nutrition-scaled CF of orange (0.5 kg CO_2-eq g^{-1} V_C on average) was significantly lower than others (3.0~5.9 kg CO_2-eq $g^{-1} V_C$). The income-scaled CF of orange and pear (1.20 and 1.01 kg CO_2-eq USD^{-1}, respectively) was higher than apple, banana and peach (0.87-0.39 kg CO_2-eq USD^{-1}). Among the inputs, synthetic nitrogen fertilizer contributed by over 50 % to the total GHG emissions, varying among the fruit types. There were some tradeoffs in product CFs between fruit nutrition value and fruit growers' income. Low carbon production and consumption policy and marketing mechanism should be developed to cut down carbon emissions from fruit production sector, with balancing the nutrition value, producer's income and climate change mitigation.

Key words: Fruit production; Life cycle assessment; Greenhouse gas emissions; Carbon footprint; N fertilizer; Orchard; Low carbon management

Abbreviations: CF, carbon footprint; LCA, life cycle assessment; GHG: greenhouse gas;

Highlights (for review):

- Both farm and product carbon footprints of five major fruit types from China were assessed using orchard survey data;
- Fruit production had high farm but low product carbon footprint relative to cereal production;
- Orange was lower in product and nutrition-scaled carbon footprint but higher in income-scaled carbon footprint among the others;
- Synthetic nitrogen fertilizer use contributed by over 50% to the total carbon footprint;
- High fruit yield with low product carbon footprint sustained under high efficiency management.

Introduction

Global agriculture had been facing a great challenge of accelerated greenhouse gas (GHG) emissions in land use due to excessive agricultural inputs such as fertilizers and pesticides, intensive energy use (Schneider and Smith 2009; Smith et al. 2009; Tilman et al. 2002; Burney et al. 2010). The production, transportation, processing and preparation of food sector contributed 20% to the global anthropogenic GHG emissions (FAO 2012). Particularly, emissions from agricultural production and the associated land use change accounted for 80%-86% of the global total food system emissions (Vermeulen et al. 2012). For assessing environmental impacts of human activities, a full life cycle assessment approach (LCA) had been increasingly used for carbon (Wiedmann and Minx 2008; BSI 2011), water (Pfister et al. 2015) and land (van Kernebeek et al. 2015) footprintings. Based on LCA, a carbon footprint (CF) was a measure of an overall potential climate forcing assessed with all direct and indirect carbon emissions in the full life cycle of a product or an activity (Wiedmann and Minx 2008; BSI 2011). Using such framework, CFs of crop production had been often assessed in order to explore low carbon farming systems or mitigation measures in agriculture (Dubey and Lal 2009; Hillier et al. 2009; Gan et al. 2011; Knudsen et al. 2014; Yan et al. 2015a,b).

In addition to crop production, fruit production had been a key sector of world agriculture, possessing 59.6 million hectares of croplands and producing 676.7 million tons of fresh fruits (FAOSTAT 2013). For the last decade, there had been increasing interests in understanding the environmental impact by the world fruit sector. For example, apple production in fruit farms from eastern Switzerland (Mouron et al. 2006) and New Zealand (Milà i Canals et al. 2006) was analyzed using the LCA methodology to evaluate the variability of different environmental impacts. Using a similar approach, Nemecek et al. (2011) could compare the environmental impacts between integrated and organic farming systems from Swiss and argued that organic farming system was either similar to integrated system in terms of carbon emissions in production or superior to integrated system in terms of resource efficiency and biodiversity in environment benefits. Michos et al. (2012) reported a similar comparative study on GHG emissions between organic, integrated and conventional peach orchards from northern Greece and supported higher energy efficiency and lower GHG emissions by organic farming systems than by conventional ones. While evaluating the CFs of 34 types of fruits and vegetables produced with a large Swiss retailer, Stoessel et al. (2012) argued that environmental impacts by fruit production could be largely reduced by consuming seasonal fruits and vegetables, without additional energy consumption for storage and processing. More recently, Svanes et al (2013) assessed the CF of bananas from cradle to retail and indicated that the GHG emissions from the transport and primary production could be significantly reduced. Thus, LCA carbon footprinting had been a powerful tool to characterize GHGs emissions and to figure out key measures for improving orchard management to cut these emissions, from fruit production.

China's agriculture had been challenged with climate change impacts and mitigation demands for the last decades. Quantified with similar CLA methodology, the works by Cheng et al. (2014) and Yan et al. (2015a) on major grain crops, and by Chen et al. (2011) on vegetables had shown that China's agriculture had been already carbon intensive or carbon insufficient, *vice versa*, largely due to high nitrogen fertilizer application and methane emission in rice paddies (Yan et al., 2015b). Fruit production had been a fast increasing sector in China's agricultural production for the last decade (Su 2012). Producing 154 million tons of fresh fruit excluding melons in 2013, China had been one of the biggest countries of fruit production in the world (FAOSTAT 2013). Contributing by 60% of China's total fresh fruit production were the five major fruit crops of apple, peach, pear, banana, and orange represented (FAOSTAT 2013). For addressing potential environmental impacts, a work by Liu et al. (2010b) quantified the GHG emissions of pear production from conventional and organic farms over the different production chains. They could highlight storage at processing stage and use of synthetic fertilizers in production stage as the major source for GHGs emission of fruit sector. China had committed to cut 25% of the nation's total anthropogenic emissions by 2025 and enforced low carbon approaches in agriculture (NDRC 2012, 2014). So far, little information had been available on the CFs of major types of fruit production of China.

Using farm survey data based on the LCA method up to harvest, the objectives of this study were to (a) quantify the CFs of China's fruit production and (b) evaluate the contributions of different farm inputs to the total CFs, of the five major types of apple, peach, pear, banana and orange. This study also aimed to provide information for policy-makers to identify key options for reducing GHG emissions from China's fruit production.

Materials and methods

Carbon footprinting methodology

Carbon footprint of fruit production was accessed by quantifying the GHG emissions associated with individual inputs for primary production and for orchard management up to harvest (farm gate principle) of yearly fruit production (Fig.1), with a LCA methodology followed in PAS 2050-1 (BSI 2012). Emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) directly or indirectly from all different inputs were accounted and expressed in carbon dioxide equivalent (CO_2-eq) using their relative warming forcing values (IPCC 2007), following a general accounting protocol described by Cheng et al (2015). As a result of carbon footprinting, the arm CF, an indicator of carbon intensity, was expressed in term of land use in t CO_2-eq ha^{-1}, and the product CF as an negative indicator of carbon efficiency in terms of fruit yield (here fresh fruit biomass harvested) in kg CO_2-eq kg^{-1} fruit. Considering the nutrition value of various fruits for consumers and the net income gained by fruit growers, the nutrition-scaled CF in kg CO_2-eq per gram Vitamin C (V_C) provided and the income-scaled CF in kg CO_2-eq per United States Dollar (USD) was respectively evaluated, for further addressing the carbon efficiency of fruit production of China.

Fig.1

Emissions accounting and carbon footprint calculation

Taken into account of carbon footprinting were all the emissions from the manufacturing of the inputs of fertilizers and pesticides for fruit growth, of paper or plastic bags for fruit coverage, emissions caused by farm machinery or associated with irrigation and soil working for orchard management and direct emissions of N_2O caused by applied N fertilizers. The overall carbon footprint of a fruit production was estimated using the following equation:

$$CF_t = \sum(AI_i \times EF_i) \quad (1)$$

where, CF_t, the total carbon footprint, is the cumuli sum of the GHG emissions (kg CO_2-eq) induced by the *i*-th agricultural input; *i*, AI_i *and* EF_i is respectively the kind, the amount (kg for fertilizer, pesticide, plastic and paper bags, or L for diesel oil, or kW h for electricity) and the GHG emission factor (kg CO_2-eq per unit volume or mass) of *i*-th agricultural input or source under accounting. The emission factors (EF_i) of the relevant inputs accounted in the present study are given in Table 1.

Table 1

The direct N_2O emissions from N fertilizer application (CF_N, kg CO_2-eq) were estimated with the following equation:

$$CF_N = AI_N \times EF_N \times \frac{44}{28} \times 298 \quad (2)$$

where, AI_N is the quantity of N fertilizer applied for fruit production (kg); EF_N is the emission factor of N_2O emission induced by N fertilizer application, and 0.01 kg N_2O-N kg^{-1} N fertilizer was adopted from IPCC (2006); *44/28* is the molecular weight of N_2 in relation to N_2O; *298* is net global warming potential (GWP) in a 100-year horizon (IPCC 2007).

Thus, the farm CF (CF_f), expressed in term of land use, was obtained using the following equation:

$$CF_f = \frac{CF_t}{A} \quad (3)$$

where, CF_f is the farm CF (kg CO_2-eq ha^{-1}), *A* is the area (ha) of fruit orchard. Similarly, the product CF (CF_p) was evaluated in terms of fresh fruit yield using the following equation:

$$CF_p = \frac{CF_t}{Y} \quad (4)$$

where, CF_p is the product CF (CF_p) (kg CO_2-eq kg^{-1} fruit); *Y* is the yield of fresh fruit (kg ha^{-1}).

Moreover, considering the nutrition value of various fruits for consumers, the nutrition-scaled CF was further evaluated in terms of vitamin C (*Vc*) provided by fruits, using the following equation:

$$CF_n = \frac{CF_p}{C} \quad (5)$$

where, CF_n is the nutrition CF scaled on vitamin C content(kg CO_2-eq g^{-1} *Vc*), *C* is the vitamin C content provided by fruits (g *Vc* kg^{-1}fruit). According to Yang et al. (2002), an averaged *Vc* content of 4, 7, 6, 8 and 28 milligrams vitamin C per 100 grams of fruit was used for apple, peach, pear, banana and orange, respectively.

In addition, considering the economic income from fruit production, an income-scaled CF_I was calculated with the following equation:

$$CF_I = \frac{CF_p}{I} \quad (6)$$

where, CF_I is the CF scaled on income by selling the fruit produced (kg CO_2-eq USD^{-1}); *I* is the net income from fruit production (USD kg^{-1} fruit). A higher CF_I suggests higher GHG emission efficiency when fruit growers gained the economic income from their fruit production. Here the net income (*I*) was the balance between the total sales revenue of fruits and the production cost from a surveyed orchard, which converted to USD using a mean ratio valid in 2013.

Data collection

Total fresh fruit production in orchards of China reached 228 Mt in 2011, predominated by apple (*Malus pumila Mill.*), banana (*Musa nana Lour.*) orange (*Citrus reticulata Blanco*), pear (*Pyrus spp*), and peach (*Amygdalus persica*) (DRSES –NBSC, 2012). These had been produced typically in provinces respectively of Shanxi, Fujian, Hubei, Hebei, and Shanghai/Jiangsu, of China. In a province typical for a specific fruit production, over 5 representative sites were selected (Fig. 2) via information available on fruit market and a total of 7-10 orchards were randomly visited for each type of fruit production during a field survey conducted in 2012/2013. The selected orchards had been managed by the fruit growers making economic income primarily by producing and selling their fruits. The basic information of the sites surveyed was presented in Table 2. During the survey, data of the agricultural inputs and yields were obtained through interview with responsible farmers who managed the orchards. The recorded data included: (1) size of orchard and annual total fruit production, (2) annual amount of fertilizers, pesticides, paper or plastic bags for fruit covering, electricity for irrigation, labor use, fossil fuel for farm mechanical operations, (3) annual costs for all the agricultural inputs (including labor costs) used in the orchard, and sale price of fruit and the annual income. Overall, valid data from 42 visited orchards (9 for apple, 8 for peach, 10 for pear, 8 for banana, and 7 for orange) were obtained to form a database (Table 3, Table S1).

Fig.2

Table 2

Table 3

Data processing and Statistical analysis

For addressing N fertilization impact on carbon footprint, a parameter of partial factor N productivity was also calculated following the equation:

$$PFP_N = Y/F_N \quad (7)$$

Where, PFP_N is the estimated partial factor N productivity (kg fruit kg^{-1} N), Y is the fruit yield (kg ha^{-1}) and F_N is the total N applied (kg N ha^{-1}) for the fruit season.

One-way ANOVA and the least significant difference test (LSD) were used to check the differences in fruit CF among the different groups. The level of significance was defined at $p < 0.05$. Data processing was performed using Microsoft Office Excel 2011 and all statistical analyses were conducted using JMP Ver. 9.0.

Results

Overall carbon footprint of fruit production

The estimated CFs of fruit production varied in a range of 2.9 - 12.8 t CO_2-eq ha^{-1} across the surveyed orchards. As shown in Table 4, the mean farm CF (CF_f) was highest for banana (9.7 t CO_2-eq ha^{-1}), followed by pear, apple, and orange (8.6, 8.2, and 7.1 t CO_2-eq ha^{-1}, respectively) and lowest for peach (5.9 t CO_2-eq ha^{-1}). Varying in a relatively wider range (0.07-0.7 kg CO_2-eq kg^{-1} fruit), the product CF (CF_p) was lower for orange and pear (0.14 and 0.18 kg CO_2-eq kg^{-1} fruit on average, respectively) than that for apple, banana and peach (0.24, 0.27 and 0.37 kg CO_2-eq kg^{-1} fruit on average, respectively).

However, considering the nutrition value of the different fruit types, orange had the lower nutrition-scaled CF (CF_n) of 0.5 kg CO_2-eq g^{-1}*Vc*, compared to other 4 types of fruits studied (3.0-5.9 kg CO_2-eq g^{-1} *Vc*). Whereas, affected by the economic benefit gained by the fruit growers, the income-scaled CF (CF_I) was 1.20 and 1.01 kg CO_2-eq USD^{-1} on average for orange and pear respectively, which was much higher than for apple, banana and peach (0.87-0.39 kg CO_2-eq USD^{-1}).

Table 4

Contributions of individual inputs to the overall CF

Data of proportions of different inputs to the total CFs is shown in Fig.3. It was obvious that fertilizer application contributed the most, with the lowest for apple (by 49%) and the highest for orange (by 81%). Across the surveyed orchards, almost 95% of the fertilizer induced emissions was by synthetic N fertilizer while organic fertilizer accounted for less than 4% of the total GHG emissions. Moreover, the product CFs of the surveyed orchards were shown very significantly correlated to the N fertilizer application rates across all the surveyed orchards (Fig.4). However, the product CFs were observed to decrease with the enhanced partial factor N productivity across these orchards (Fig. 5).

Use of pesticides was seen as an important contributor, second to fertilizer, being the lowest for banana (4%) and the highest for peach (26%). In addition, irrigation management made also a significant contribution to the overall CFs for banana, apple and pear, accounting for 23%, 21% and 14% of their total GHG emissions respectively. Emissions with irrigation were induced by machineries pumping surface water for banana in southern China but mostly underground water for pear and apple in northern China, generally with furrow irrigation in the orchards. However, irrigation was not a player in the farm CF for peach and orange. Besides, accounting for less than 8% of the total GHG emissions, bag coverage made a small contribution to total CF for the fruits except for orange. Fossil fuel use for farm mechanical operations also contributed by 9% and 17% to the total CF for apple and pear, respectively.

Fig. 3

Fig. 4

Fig. 5

Carbon footprint difference between management systems

While plotting the product CFs against fresh fruit yields using the whole data, there was an overall very significant negative correlation of product CFs to fresh fruit yield (Fig. 6). When grouping by the fruit types, however, such negative correlation was valid for apple (Fig.6a) and banana (Fig. 6b) production but not in peach, pear and orange production (Fig.6c-e). Based on the information from Fig. 5 and Fig. 6f, orchards surveyed were divided into low and high management efficiency systems (Table 5). Consequently, higher fruit yields but lower product CFs were found under high efficiency management compared to low efficiency management. There were some differences in GHG intensities from individual inputs between orchard managements. In particular, inputs of fertilizers and irrigation exerted higher GHG intensities under low efficiency management than under high efficiency management.

Fig. 6

Table 5

Discussions

GHG emissions from fruit production

In this study, there were wide variation of carbon footprints across the surveyed orchards, with a range of 2.9-12.8 t CO_2-eq ha^{-1} in farm CF and of 0.07-0.7 kg CO_2-eq kg^{-1} fruit in product CF, respectively. On average, the product CF was 0.24, 0.27, 0.14, 0.37 and 0.18 kg CO_2-eq kg^{-1} fruit respectively for apple, banana, orange, peach and pear. The mean CFs in arrange of was similar to the fruit sector from Switzerland in a range of 0.08-0.36 kg CO_2-eq kg^{-1}, which included the emissions in cultivation, storage and distribution (Stoessel et al. 2012). In a work by Liu et al. (2010b), Chinese pear production under different farm types was shown CFs in a range of 0.06-0.38 kg CO_2-eq kg^{-1} fruit though the emissions involved in sorting and storage post production was accounted. Production of banana from cradle to retail was shown at a GHG emission cost of 1.37 kg CO_2-eq kg^{-1} fruit on average, of which only 16% was exhausted with primary production in orchard (Svanes et al. 2013). However, quantified by Milà i Canals et al. (2006), apple production was seen much lower in CFs in New Zealand, ranging from 0.04 kg CO_2-eq kg^{-1} to 0.10 kg CO_2-eq kg^{-1}. Compared to these reported CFs from western countries and other regions of the world, primary production of China's fruit sector seemed already carbon intensive in land use and carbon inefficiency in product. Thus, China's fruit production could likely lead to higher impacts on climate change than the western countries. The high carbon intensity raised a big challenge for the sustainability of the fast increasing sector concerning both the environmental impacts and the livelihood for almost 100 million farmers (Su, 2012).

The averaged farm CF and product CF was in a range of 5.9-9.7 t CO_2-eq ha^{-1} and of 0.14 – 0.37 kg CO_2-eq kg^{-1} fruit respectively, across the major fruit types. Farm CF, carbon intensity in land use of fruit production, was found in a range of 2.9-12.8 t CO_2-eq ha^{-1} across the orchard surveyed. The farm CFs were 9.7, 8.6, 8.2, and 7.1 and 5.9 t CO_2-eq ha^{-1} on average respectively for banana, pear, apple, and orange and peach. In our previous works, the mean farm CF of rice, wheat and maize was 6.0, 3.0 and 2.3 t CO_2-eq ha^{-1} using farm survey (Yan et al. 2015a) and 9.0, 2.9 and 2.9 t CO_2-eq ha^{-1} using statistical data (Cheng et al., 2014), and of vegetables in a range of 3.2-7.5 t CO_2-eq ha^{-1} from a regional survey (Chen et al. 2011). Obviously, orchards for fruit production studied here could be concerned highly carbon intensive land use compared to grain production. However, this was not the case for product CF. Respectively of rice, wheat and maize, a mean product CF was predicted of 0.80, 0.66 and 0.33 kg CO_2-eq kg^{-1} in a farm survey study by Yan et al (2015a) and of 1.36, 0.51 and 0.44 kg

CO_2-eq kg^{-1} in a study using statistical data by Cheng et al. (2014). Comparatively, the product CFs of fruit production here, scaled by fresh fruit yield harvested, were lower than these estimates for grain production of China. Therefore, fruit production in terms of harvested fresh fruit was relatively higher carbon efficiency than grain production in China. Up to 2013, a total of 154 million tons of fruit was produced in a total fruit production area of 13.2 Mha (NBSC 2014). A potential carbon emissions from the primary production of these fruits could be predicted only 15.5 Mt CO_{2-}e in 2013. In comparison, a potential carbon emission of 438 Mt CO_{2-}e was predicted for 556 Mt total grain production of rice, wheat and maize, exhausting a total cropland of 88.6 Mha, of China in 2011 (Cheng et al., 2014). Of course, the potentially increasing carbon emissions with the fast increasing fruit cultivation should be given much attention for its high emission intensity in land use in China's agricultural production sector.

Mitigation options in fruit production

Of the total CF, fertilizer use made a major contribution across the fruit types. Fertilizer induced GHGs possessed half of the CF for apple and pear and almost 70% for peach and banana up to 90% for orange. Overall, the GHG emissions from N inputs through synthetic fertilizer application contributed by 47%-75% (93-204 kg CO_2-eq t^{-1} fruit) to the total GHG emissions. N fertilizer induced emissions was in a proportion of 70%-80% to total CF for conventional pear production at the farm gate from China (Liu et al. 2010b). In apple production from New Zealand, less fertilizer use contributed about 25%-51% to the total GHG emissions (Milà i Canals et al. (2006).

In this study, synthetic N fertilizer use was seen playing a determinant role in overall carbon footprint of primary production of China's fruit (Fig. 3). An excessive N input (297-567 kg N ha^{-1}) was seen in our surveyed orchards and such luxury N input led to a high emission from N fertilizer (3.3-6.3 t CO_2-eq ha^{-1}, Fig. 5). Particularly, N-fertilizer input for apple here (348 kgN ha^{-1} on average) seemed very high compared to that of 62 kg N ha^{-1} on average used in apple orchards from Switzerland (Mouron et al. 2006). However, fresh apple yield was similar between this study (37 t ha^{-1} on average) and the study by Mouron et al. (2006) (31 t ha^{-1} on average). The issue of excessive N input applied for fruit cultivation in China was also critically concerned with other studies (Zhao et al. 2012, 2013; Ju et al. 2006). In an extensive survey of 6863 Chinese fruit orchards, Zhang et al. (2013) reported an excessive N fertilizer as much as 550 kg N ha^{-1} on average for an average fruit yield of 36.7 t ha^{-1}. Similarly, in a survey of 34 apple orchards, Ju et al. (2006) reported a high N application rate up to 661 kg N ha^{-1} on average. All these again evidenced that China's fruit production had been already N excessive and thus highly carbon intensive, being similar to China's cereals production (Cheng et al., 2011; Yan et al., 2015a).

While the product CF largely depended on N application rate (Fig. 4), increasing partial factor N productivity (PFP_N) led to a sharp decrease in product CF (Fig.5). The overall product CF could decrease to as low as 0.2 t CO_2-e per ton fresh fruit produced when PFP_N reached up to 100 kg fresh fruit per kg N. Zhang et al. (2009) considered an application rate of 150-250 kg N ha^{-1} suitable for fruit production in China. Recently, Zhao et al. (2012) recommended N fertilization in a range of 240-360 kg N ha^{-1} for apple yield in a range of 25-45 t ha^{-1} across China, based on the results from their experiment and expert design of fruit orchard fertilization. Therefore, to reduce N application rates with enhanced N efficiency would be of priority demand to cut greenhouse gas cost of China's fruit production. According to the comparison in Table 5, high fruit yield could be sustained even N fertilization greatly reduced. Generally, 15%-24% of GHG emissions could be avoided when 30% of N inputs could be saved in the surveyed orchards. Among the potential measures to save synthetic N fertilizer use, increase the relative proportion of manure of the total fertilizers used could help increase fertilizer use efficiency and thereby reducing GHG emissions (Zhang et al. 2013). Organic manure amendment at 40-60 t ha^{-1} could be suitable for fruit cultivation in China (Zhao et al. 2012, 2013; Wang et al. 2013). Application of chemical fertilizers combined with organic manure could not only increase the fruit yield but also improve fruit quality (Zhao et al. 2013). Best farm management practices to enhance orchard productivity could also help reduce the product CF, which was in a significantly negative correlation to fresh fruit yield for apple and banana (Fig. 6). Data in Table 5 depicted a great a great potential to increase fruit yield through improving orchard management. With low efficiency management, mean fruit yield of 33 ton per hectare exhausted N induced emission of almost 200 kg CO_2-eq per ton fresh fruit produced. With high efficiency management, however, an overall mean fruit yield of 46 t ha^{-1}, could be reached at a N-induced emission cost of 72 kg CO_2-eq per ton fresh fruit produced. This is very close to a N emission cost of 82 kg CO_2-eq per ton of fruit in the study by Mouron et al. (2006). In the present study, improving by15% fruit yield could save GHG emissions by about 13% on average. Overall, the important options for mitigating environmental impacts in China's fruit production included reducing the synthetic N application and increasing organic manure use, improving N fertilizer use efficiency as well as other good management practices to increase fruit yield.

Low carbon production and consumption of fruit

In 2013, consumption of fresh fruits reached 37.8 kg per capita in China (NBSC 2014), compared to the mean of 61 kg globally and of 83 kg in OECD countries. China launched a national planning for people's nutrition in 2014, which aimed to realize a target of 60 kg per capita per year of fresh fruit consumption in 2020 (SCC 2014). Low carbon dietary consumption had been advocated for balancing the food supply and land exploitation (van Kernebeek et al. 2015). The total fruit consumption of fruit planned for 2020 would result in a total carbon emission of 18.7 Mt CO_2-eq, using the mean product CF value (0.24 kg CO_2-eq kg^{-1} fruit) here. However, if orange, high in Vc but low in product CF, could be chosen for fruit consumption, a total of 8 million ton of CO_2-eq would be saved. This would be even saving land, since orange was generally most productive among the surveyed fruit types (Table 4). It would be particularly important for China for its cropland area had been already tightening due to its fast urbanization. Of course, low carbon fruit could not necessarily bring high income for fruit producers (Table 4). This issue had been considered with marketing mechanisms such as low carbon labelling or even potential carbon tax (Cros et al. 2010; Jungbluth et al. 2011). China had a great ambition to cut its huge GHG emission and recently launched a national strategy for tackling climate change. For this, low carbon dietary consumption had been recommended among a couple of attainable approaches (NDRC 2014). To compensate the carbon benefits to climate mitigation, national incentives or marketing mechanisms should be to develop. Overall, low carbon production and consumption should be encouraged so that fruit production could be sustained not only for climate change mitigation but also for land sustainability for a great country with huge population. Nevertheless, there is still a knowledge gap as how to balance fruit yield and quality, the environment impacts, fruit grower's income and human nutrition intake from agro-products.

Conclusions

The fruit production was characterized by a high farm carbon footprint but a relative low product carbon footprint compared to grain production in China's agriculture. Orange had a lower product carbon footprint but higher income- and nutrition (*Vc content*)-scaled carbon footprint than apple, banana and peach. Synthetic N fertilizers contributed over half to the total greenhouse gas emissions from primary production of fruit and reducing synthetic N fertilizer application should be of priority demand to cut greenhouse gas emission from the fruit production sector. In addition, there could be tradeoffs in product CF between nutrition and economic income. However, to stabilize or even to cut carbon emissions and to save the land of fruit production sector, national policies and market mechanism for low carbon dietary consumption should be developed. For this, how to balance nutrition requirement and incomes for fruit growers is still a great challenge.

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Figure captions

Fig.1 System boundary of fruit production in this study.

Fig.2 Site location of the apple, peach, pear, banana, and orange orchards surveyed (The value in parenthesis is the number of orchards surveyed).

Fig.3 Contribution of individual inputs to the total GHG emissions.

Fig.4 Correlation of the product carbon footprint (CF) with N fertilizer application rate (a, apple; b, banana; c, orange; d, peach; e, pear and f, total).

Fig.5 Change in product carbon footprint (CF) with the partial factor productivity from applied N (PFP_N) (a, apple; b, banana; c, orange; d, peach; e, pear and f, total).

Fig.6Correlation of the product carbon footprint (CF) with fruit yield.