Optimization of Different Carbohydrate-rich Foods Combining Carbon Footprint and Nutritional Value

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Abstract. Background: The food system significantly contributes to global carbon emissions. Carbohydrate-rich (CR) foods are very important components of Chinese traditional foods. However, it is often neglected because animal-based foods are considered as more efficient to reduce GHG emissions. Optimized dietaries through linear programming considering nutrients intake and carbon emissions have raised attention of many researchers. Objectives: This study was highlighted on the carbon emissions of 19 common CR foods consumption in China and tried to develop a sustainable dietary scenario that can be both environment friendly and healthy. Results: Results showed that when providing sufficient nutrients, optimized refined grain produced much higher carbon emissions than the current CR food diet. A theoretical dietary pattern and a realistic dietary pattern could reduce carbon emissions significantly. Rice and tailored flour consumption substituted by whole grains, beans and tuber foods can both reduce GHG emissions and increase nutrients intake. Due to the demand difference in nutrients, dietary structure of males and females were significantly different. Conclusion: The importance of this study was showed implied potential for reducing carbon emissions from CR foods that was neglected usually. Besides, sustainable CR foods dietary patterns also generated to combine ecological and nutritional aspects.

1. Introduction

Reducing greenhouse gas (GHG) or carbon emissions has aroused widely attention all over the world. Previous studies highlighted on technology or production departments (Ganda, 2019). One important direction to reduce carbon emissions is through technological methods such as optimizing fertilizers inputs or enhancing the production capacity of per unit emissions generated (Wener, 2009). Technological method was useful whereas improvements could reach the ceiling in a period of time (Thorburn et al., 2010). On the other hand, carbon emissions from food consumption are usually neglected, although it takes up about 30% global GHG emissions (Garnett, 2011). To identify the most environment-friendly foods, studies have evaluated emissions from different dietary patterns, i.e., four dietary patterns in Italy (Pairotti et al, 2015), seven patterns in Canada (Veeramani et al., 2017), and six patterns in the Netherlands (van Dooren et al., 2014). A study by Hallström et al. (2015) has concluded that diet with animal-based foods consumption exerts the largest emissions, followed by
vegetarian diet (avoiding all the meats), and vegan diet (none animal based productions) produced the least impacts on the environment. Reducing carbon emissions by foods substitution or reducing meats intake level has been demonstrated by Song et al. (2017), in which set nine diet scenarios with different level of meats and dairy products consumption, and results showed that utmost 28% reduction in emissions compared to current diets can be reached. Recommendation for improving food choices to reduce GHG emissions must be balanced against dietary requirements for health (Macdiarmid et al., 2012). Lots of studies have investigated the environmental impacts of healthier diets (Arnoult et al., 2010). Sustainable diet was defined as the diet with low environmental impacts and enough nutrition (Burlingame and Dernini, 2012). In 2010, according to the report issued by Food and Agriculture Organization (FAO), sustainable diets have great potential to settle the combination of environment and healthy, which was defined as the diets with low environmental impacts that contribute to food and nutrition security and to healthy life for present and future generations. Studies have established sustainable diets through setting certain criteria to reach the reduction goals (Vieux et al., 2012). Linear programming is a very useful tool to arrive at optimized goal with different constrains. Diet optimization combining low price, low climate impact, and high nutritional value was carried out by linear programming, and the results showed that 63 popular and low-price basic products could meet all requirements (van Dooren et al., 2015).

Generally, reducing carbon emissions by foods substitution highlighted on reducing meats intake level (Song et al., 2017). Although results showed that change ratio of meat in current diets was beneficial to environment (Vieux et al., 2012), a study by Macdiarmid et al. (2016) showed that consumers were reluctant to eat less meat. On the other hand, carbohydrate-rich (CR) foods, as the main energy source of Chinese people, include cereals, beans, and tuber foods. According to the information from NBS (2018), consumption of CR foods was 130.1 kg per capita in 2017. The study from Xu et al. (2018) has approved that rice products and tailored wheat flour are higher carbon footprints (CFs). Considering the population of China, consumption of CR foods also laid a great burden on the environment, which was often ignored by public (Garnett, 2011).

GHG emissions of China were still ranked the highest in the world. Although it is of great significance to carry out sustainable CR foods consumption patterns in China, the relevant researches are still in fancy. Thus, the main objectives of this study were to develop sustainable patterns of CR foods consumption among Chinese men and women through linear programming, and to evaluate the potential of reducing carbon emissions compared to the current diet.

2. Methodology

2.1. Nutrition data

Nineteen most common CR foods in Chinese diets were chosen in this study and were aggregated into 4 groups (polished rice & wheat flour, whole grains, beans except soybeans, and tuber-food) in accordance with the Chinese dietary guidelines, which are shown in Table 1. Surveys were conducted in 2010-2012 to investigate proportions of nutrients in Chinese diets, and results showed that 10 nutrients (protein, carbohydrate, vitamin B1, vitamin B2, niacin, magnesium, iron, calcium, potassium, and zinc) from CR foods were took up over 20% in the whole diets. These 10 nutrients and energy were adopted as nutritional indices for calculation, and their contents were from the China Food Composition (CFC) (Yang et al., 2009).

2.2. Carbon footprints data

Carbon footprints (CFs) was established to measure and communicate GHG emissions related to consumer product. CF calculated according to life cycle assessment (LCA) method is usually used as an expression of total amounts of GHG or carbon emissions during the whole food-provision chain. Up to now, a CF database established by Barilla Center for Food & Nutrition (2012) has illustrated thousands of food CFs studies through LCA methodology. However, difference in life cycle boundaries and calculation formation lead to varieties in CF values for the same kind food. Besides,
coarse foods like avena nuda and sorghum which are the important parts of Chinese diets were hardly found in former researches. To conclude more scientific and accurate conclusions, the data by Xu et al. (2018) were adopted in this study, which covered CR foods consumed frequently in China. Detail information was illustrated in Table 1 and Table 2.

Table 1. The CF (Xu et al., 2018), energy, protein, carbohydrate, vitamin B1, and vitamin B2 content of CR foods per 100 g (Yang et al., 2009)

| Groups | Foods                  | GHG (kg CO2eq) | Energy (kcal) | Protein (g) | Carbohydrate (g) | Vitamin B1 (mg) | Vitamin B2 (mg) |
|--------|------------------------|----------------|---------------|-------------|------------------|-----------------|-----------------|
| G1     | Rice with top grade    | 0.28992        | 343.96        | 8.59        | 76.36            | 0.11            | 0.07            |
|        | Polished rice (second) | 0.22301        | 343.98        | 9.04        | 74.96            | 0.19            | 0.07            |
|        | Tailored flour         | 0.12233        | 350.00        | 10.30       | 74.60            | 0.17            | 0.06            |
|        | Wheat flour (second)   | 0.10605        | 349.00        | 10.40       | 74.30            | 0.15            | 0.08            |
| G2     | Corn cob               | 0.05910        | 335.00        | 8.70        | 66.60            | 0.21            | 0.13            |
|        | Maize flour            | 0.10255        | 340.00        | 8.10        | 69.60            | 0.26            | 0.09            |
|        | Millet                 | 0.10611        | 358.00        | 9.00        | 73.50            | 0.33            | 0.10            |
|        | Millet flour           | 0.11229        | 356.00        | 7.00        | 77.00            | 0.00            | 0.00            |
|        | Standard wheat flour   | 0.09384        | 344.00        | 11.20       | 71.50            | 0.28            | 0.11            |
|        | Sorghum flour          | 0.10294        | 351.00        | 10.40       | 70.40            | 0.29            | 0.10            |
|        | Buckwheat flour        | 0.16042        | 304.00        | 9.70        | 60.20            | 0.32            | 0.21            |
|        | Brown rice             | 0.17932        | 448.75        | 12.38       | 93.50            | 0.18            | 0.06            |
| G3     | Avena nuda flour       | 0.19201        | 385.00        | 12.20       | 67.80            | 0.39            | 0.04            |
|        | Mung bean              | 0.12148        | 316.00        | 21.60       | 55.60            | 0.25            | 0.11            |
|        | Mung bean flour        | 0.12684        | 330.00        | 20.80       | 55.00            | 0.00            | 0.00            |
|        | Azuki bean             | 0.11714        | 309.00        | 20.20       | 55.70            | 0.16            | 0.11            |
|        | Azuki bean flour       | 0.12250        | 309.00        | 20.20       | 55.70            | 0.16            | 0.11            |
| G4     | Potato                 | 0.02240        | 76.00         | 2.00        | 16.50            | 0.08            | 0.04            |
|        | Sweet potato           | 0.02725        | 99.00         | 1.10        | 23.10            | 0.04            | 0.04            |

Table 2. The niacin and mineral content of these CR foods per 100 g (Yang et al., 2009)

| Groups | Foods                  | Niacin (mg) | Magnesium (mg) | Iron (mg) | Zinc (mg) | Calcium (mg) | Potassium (mg) |
|--------|------------------------|-------------|----------------|-----------|-----------|--------------|----------------|
| G1     | Rice with top grade    | 1.55        | 34.87          | 0.80      | 2.00      | 6.00         | 107.49         |
|        | Polished rice (second) | 2.80        | 69.32          | 1.92      | 2.00      | 6.00         | 158.26         |
|        | Tailored flour         | 2.00        | 32.00          | 2.70      | 1.00      | 27.00        | 128.00         |
|        | Wheat flour (second)   | 2.00        | 48.00          | 3.00      | 1.00      | 30.00        | 124.00         |
| G2     | Corn cob               | 2.50        | 96.00          | 2.40      | 2.00      | 14.00        | 300.00         |
|        | Maize flour            | 2.30        | 84.00          | 3.20      | 1.00      | 22.00        | 249.00         |
|        | Millet                 | 1.50        | 107.00         | 5.10      | 2.00      | 41.00        | 284.00         |
|        | Millet flour           | 2.00        | 57.00          | 6.00      | 1.00      | 40.00        | 129.00         |
|        | Standard wheat flour   | 2.00        | 50.00          | 3.50      | 2.00      | 31.00        | 190.00         |
|        | Sorghum flour          | 1.60        | 129.00         | 6.30      | 2.00      | 22.00        | 281.00         |
|        | Buckwheat flour        | 1.50        | 94.00          | 4.40      | 2.00      | 39.00        | 320.00         |
|        | Brown rice             | 6.25        | 79.00          | 6.38      | 3.75      | 16.25        | 267.50         |
|        | Avenanuda flour        | 3.90        | 146.00         | 13.60     | 2.00      | 27.00        | 319.00         |
| G3     | Mung bean              | 2.00        | 125.00         | 6.50      | 2.00      | 81.00        | 787.00         |
|        | Mung bean flour        | 0.70        | 0.00           | 6.10      | 3.00      | 74.00        | 750.00         |
|        | Azuki bean             | 2.00        | 138.00         | 7.40      | 2.00      | 74.00        | 860.00         |
|        | Azuki bean flour       | 2.00        | 138.00         | 7.40      | 2.00      | 74.00        | 860.00         |
| G4     | Potato                 | 1.10        | 23.00          | 0.80      | 0.00      | 8.00         | 342.00         |
|        | Sweet potato           | 0.60        | 12.00          | 0.50      | 0.00      | 23.00        | 130.00         |

2.3. Linear programming

Linear programming is an algorithm that can generate optimal choice under certain constrains. In this study, linear programming was adopted to optimize diets for Chinese men and women with qualifying low carbon emissions and nutrients criteria (Dantzig and Thapa, 1997). The models were set as below:

$$GHG_i = \sum_{j=1}^n x_i CF_j$$  (1)
Where GHG<sub>t</sub> was the total carbon emissions of food (kg CO<sub>2</sub>eq); X<sub>i</sub> was the amount of food i consumption per day (kg); CF<sub>i</sub> was the CFs of food i, which is calculated by Xu et al. (2018).

\[ N_{tu_j} = \sum_{i=1}^{n} x_i a_{ij} \]  

(2)

\[ RNI_j \leq N_{tu_j} \leq UIL_j \]  

(3)

Where N<sub>tu</sub> is the total amount of 10 nutrients, and j=1, 2, 3, ...or 10; a<sub>ij</sub> represents the content of nutrient j per edible 1 kg. According to the study of Song et al. (2017), the upper and lower bounds of nutrients intake were set as Tolerable Upper Intake Level (UIL) and Recommended Nutrient Intake (RNI) in order that radical changes in CR foods consumption could be avoided which may lead to unhealthy situation.

\[ E_{\text{min}} \leq \sum_{i=1}^{n} x_i e_i \leq E_{\text{max}} \]  

(4)

Because CR foods is the main energy source, accounting for 50 % to 65 % of total energy requirement (CNS, 2016), energy from CR foods should be constrained at the same time. Chinese adults under 65 years old are suggested to intake 2250 kcal d<sup>-1</sup> for men and 1800 kcal d<sup>-1</sup> for women (CNS, 2016). Thus, the energy intake limitation of CR foods E<sub>min</sub> equals 50 % of 2250 kcal d<sup>-1</sup> for men and 50 % of 1800 kcal d<sup>-1</sup> for women, and E<sub>max</sub> was 65 % of 2250 kcal d<sup>-1</sup> for men and 65 % of 1800 kcal d<sup>-1</sup> for women. In this research, e<sub>i</sub> of each 19 CR foods came from the China Food Composition (Yang et al., 2009).

In addition, the diet should be constrained by those limitations simultaneously:

\[ C_{\text{min}} \leq \sum_{i=1}^{n} x_i \leq C_{\text{max}} \]  

(5)

| Group Number | Group Name | Constraints lower | Constraints upper |
|--------------|------------|-------------------|-------------------|
| G1           | Polished rice & wheat flour | 150              | 150               |
| G2           | Whole grains       | 50                | 150               |
| G3           | Beans (excluding soybeans) | 50                | 100               |
| G4           | Tuber foods       |                   |                   |
| Total        |              | 250               | 400               |

Consumption of each group should be in a certain range respectively (CNS, 2016). The detail lower bound (C<sub>min</sub>) and upper bound (C<sub>max</sub>) were shown in Table 3. Consumption constrains of G2 and G3 in Table 3 were merged into one item.

The principle of dietary guidelines for Chinese residents was to encourage people to consume more types of food (CNS, 2016). Thus, 19 CR foods should join the daily diet. In this study, at least 5 g for each food per day was eaten by Chinese residents.

\[ x_i \geq 5 \]  

(6)

2.4. Three scenarios

This study aims to develop sustainable patterns of CR foods consumption, and three scenarios were considered. The first scenario is optimized diet considering the G1 foods. The diet was constrained by 10 nutrients intake. The second scenario is the optimized diet constrained by recommended weight, energy, and nutrient intake. The optimized diet included 19 types of foods. The third scenario is the
optimized diet restrained by recommended weight, energy, and nutrient intake. The third diet included at least one type of food in each of the four groups (Table 3).

3. Results
Optimized diets under nutritional requirements and food types are shown in Table 4. In the first scenario, only G1 foods were considered. When food weight and nutrient constrained was considered, no optimized scheme was found. The main function of food was to provide nutrients, thus, only 10 nutrient constraints were used in this dietary pattern. The results showed that wheat flour (second) was largely consumed. Because of less polishing process, wheat flour (second) contains more nutrients and produces fewer emissions from machine use. Rice and tailored flour were consumed at their own minimum limits. The results showed that total amounts of G1 foods were much larger than the recommended range (250-400 g). In scenario 2, wheat flour (second) was still better choice among G1 foods. Due to lower CF values, wheat flour (second) was consumed in great quantities. In G2, millet and avena nuda flour products should pay more attention by males, accounting for 57.38 % of total G2 foods in grams. While corn cobs and buckwheat flour products were significant to females, accounting for 56.10 %. In Group 3, mung beans were recommended for both genders. However, a huge discrepancy was shown in different gender between Group 4. Consumption of potatoes was 95 g per day for men, which can be both nutritious and environmental-friendly. However, amount of potato was only 5 g for women, and sweet potato increased from 5 to 91 g. Compared to the scenario 2, the same trend was shown in scenario 3, i.e., the foods with higher CF were removed. However, more kinds of foods were consumed by males compared to females. Group 1 was traditional staple foods in Chinese foods, and in this group rice with top grade, polished rice (second), and tailored flour were completely removed. Intake of whole grains and beans were help to keep nutrients balance. For G2 foods, millet took the top spot in male diet, while the consumption of corn cob was the largest in female diet. For G3 foods, mung bean was the only chosen food. In addition, consumption of G3 foods in female diet was 73 g, which was higher than that of male. For G4 foods, consumption trend was similar to that in scenario 2. The males should consume more potato, and females should consume more sweet potato. The results in Table 4 showed that due to the demand difference in nutrients, dietary structure of males and females were significantly different.

The total carbon emissions from three scenarios were also illustrated in Table 4. These patterns showed potential of reducing emissions through changing ratios of some foods. A study on carbon emissions from Chinese healthy dietary showed that emissions from grains and beans were about 225 g CO₂eq (Xu and Lan, 2016), however, in this research, at least 325.7 g CO₂eq were produced. The reason that causes the difference is that CFs of grains have large discrepancy. For the study of Xu and Lan (2016), carbon emissions value was calculated by using the weighted average CF factor for each food category. Besides, different consumption data are adopted, which could lead to difference in statistics. Song et al. (2017) showed that rice, wheat, legumes, and other cereals are totally consumed 501 g d⁻¹, which produced about 1200 g CO₂eq d⁻¹. Using the same CF data source, Yang et al. (2019) showed that total carbon emissions by CR foods in Chinese current diets was 683.38 g CO₂eq per day per capita. The main compounds of Chinese diets are rice and wheat flour products (Batis et al., 2014). Considering only G1 foods, optimized diet in scenario 1 in this study can increase about 19.56 % of total carbon emissions. In addition, the energy provided by optimized G1 foods (2635.08 kcal) was also larger than the recommended range (900-1462.5 kcal). Scenario 2 included 19 CR foods in the diet, which should be implemented within a short period of time. It could be considered as a theoretical pattern. Optimized diet in scenario 2 could reduce about 42.61 % of total carbon emissions for the males and 44.50 % for the females. Compared to scenario 2, scenario 3 was easier to be carried out, and more emissions were reduced. Scenario 3 could be considered as a realistic pattern.

Table 4. Food consumption per day (g) under three scenarios

| Groups | Foods                | Scenario 1 Consumption per day (g) | Scenario 2 Consumption per day (g) | Scenario 3 Consumption per day (g) |
|--------|----------------------|------------------------------------|------------------------------------|------------------------------------|
|        |                      | Male | Female | Male | Female | Male | Female |
| G1     | Rice with top grade  | 5.0  | 5.0    | 5.0  | 5.0    | 0.0  | 0.0    |
4. Conclusions
CR foods are very important components of Chinese traditional foods, are the most important energy sources for human body. However, it is often neglectable element because animal-based foods are considered as more efficient to reduce GHG emissions. In this research, linear programming was used for diet optimization of different CR foods combining carbon emissions and nutritional value. The results showed that when to provide sufficient nutrients, optimized G1 foods produced 817.1 g CO2eq. It is much higher than the current CR food diet. A theoretical scenario is generated, which showed that carbon emissions per capita were 392.2 g CO2eq for the male and 379.3 g CO2eq for the female, respectively. In addition, a more realistic scenario with 346 g CO2eq d⁻¹ for the male and 325.7 g CO2eq d⁻¹ for the female was developed. Dietary pattern in scenario 2 and scenario 3 could reduce carbon emissions significantly. Rice and tailored flour consumption substituted by whole grains, beans and tuber foods can both reduce GHG emissions and increase nutrients intake. Due to the demand difference in nutrients, dietary structure of males and females were significantly different. The consumption of G2 foods and potato for the males was much higher than that for the females. However, consumption of G3 foods and sweet potato for the males was much lower than that for the females. On the other hand, sustainable CR food diets were developed in this study. However, food choices of residents are affected by many factors, such as consumer culture and food price. Therefore, research on policy guidance for the low carbon consumption behaviour of residents should be paid more attention.

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