A Comparative Study on Carbon Footprints between Wheat Flour and Potato in China Considering the Nutrition Function of Foods

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Abstract. The food production is a significant contributor to global greenhouse gas (GHG) emissions, and it has attracted many researchers’ attention. In the present study, carbon footprints (CFs) of wheat-based foods and potato during cultivation, transportation, storage, and processing phases were investigated according to the LCA (life cycle assessment) principle. The results showed that wheat-based products were associated with much higher carbon emissions than potato per kilogram of edible portion. Cultivation phase is the most important stage, and carbon emissions per kg food increased with more machining process. For different carbon emission sources, fertilization, electricity use, and N2O emissions are the top three contributors. On the other hand, CFs of foods were evaluated based on carbohydrate based-, protein based-, fat based-, dietary fiber based-, and nutrient density based functional units. CF values of product per functional unit varied depending on the functional unit used. When the macro-nutrients were considered, the low-carbon emissions competitiveness of potato over wheat flour was reduced significantly. In this research, nutrient density used as the basis of functional unit could be more appropriate than individual nutrient alone to illustrate the environmental impacts of different foods. In summary, consumption of more standard grade flour and potato instead of tailored flour (grade one) could cut a considerable amount of GHG emissions in China.

1. Introduction
Global warming caused by a number of greenhouse gas (GHG) emissions is a worldwide issue with its evident impacts across a wide range of systems and sectors. The Paris Agreement 2015 would reinforce the global response to the threat of climate change (Hohne et al., 2017) [1]. With the increasing awareness of climate change, CF was developed as a standard procedure to measure and communicate GHG emissions linked to consumer products. CF, normally expressed in carbon dioxide equivalent (CO₂eq), is defined as the exclusive total amount of GHG emissions over the life stages of a product (Wiedmann & Minx, 2007) [2]. Food consumption is a significant driver for global environment pressure (Xu et al., 2015) [3]. More than 427.64 Tg CO₂ from Chinese dietary was produced in 2013 (Xu & Lan, 2016) [4]. Thus, increasing GHG emissions from food consumption has become an interesting area of research (Rosi et al., 2017[5]; Song et al., 2015[6]). Wheat is one of the world’s most favored food sources, which reaches millions of people on a daily basis. In China, wheat is a chief staple food, which contributes significantly to national food security. In 2015, wheat production constituted of 20.9% (130.2 million tons) of the total national grain production (NBS, 2016) [7]. However, wheat consumption causes significant environmental impacts (Song et al., 2015) [6]. The CFs of wheat production in China over the period of 1978-2012 were measured, and the results
showed that area-scaled CF of wheat production increased gradually from 937 kg CO₂eq/ha in 1978 to 2978 kg CO₂eq/ha in 2012 (Huang et al., 2017) [8]. In addition, CF of wheat in China was higher than that in many other countries, such as the United States, Canada, and India (Zhang et al., 2017) [9]. Characterizing the product CF is still one of the prior research foci to identify the key options for mitigating climate change (Ali et al., 2015[10]; Ali et al., 2017[11]; Huang et al., 2017[8]; Wang et al., 2016[12]; Wang et al., 2017[13]; Zhang et al., 2017[9]). On the other hand, the global warming potential (GWP) of different types of foods is diverse. Thus, quantifying the CF differences of various foods could offer the method for GHG mitigation through choosing foods with lower CF. For example, a shift towards dietary patterns with greater consumption of animal source foods greatly increased carbon emissions from Indian agriculture (Vetter et al., 2017) [14]. On the other hand, the potato, as one of the most important staple food in the world, also plays an important role in ensuring food safety and nutrition (Lu, 2015) [15]. However, the amount of potato consumption is low at present (NBS, 2016) [7]. In 2015, the Ministry of Agriculture of China launched the strategy of developing potato as the staple food (People net, 2015) [16]. Potato and wheat-based foods have very different life cycles and therefore potentially make different environmental burdens. In addition, wheat-based foods with different processing levels, such as standard grade flour and tailared flour (grade one) are consumed, which also cause different environmental impacts. Thus, it is of great importance to study the CFs of wheat flour and potato food. Many studies investigated the CFs of wheat-based foods and potato, and the results were shown in Table 1. However, the comparative studies of CFs between wheat-based foods and potato in China using the same data source, life cycle scope, emission factors, and by-products allocation method were rarely reported. Many studies on product CF in food systems were usually compared based on mass or volume. Although mass or volume as the basic quantities is used the most often and straightforward for many researches, it ignores an important fact, i.e., function of food products is to provide nutrition and energy for human. Using a functional unit involving only CF per kg food item could reach the conclusion that vegetable alternatives are always better than those of animal origin (Smedman et al., 2010)[17]. Nutrient content of foods could reflect the function of foods better in comparison with mass or volume (Schau & Fet, 2008)[18]. Individual nutrient has been used to evaluate CFs of foods, such as protein (Sonesson et al., 2017[19]; Tessari et al., 2016[20]) and carbohydrate (Hess et al., 2016)[21]. Different kinds of nutrients were provided by foods, such as protein, iron, fiber, and so on. If a food product A is lack of carbohydrate but rich in protein, and another food product B is rich in carbohydrate but lack of protein, it is unreasonable to use either carbohydrate or protein alone as the basic quantity to compare with the environmental influences between the food product A and B, in terms of their nutrition. Recently, nutrient density (ND) considering multiple nutrients has been used to evaluate the CF of food (Drewnowski et al, 2015[22]; Saarinen et al., 2017[23]; Smedman et al., 2010[17]; Van Kernebeek et al., 2014[24]). However, considering both the CF and nutrition of staple foods in China, few analyses have been conducted. The present study aimed to evaluate CFs of wheat-based foods and potato based on a unique CF measurement method and data source considering different kinds of nutrients, and thus to supply data to assist the reduction of GHG emissions from Chinese food systems.

In many studies, the selection of nutrients in the ND model was based on current knowledge of typical western diet (Drewnowski, 2010[17]; Saarinen et al., 2017[23]). The Chinese Nutrition Society suggests 6 major food groups in Chinese diet, i.e., water; cereals and tubers; vegetable and fruits; legumes, milk and derivates; meat, fish, and eggs; and oil, salt, sugar, and other seasoning (CNS, 2016)[25]. The ND model considered the nutritional character of Chinese diet by using the Chinese referenced data. Besides, the choice of qualifying nutrients is most often guided by the shortfall nutrients in the population diet. The model ND emphasized the nutritional function of deficient nutrients in China. In summary, the CFs of foods based on the nutrition profiling model ND could more realistically demonstrate the environmental impacts of food in China.

2. Methods
This study was carried out in accordance with the principle of the PAS2050:2011 (BSI, 2011)[26] and ISO 14067 (2011)[27], including three steps, i.e., goal and scope definition, life cycle inventory (LCI),
and calculating the product CF.

2.1. Goal and scope definition
The goal of this study was to analyze the CFs of wheat-based foods and potato to examine the environmental benefits caused by possible dietary changes, thus to supply information to consumers for their dietary choices, about their dietary ecological impact per nutritional unit. The wheat-based foods included the standard grade flour, wheat flour with the second class, and tailared flour (grade one). Although Berry et al. (2008) [28] showed that 1 kg of grain yields approximately 1 kg whole meal flour, in this research, 1 kg wheat could produce 0.8 kg standard grade flour, 0.7 kg wheat flour with the second class, or 0.6 kg tailared flour (grade one), respectively.

2.1.1. Functional unit. Functional unit defines the quantification of the identified functions of a product to ensure comparability of LCA results, when CF is used for comparisons between different products or services (ISO 14040, 2006) [29]. This research investigated the CFs of different foods, at the same time considering the nutrition function of the foods. Different functional units were used in this study.

(1) Weight-based functional unit
Food weight is used the most often in the food LCA research. In order to compare with the results of other studies, one of the functional units refers to unit mass (1 kg) of food product.

(2) Individual nutrient based functional unit
Protein, fat, and carbohydrate are important macronutrients. In addition, grains are important food source of dietary fiber for Chinese (CNS, 2016) [25]. Thus, the amount of food considering the four individual nutrients separately was used as another four functional units.

(3) ND-based functional unit
ND is defined as the ratio of the nutrient composition of a food to the nutrient requirements of the human (Hansen et al., 1979) [30]. In this research, twenty-one types of macro- and micro-nutrients (protein, fat, carbohydrates, dietary fiber, retinol, thiamine, riboflavin, niacin, Vitamin C, Vitamin E, potassium, sodium, calcium, magnesium, iron, manganese, zinc, copper, phosphorus, selenium, and cholesterol) included in the Chinese nutrient database were considered. However, Padberg et al. (1993) [31] showed that a product containing less than 10% daily values of a given nutrient are not permitted source claims. In this research, 10% was used as a cut-off level for nutrients with a significant contribution. The used ND calculating method was based on the model described by Drewnowski (2005) [32] and Smedman et al. (2010) [17]. Equations (1) - (3) were employed to calculate the ND of the product.

\[ X_i \% = \frac{X_i}{NRV_i} \times 100\% \]  

\[ NI = \frac{X_i}{NRV_i} \times \frac{2000}{C} \]  

\[ ND_{10\%} = \sum_{i=1}^{21} X_i \% \times \frac{n}{21} \]  

where \( X_i \) is the amount of nutrient \( i \) in the food, which is from the Chinese nutrient database (Yang et al., 2009); \( NRV_i \) represents the daily reference intake value of nutrient \( i \) in China (Chinese Ministry of Health, 2008); \( X_i \% \) represents the contribution of nutrient to the reference requirement with respect to specific nutrient; \( NI \) is the nutritional index, representing the relative nutrition value of nutrient \( i \) in the food based on the consumption of 2000 kcal energy; \( C \) is the amount of energy in food; \( n \) is the number of NI value of nutrient \( j \) \( \geq 0.1 \); \( ND_{10\%} \) is the sum of relative values of the nutrient \( j \) in food.

(4) System boundary
The system boundaries include the agricultural production process, transportation process, storing process, and manufacture process. The CF of products comprises direct and indirect emissions. Direct emissions include \( CO_2 \) from fuel consumption and \( N_2O \) caused by fertilization. Indirect emissions are
from the production of fertilizer, pesticide, film, seeds, etc. CH\textsubscript{4} emissions from the field are not considered due to little contribution to the GWP in upland areas (Wang et al., 2016)[12]. In addition, land use change and carbon sequestration in soil were also excluded in accordance with the PAS 2050 guidelines (Yan et al., 2015)[35].

(5) Allocation
In addition to the major food, large amounts of by-products such as straw were also produced from the agricultural sector. In this research, the ratio of the economic value of the major product to that of by-product was used to allocate the total GHG emissions during cultivating process. The economic outputs of the major product and by-product for the wheat and potato were from China Agricultural Products Cost-Benefit Yearbooks (NDRC, 2015)[36]. On the other hand, large amounts of by-products such as bran were also produced from food processing sector. Ninety-one percent of the total impact was assigned to wheat flour based on the economic value of wheat flour and by-products (Davis, 2008)[37]. During the processing stage, the allocation based on the economic value of major product and co-products was also used, in which about 90% of the total carbon emissions was assigned to the major foods in this research.

2.2. Life cycle inventory
Inventory analysis phase of LCA is to compile and quantify inputs and outputs of a product throughout its life cycle (ISO 14040, 2006)[29]. The total CF of food products consists of the direct carbon emissions and indirect carbon emissions.

2.2.1. Emission quantification protocol. The following equations were employed to calculate the product CF:

\[
GHG_{\text{total}} = GHG_{\text{direct}} + GHG_{\text{indirect}} \quad (4)
\]

\[
GHG_{\text{direct}} = GHG_{N,O} + GHG_{CO_2} \quad (5)
\]

where \(GHG_{N,O}\) represents the N\textsubscript{2}O emissions from crops; \(GHG_{CO_2}\) represents the CO\textsubscript{2} emissions from fuel burning.

In this research, equations (6) to (8) based on the methods proposed by Wang et al. (2015) [38] were used to estimate N\textsubscript{2}O emissions from the three major N input sources including synthetic fertilizers, organic manure, and crop residues.

\[
GHG_{N,O} = \frac{N_{2}O_{\text{N}} \times EF_i \times \frac{44}{28} \times GWP_{N,O}}{\text{Crop yield}} \quad (6)
\]

\[
N_{2}O_{\text{N}} = F_{SN} + F_{AM} + F_{CR} \quad (7)
\]

\[
F_{CR} = \sum \text{Crop yield} \times (\text{Straw seed ratio}) \times N \text{ content in straw of crop} \times \text{Utilization status in China} \quad (8)
\]

where \(N_{2}O_{\text{N}}\) represents the total N inputs (kg N/ha); \(EF_i\) is the specific emission factor for N\textsubscript{2}O-N emissions from the total N inputs (kg N\textsubscript{2}O-N/kg N input) in China, which are 0.0105 and 0.0041 for upland and rice paddies, respectively (Gao et al., 2011)[39]; 44/28 is to convert emissions from kg N\textsubscript{2}O-N to kg N\textsubscript{2}O; \(GWP_{N,O}\) denotes the GWP of N\textsubscript{2}O, which is 298; \(F_{SN}, F_{AM},\) and \(F_{CR}\) represent N inputs from synthetic fertilizers, animal manure, and crop residues, respectively (kg N/ha); Crop yield denotes the average production of crop \(i\) per hectare (kg/ha); Straw/seed ratio, N content in straw of main crop, and its utilization status in China was according to Zhang et al. (2010)[40]. Because the amount of animal manure is much smaller compared to the synthetic fertilizer (NDRC, 2015)[36], the N\textsubscript{2}O emissions from manure were ignored in this research.

Indirect emissions for the foods were generated during producing fertilization, pesticides, agriculture film, diesel fuel, electricity, and seed. Equation (9) was used to calculate the indirect emissions.

\[
GHG_{\text{indirect}} = GHG_{\text{fertilization}} + GHG_{\text{pesticide}} + GHG_{\text{film}} + GHG_{\text{fuel}} + GHG_{\text{electricity}} + GHG_{\text{seed}} = \sum_i (EF_i \times \text{Activity}_i) \quad (9)
\]
2.2.2. Data sources. The inputs and outputs of a food product throughout cultivation, transportation, storage, and producing processes were shown as below. Even though many data sources of inventory are available, domestic parameters for China were used as the first alternative to achieve more accurate results.

1. Crop cultivation
In this research, farming activity data such as the amount of fertilizer, seed, energy, and agriculture film per hectare for wheat and potato were all from the China Agricultural Products Cost-Benefit Yearbooks (NDRC, 2015) [36]. In this research, part of machinery operating costs and all of fuel cost during cultivation in the China Agricultural Products Cost-Benefit Yearbooks were assumed from farm diesel. In addition, irrigation cost (except water cost) in the China Agricultural Products Cost-Benefit Yearbooks was assumed to be all caused by electricity consumption. Emission factors are important data sources for the life cycle inventory. A set of emission factor were used, such as 22.72 kg CO2eq/kg for agricultural film (Ecoinvent database, 2011) [41], 1.03 kgCO2/kWh for electricity (Hou et al., 2012) [42], and 0.102 kgCO2eq/MJ for diesel fuel (Ou and Zhang, 2009)[43]. On the other hand, the emission factors of nitrogen, phosphorus, and potassium fertilizers were from the study of Chen et al. (2015) [44], and carbon emissions from seed production originated from the study by West & Marland (2002)[45]. In addition, carbon emissions of production and transportation of herbicides, insecticides, and fungicides were from the studies by Chen et al (2016) [46] and Zhang et al (2016) [47].

2. Transportation
For the food transportation, only the GHG emissions of fuels were considered. The emission factor for the transportation of wheat and potato in China from Xu & Lan (2016)[4] were used, which were 2.04×10⁻³ and 1.30×10⁻⁵ kg CO2eq/kg, respectively. This emission factor is a weighted average of railway and highway emissions, and the railway emission was the weighted average of diesel oil power train and electric power train emissions.

3. Drying and storage
Before storage, drying is necessary for the wheat production. In rural areas, drying wheat by the sunshine is a conventional method. According to the study of Ali et al. (2015) [10], the carbon emissions from wheat drying was ignored in this research. In addition, for the wheat storage phase, according to the guide for storing wheat in Japan, the energy consumption in a storage facility was 2.2×10⁻⁴ kWh kg⁻¹ day⁻¹ (Roy et al., 2009) [48]. And the storage period of wheat is considered to be 6 months. On the other hand, potatoes with high moisture content are perishable, thus precise storage is very important. In this research, the information according to Williams et al. (2010) [49] was used to estimate carbon emissions during storage.

4. Processing
For the wheat processing, survey data was mainly used. The energy consumption for the wheat processing was measured at a farm (pneumatic roller mill; power meter: 7.5 kW; Xinjiang flourmill Co., Ltd.) in Shandong Province, China. Every year, about 3000 tons of grain was processed in this company. The total energy consumption and wheat flour yield for every hour were 13.5 kWh and 150 kg, respectively. This figure was similar to the study by Berry et al. (2008) [28], in which energy usage equates to 0.114 kg CO2eq/kg grain for flour for human consumption.

2.3. Calculating the product CF
In this research, the CFs translated from the primary and secondary activity data by multiplying the emission factor for each activity were compared. For comparison with published data, GWP of 25 for CH4 and 298 for N2O were used according to IPCC (2006) [50] rather than the recently modified GWP values given in the Fifth Assessment Report of IPCC (IPCC, 2013)[51].

3. Results

3.1. CFs of different food products
CFs of different kinds of food products per kg edible portion in the cultivation, transportation, storage, and processing stages were shown in Figure 1. The results showed that among the investigated foods,
wheat-based products are associated with much bigger CFs than potato. The CF of potato is only 24.2%, 21.4%, and 18.6% of that of standard grade flour, wheat flour with the second class, and tailared flour (grade one), respectively. Root and tuber crop generally showed smaller CF values compared to cereals (Nemecek et al., 2012) [52]. The results in Figure 1 also display that the CF of tailared flour (grade one) is larger than the other two kinds of wheat-based foods. It indicated that lowering product processing could reduce GHG emissions. Thus, governments should encourage people to consume less processed foods to reduce GHG emissions. Cultivation phase is the predominant source stage, in which more than 85% and 75% of total carbon emissions were produced for wheat-based foods and potato, respectively. For the wheat-based foods, processing stage is the second contributor, which produced 8.9% for the standard grade flour, 7.9% for the wheat flour with the second class, and 6.8% for tailared flour (grade one). While for the potato, storage stage is the second contributor, accounting for 24.3% of total emissions. Many studies also demonstrated that main crop potato energy needs were closely related to cold storage (Webb et al., 2013; Williams et al., 2010)[53].

The percentage of different carbon emissions sources was shown in Figure 2. According to Ou and Zhang (2009) [43], 72% of carbon emissions from fuel were produced during the use stage, which was considered as direct emissions. Finally, the proportion of direct emissions was 27.7% for the standard grade flour, 28.0% for the wheat flour with the second class, 28.3% for the tailared flour (grade one), and 24.8% for the potato. Corresponding, 71%-75% of total carbon emissions were from the manufacture process of agriculture inputs. Xu & Lan (2016)[4] also showed that for plant products emissions caused by manufacturing agriculture inputs accounted for 63.9%-72.1%. It indicated that indirect emissions should be paid more attention. For the foods studied, the biggest GHG emissions source is fertilizer production, which contribute 36.4% for the standard grade flour, 36.8% for the wheat flour with the second class, 37.2% for the tailared flour (grade one), and 35.6% for the potato. It was consisted with the results from Zhang et al. (2016b)[54]. Thus, there is great potential to decrease the product CF through reducing chemical fertilizer use rate. Comparison of GHG emissions of chemical fertilizer types was carried out by Wang et al. (2017)[13], indicating that changing to an appropriate fertilizer type could be an efficient option for mitigating GHG emissions in China. In addition, increasing the price of fertilizer and recognizing farmers’ decision-making processes related to fertilizer were useful to improve the fertilizer use efficiency (Ha et al., 2015)[55]. Besides, nitrogen fertilizer usage is a special case because not only are GHG emissions associated with its manufacture and apply operations, but direct emissions of N₂O from the soil are also associated with its use.
(Albanito et al., 2017[56]; Berry et al., 2008[28]). However, it is noted that the increase in GHG emissions due to the increase in N fertilizer rate did not necessarily lead to a higher CF, but very much depended on whether or not the cropping practices resulted in greater grain yields (Ali et al., 2017 [11]. The results in Figure 2 showed that electricity use is the second contributor, which is accounted for about 30% of CF of the foods studied. Electricity was used for irrigation, transportation, storage, and processing. N$_2$O emissions from wheat and potato fields are the third contributor, which is up to 21% of total CF for the wheat flour and 18% of total CF for the potato. Improving nitrogen fertilizer application technique could reduce N$_2$O emissions (Ali et al., 2015[10]; Bernstein et al., 2008[57]). In addition, when irrigation was reduced, N$_2$O emissions per unit of area were decreased (Wang et al., 2016) [12]. The influence of straw returning on N$_2$O emissions has been investigated by many studies. However, both negative and positive influences were found, which was mainly ascribed to the different soil moisture (Zhou et al., 2017) [58]. On the other hand, in modern agriculture, farm operations such as tillage, sowing, spraying, and harvesting consume large amounts of diesel. Berry et al. (2008) [28] also showed that diesel used during farm operations accounted for 12% of total GHG emissions for the wheat production in the UK. In this research, it contributed about 9% for the wheat foods and 10% for the potato.

![Figure 2. The percentage of different carbon emissions sources.](image-url)

3.2. Comparative studies
In this section, the results of this research were compared with previous studies. The CF values of wheat production in other studies were shown in Table 1. Different values of product CF are showed in varied studies. In the current study, the GHG emissions caused by gaining 1 kg of wheat was 0.72 kg CO$_2$eq, which are comparable to the CF values found by some previous studies (Ha et al., 2015[55]; Yan et al., 2015[35]; Zhang et al., 2016b [54]). In addition, a systematic literature review of GHG emissions for different food categories was carried out, and the results showed that mean, minimum, and maximum product CF values of wheat were respectively 0.51, 0.18, and 1.10 kg CO$_2$eq/kg food with the life cycle from farm to the regional distribution centre (Clune et al., 2017) [59]. However, the CF for wheat studied is higher than the results of many other researches in China (Xu & Lan, 2016[4]; Xu and Lan, 2017[60]). The gap of values was mainly attributed to the varied life cycle definition (with or without soil carbon sequestration). In upland cropping systems, 27-41% of the gross GWP could be offset by soil organic carbon sequestration (Zhang et al., 2014) [61]. On the other hand, the results in Table 1 also showed that compared to other countries, the CF values of wheat in China are noticeably higher than those in India, the United States, Canada, Italy, UK, and Australia. The big gap between China and other countries is mainly due to different emission factors and management technologies (Chen et al., 2015[44]; Zhang et al., 2017[9]).

CF of potato was also compared with the results of other similar researches. The CF values of potato in other studies were also shown in Table 1. The CF of potato in this study is comparable to the CF
values found by some previous studies (Webb et al., 2013[53]; Williams et al., 2010[49]). Besides, CF of potato was estimated based on a literature review, and the results showed that GHG emissions from primary production of maincrop potatoes are ranging from 0.10 to 0.17 kg CO₂e kg⁻¹ net weight (Hess et al., 2016) [21]. In addition, a systematic literature review of CF for potato showed that CF value of potato was 0.20±0.08 kg CO₂eq/kg (Clune et al., 2017)[59]. Our result was also comparable to the conclusions of these two review studies.

| Item                                      | System boundary                             | Locations  | Results                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------------------|---------------------------------------------|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wheat based foods                         | From resource extraction to farm gate       | China      | The mean, minimum, and maximum CF of winter wheat from 65 farm households was 0.90, 0.25, and 2.61 kg CO₂eq/kg product, respectively (Ha et al., 2015)[55].                                                                                                                                                                                      |
| From raw material acquisition to wheat harvest | China                                        |            | The CF of wheat in a winter wheat-summer maize cropping system was investigated, and the results showed that the CFs for the winter wheat under different tillage methods were ranged from 0.65 to 0.72 kg CO₂eq/kg grain (Zhang et al., 2016b)[54].                                                                                       |
| From the production of India agricultural inputs to farm gate | China                                        |            | The GHG emissions associated with the production of major food commodities are calculated, and the results showed that CF of wheat was 0.34±0.21 CO₂eq/kg grain (Vetter et al., 2017)[14].                                                                                                                                 |
| From the production of Polish agricultural inputs to the harvest | Italy                                        |            | The environmental performance of rainfed durum wheat under different management practices were studied, and the results showed that the CF of wheat was 0.22 kg CO₂eq/kg grain (Ali et al., 2015)[10].                                                                                           |
| From the production of UK agricultural inputs to the harvest | Italy                                        |            | The CF of wheat was 0.30 kg CO₂eq/kg grain on average, which varied significantly between the proposed management systems (Ali et al., 2017)[11].                                                                                                                                                                                                                   |
| From the production of Night agricultural inputs to farm gate | Italy                                        |            | The CF of spring wheat was 0.33±0.02 kg CO₂eq/kg grain in the high agro-technical intensity level (Wojcik-Gront & Bloch-Michalik, 2016)[63].                                                                                                                                                                                                                |
| From resource extraction to farm gate     | China                                        |            | The production and drying of 1 kg wheat was associated with 0.41 kg CO₂eq (Berry et al., 2008)[28].                                                                                                                                                                                                                                                   |
3.3. CFs of foods based on different functional units

To depict more accurately the impacts of food choice on the environment, the carbon emissions produced by different foods were evaluated based on different functional units. For convenient description, the relative CF value of different foods to potato was used to represent their environmental influence. The relative CF values of foods based on different functional units (mass, carbohydrate, protein, fat, dietary fiber, and ND) were shown in Figure 3. Although CF value per kg potato was much lower than that of wheat flour, when carbohydrate, protein, and fat were considered, the results showed that the ratio of wheat flour to potato became smaller. When to provide the same amount of carbohydrate, the carbon emissions produced by wheat flour is closed to that produced by potato. Hess et al. (2016)[21] also found that when the weight of food was considered, the CF value of pasta was about 5 times more than that of potato. However, when carbohydrate content was considered, the CF value of pasta was only 1.1 times more than that of potato. Protein and fat are also significant nutrients. When to provide the same amount of protein and fat, the carbon emissions produced by standard grade flour and wheat flour with the second class are lower than that produced by potato. Especially, the CF value of stand grade flour was only 78.4% and 58.5% of the CF of potato when the protein content and fat content are considered, respectively. Moreover, when the macro-nutrients are considered, the CF value of tailared flour (grade one) is closed to that of potato. These were all related to higher carbohydrate, protein, and fat content per kg food product from wheat flour compared to the potato. On the other hand, when the dietary fiber was considered, although the relative CF values of standard grade flour and wheat flour with the second class are reduced significantly compared with that when weight-based functional unit was used, potato is still one lower CF food. However, among the foods studied, the amount of dietary fiber per kg food product provided by tailared flour (grade one) was the lowest. Thus, the relative CF value of tailared flour (grade one) increased rapidly compared to other foods, and is larger than that when weight-based functional unit was used.

The changes of ratio between wheat flour and potato showed that it is unfair to use weight alone or individual nutrient as the basic quantity to compare with the CF of foods. Saarinen et al. (2017) [23] also showed that discrimination between sustainable and unsustainable foods based on consideration of individual nutrients was impossible, because GWP/individual nutrient varied greatly. One the other hand, many nutrients abound in food, which are important for human health. The role of these nutrients should be reflected when they were used to evaluate the CF of food. Thus, ND used as the basis of functional unit was important to compare with CF values of the food product. The relative CF of different foods to potato based on ND-based functional unit was also shown in Figure 3. It showed that the ration of wheat flour to potato is reduced compared to that when the weight of food is considered. However, it is larger than that when carbohydrate, protein, or fat is considered. When the ND was considered to compare with the CFs of foods, the nutrient types chosen had important

| Item                        | System boundary                  | Locations          | Results                                                                                                                                                                                                 |
|-----------------------------|----------------------------------|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| From resource extraction to | From cradle to farm gate         | Canada             | The CFs of animal feed and wholemeal flour were 0.48 and 0.53 kg CO$_2$eq/kg, respectively (Berry et al., 2008)[28]. Without considering the soil organic carbon, CF of spring wheat over 25 years averaged 0.34 kgCO$_2$eq/kg grain (Gan et al., 2014)[64]. |
| transportation and milling  |                                   |                    |                                                                                                                                                                                                          |
| From cradle to farm gate    | From resource extraction to      | Australia          | The CF of wheat was 0.30 kg CO$_2$eq during the production and delivery of 1 kg of wheat to port (Biswas et al., 2008)[65].                                                                                     |
|                             | transporting to port.            |                    |                                                                                                                                                                                                          |
| From the production of      | From the production of            | Australian         | The CF of wheat production in an Australian wheat cropping system was 0.19 kg CO$_2$eq/kg grain on average (Wang & Dalal, 2015)[38].                                                                            |
| agricultural inputs to the  | agricultural inputs to the harvest|                    |                                                                                                                                                                                                          |
| harvest                     |                                   |                    | The CFs of 1st earlies, 2nd earlies, and maincrop were 0.29, 0.13, and 0.17 kg CO$_2$eq/kg, respectively (Williams et al., 2010)[49].                                                                               |
| Potato                      | From cradle to sale              | UK                 | The potato CF fell in the range 0.10–0.16 kg CO$_2$eq/kg potatoes with 95% certainty for an arbitrary year and field (Röös et al., 2010)[66].                                                              |
|                             | From cradle to retail            | Sweden             |                                                                                                                                                                                                          |
|                             | From fromale sale                | UK                 | The environmental burdens of potato sold in the UK were assessed, and the results showed that CF of early potatoes in the UK and Israel were 0.3 and 0.5 kg CO$_2$eq/kg, respectively (Webb et al., 2013)[53]. |

The environmental burdens of potato sold in the UK were assessed, and the results showed that CF of early potatoes in the UK and Israel were 0.3 and 0.5 kg CO$_2$eq/kg, respectively (Webb et al., 2013)[53].
influence on the results. When 10% was used as a cut-off level for nutrients with a significant contribution, 16 and 15 kinds of nutrients were chosen for the wheat-based foods and potato, respectively. Fat, manganese, and zinc were only chosen for the wheat-based foods, while retinol and Vitamin C were only chosen for the potato. The ND model in the current study reflected the difference of nutrient types and food types. Although the nutrients not considered in the nutrition profiling models ND are essential to health, the amount of these nutrients was small and they could be easily obtained from other types of food. Energy and nutrient adequacy is the basis of sustainability diets (Masset et al., 2014). ND method in this research evaluated nutrition value of food based on the consumption of 2000 kcal energy, thus it demonstrated more realistically the environmental impacts of foods. Although it was more complex than the weight-based methods and individual nutrient-based methods, the CFs of foods based on ND could demonstrate the impacts of foods more appropriately. On the other hand, the results in Figure 3 showed that irrespective of the employed functional unit, tailored flour (grade one) produces more carbon emissions than the other types of foods. Currently, wheat-based foods are staple foods in China. Thus, more consumption choice to standard grade flour could be a feasible plan to reduce carbon emissions. Besides, the Chinese government is implementing the plan of developing potato as the staple food. Therefore, displacing tailored flour (grade one) by potato could also cut a considerable amount of GHG emissions.

![Figure 3. Relative CF values of different foods based on different functional units](image)

4. Conclusions
In this study, the CFs of wheat flour and potato from their cultivation, transportation, storage, and processing phases were investigated according to the LCA principle. From the view point of food types, wheat-based products produced much more carbon emissions than the potato per kg. In addition, the results indicated that less product processing could reduce GHG emissions. From the view point of life stage, cultivation phase was the most important stage. In addition, the biggest carbon emission source was fertilization, followed by electricity use and N₂O. To illustrate the impacts of consumption choice of foods on the GHG emissions more accurately, the CFs of wheat flour and potato were evaluated based on nutrition content. Product CF per functional unit value varied depending on the functional unit used. When carbohydrate content was considered, the CF values of wheat flour and potato were similar. When protein and fat content were considered, the CF values of standard grade flour and wheat flour with the second class are smaller than that of potato. However, when the dietary fiber was considered, the relative CF value of tailored flour (grade one) increased significantly compared to other foods, and is larger than that when weight-based functional unit was used. It indicated that ND used as the basis of functional unit was important. As for a further comment, the ND model reflected the difference of nutrient types and food types, and it used as the basis of functional unit could demonstrate more realistically the impacts of food in China. On the other hand, the results
showed that no matter which functional unit was used, tailored flour (grade one) produced more GHG emissions than the other kinds of foods. Finally, the results showed that more consumption choice to standard grade flour and potato could cut a considerable amount of carbon emissions.

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