How China’s nitrogen footprint of food has changed from 1961 to 2010

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Abstract
People have increased the amount of reactive nitrogen (Nr) in the environment as a result of food production methods and consumption choices. However, the connection between dietary choices and environmental impacts over time has not yet been studied in China. Here we combine a nitrogen footprint tool, the N-Calculator, with a food chain model, NUFER (NUtrient flows in Food chains, Environment and Resources use), to analyze the N footprint of food in China. We use the NUFER model to provide a detailed estimation of the amounts and forms of Nr released to the environment during food production, which is then used to calculate virtual nitrogen factors (VNFs, unit: kg N released/kg N in product) of major food items. The food N footprint consists of the food consumption N footprint and food production N footprint. The average per capita food N footprint increased from 4.7 kg N capita⁻¹ yr⁻¹ in the 1960s to 21 kg N capita⁻¹ yr⁻¹ in the 2000s, and the national food N footprint in China increased from 3.4 metric tons (MT) N yr⁻¹ in the 1960s to 28 MT N yr⁻¹ in the 2000s. The proportion of the food N footprint that is animal-derived increased from 37% to 54% during this period. The food production N footprint accounted for 84% of the national food N footprint in the 2000s, compared to 62% in the 1960s. More Nr has been added to the food production systems to produce enough food for a growing population that is increasing its per-capita food consumption. The increasing VNFs in China indicate that an increasing amount of Nr is being lost per unit of N embedded in food products consumed by humans in the past five decades. National N losses from food production increased from 6 MT N yr⁻¹ in the 1960s to 23 MT N yr⁻¹ in the 2000s. N was lost to the environment in four ways: ammonia (NH₃) emissions and dinitrogen (N₂) emissions through denitrification (each account for nearly 40%), N losses to water systems (20%), and nitrous oxide (N₂O) emissions (1%). The average per capita food N footprint in China is relatively high compared with those of developed countries in the 2000s. To reduce the food N footprint in China, it is important to both reduce the Nr losses during food production and encourage diets associated with a lower N footprint, such as shifting towards a more plant-based diet.
1. Introduction

The global anthropogenic creation of reactive nitrogen (Nr, all nitrogen species except N2) continues to break records (Galloway and Cowling 2002, Gruber and Galloway 2008, Vitousek et al 1997, Galloway et al 2014). Food production has contributed the biggest part to increases in Nr creation. Nitrogen (N) is an essential element for crop production and a main constituent of protein in crops, animals and humans. As populations grow and per-capita consumption of animal protein increase, more Nr is required to produce the food consumed. The creation of N fertilizer for crop production through the Haber–Bosch process is now the major source of Nr in the world. Most of the Nr used to produce plant and animal derived food is lost to the atmosphere and water systems, and these losses have negative human health and biosphere impacts, which have worsened over the last several decades (Galloway et al 2008, Conley et al 2009, Smil 2002, Strokal et al 2016, Rabalais et al 2002).

The types and amounts of food consumed by humans are the main drivers of food production system: these choices influence food production, N requirements, and environment losses (Ingram 2011, Sobota et al 2015, Reis et al 2016, Sutton et al 2013). Urbanization and the centralization of the food chain, which are relevant to economic and political development, further change the food demand and diet structure with impacts on global food trade and the N cycle (Lassaletta et al 2014, Billen et al 2015, Oita et al 2016). We can reduce Nr inputs and environmental losses and improve nitrogen use efficiency (N) by reducing consumption of food with a relatively high N burden, which is generally animal-derived food items (Xue and Landis 2010, Howarth et al 2002). Changes towards diets with smaller portions of animal-derived food can have significant Nr and greenhouse gas (GHG) benefits globally, and these dietary changes can also reduce the demand for water and agricultural land (Tilman and Clark 2014, Gu et al 2015). The previous studies have provided important information on the environmental impacts of different dietary choices of a country or region.

The N footprint is defined as the total amount of Nr released to the environment from an entity’s consumption and the associated production, of food and energy (Leach et al 2012). N footprint is a powerful method that links consumers with their environmental impacts (Galloway and Leach 2016, Galloway et al 2014). Per capita N footprints have been calculated for the US, Netherlands, Japan, Germany, Austria, the UK, Australia and Tanzania, using the N-Calculator model (Leach et al 2012, Shibata et al 2014, Stevens et al 2014, PIERER et al 2014, LIANG et al 2016, HUTTON et al 2017). N footprints have also been calculated for China and the EU using different approaches (Gu et al 2013, Leip et al 2014, Cui et al 2016). The N-Calculator model was developed to aid the consumer in determining how their use of resources contributes to N pollution, and to give them a platform (www.n-print.org) to learn how changes in resource use results in changes to their N footprint. However, the N-Calculator method is not designed to provide information on the chemical speciation of the N that is lost.

Diets and life-styles have changed dramatically in China during the last several decades. The proportion of animal-derived protein supply increased from a mean of 8% in 1961 to 38% in 2011 (FAOstat 2016). The resource needs and environmental costs of animal-derived protein exceed that of crop production (Tubiello et al 2014). The increasing consumption of animal-derived protein means that more resources, such as chemical fertilizer, water and land, are needed per capita (Tilman and Clark 2014, Lassaletta et al 2014). However, the changes in the N footprint during the last 50 years, and changes in the form, fate and impact of the N losses to the environment in China are not yet well quantified. Therefore, we use the N-Calculator model together with food production Nr losses calculated using the NUFER model (NUtrient Flows in Food chains, Environment and Resources use) specifically for China to study how the Chinese N footprint has changed over time.

The NUFER model is a deterministic model with large databases that calculates the flows, use efficiencies, and emissions of N and phosphorous (P) in the food chain of China and the 31 provinces (regions) on an annual basis. NUFER uses a mass balance approach with detailed accounts of the partitioning of N and P inputs and outputs (Ma et al 2010, Ma et al 2012). With the NUFER model, the nutrient flows between different compartments (crop production, animal production, food processing and household consumption), nitrogen use efficiency (NUE) and environmental losses can be calculated (Ma et al 2010, Ma et al 2012). The comprehensive indicators of the NUFER model make it possible to analyze different processes that contribute to N uses and specific environmental losses.

In this paper, we combined the N-Calculator with NUFER to determine the N footprint of food products consumed by individuals and to estimate the N losses in different forms during food production in China over the past five decades. The specific objectives are:

- To quantify the N footprint of the main food items in China from 1961 to 2010;
- To analyze the fate of N losses to the environment from food production in China over time; and
- To compare the N footprint of food in China with those of other countries.
2. Materials and methods

2.1. Calculation of the food N footprint
The calculation of the N footprint of food production and consumption in China (hereafter ‘N footprint’) is based on a modified version of the N-Calculator (Leach et al. 2012). The N-Calculator approach is modified in three ways with respect to the food component. First, we did not consider the energy consumption of food production and consumption in the N footprint calculation because it contributes in general a very small proportion to the total N footprint (Leach et al. 2012). Second, we used a separate model (NUFER) to calculate virtual N factors, which are explained in more detail below. Third, we did not consider fossil fuel combustion associated with heating, electricity, transportation and production of goods and services.

‘Food’ is a generalized definition in this study, which does not distinguish different existing forms of food products before and after food processing. For example, wheat grain after harvest is the primary food commodity, bread, cake and noodles are different food products after processing. We use ‘wheat’ to represent all these food products originated from wheat as a whole. The N footprint of food is the sum of the N losses related to food production and consumption. The food consumption N footprint is the quantity of food N actually consumed by human beings based on the assumption that adults excrete the equivalent N contained in the food they eat (i.e. no net N retention). The food production N footprint represents all the N losses along the chain of food production to food consumption (Leach et al. 2012). Here we chose 13 different food items, including seven plant-derived (wheat, maize, rice, soybeans, vegetables, fruits and roots), and six animal-derived (pig meat, beef, chicken meat, eggs, milk and fish & seafood) food items. The total per capita food N footprint in China is the sum of the per capita food consumption N footprint and food production N footprint of the 13 selected food types.

We used food protein supply data from the Food and Agricultural Organization of the United Nations Statistical Database (FAOSTAT) for the period 1961 to 2010 to calculate the food consumption N footprint in China (FAOstat 2016). Data and information about food losses and wastes that occurs at the retailer, food services and consumer were derived from literature (supplementary table S4, available at stacks.iop.org/ERL/12/104006/mmedia). Food production data were derived from the NUFER model and data on N fertilizer application for different crops were derived from literature and statistical data (tables S2 to S5).

The following equation shows the calculation method of the total per capita N footprint of food (NFfood):

\[ NF_{food} = \sum_{i=1}^{n} NF_{food \_i} = \sum_{i=1}^{n} (NF_{consumption \_i} + NF_{production \_i}) \]  

where NFconsumption represents the food consumption N footprint; NFproduction represents the food production N footprint; and i represents the different types of food \((n = 13)\). The results will be shown as the average value per decade, for example, NFfood in the 1960s is the average value from 1961 to 1970.

2.2. Calculation of the food consumption N footprint
The average per capita food consumption N footprint \((NF_{consumption})\) of a certain food type in a certain year followed the definition by Leach et al. (2012), as follows:

\[ NF_{consumption \_i} = S_{protein \_i} \times NC_{protein \_i} - W_{food \_i} \]  

where \(S_{protein \_i}\) is the per capita protein supply of a certain food item, as derived from FAOSTAT (FAOstat 2016); \(NC_{protein \_i}\) is the N content of protein \((16\%)\); and \(W_{food \_i}\) is the per capita food waste related to consumption (at the retailer, food service, and consumer levels). We assumed that the average adults do not accumulate nitrogen, meaning that all N consumed enters the sewage stream. Sewage treatment with N removal technology was not considered in this study because of the low application rate and efficiency in China (Gong 2000). Therefore, all N consumed is considered to be released to the environment as human waste. It should be noted that this assumption is likely an overestimate because of recycling pathways (e.g. human waste used as fertilizer) and denitrification that occurs without sewage treatment.

2.3. Calculation of the food production N footprint
Virtual nitrogen is defined here as N that was used in the food production process and is not contained in the food product that is consumed. It includes fertilizer volatilization and runoff, losses during food harvest and processing, animal manure losses, and food waste (Galloway et al. 2014, Leach et al. 2012). The N released to the environment in the process of food production to consumption per unit of N consumed is described by virtual nitrogen factors (VNFs). The average per capita food production N footprint \((NF_{production})\) of a certain food type in a certain year is calculated as

\[ NF_{production \_i} = NF_{consumption \_i} \times VNF_{food \_i} \]  

where \(VNF_{food \_i}\) is the virtual N factor of a certain food item, representing the amount ofNr lost to the environment per unit N consumed (Leach et al. 2012).

Similar to the description by Leach et al. (2012), we assume that N flows between production and consumption of plant-derived food to have the following five steps: 1) input of new N, 2) crop production, 3) crop harvesting, 4) plant-derived food processing, and 5) food consumption. Nitrogen flows between production and consumption of animal-derived food can be captured in the following seven
steps: 1) input of new N, 2) feed production, 3) feed processing, 4) animal production, 5) animal slaughtering, 6) animal-derived food processing, and 7) food consumption. Figure S1 conceptualizes the different stages of plant-derived and animal-derived food production and consumption.

During crop and animal production, N may be lost to the environment in four ways: ammonia (NH3) emission, nitrous oxide (N2O) emission, dinitrogen (N2) emission and N losses to water (including N losses through surface runoff, leaching and erosion). Unlike other nitrogen species, N2 emission does not cause environmental problems. Here we use emission factors derived from the NUFER model (Ma et al 2012) to calculate N losses in different forms that occur during food production. Calculation methods are presented in the supplementary information; detailed information on emission factors is presented in table S5.

To calculate VNFs, Leach et al (2012) use two indicators at each step of the food production process: N that continues to the next step (N uptake or % of previous) and N that is recycled (N recycled or % recycled). In this study, we rename these two indicators as NUE and nitrogen recycling efficiency (NRE), respectively, and use the same calculation methods to calculate VNFs of 13 major food items for China. However, as noted earlier, nutrient flows of food production and consumption in China are largely different from the US, thus it is very important to calculate local NUE and NRE for China. We use the NUFER model to provide the detailed information for the data points to calculate the NUE and NRE of 13 kinds of food items, which is described in the supplementary information. Results for the NUE and NRE at different stages used in the calculations of VNFs are presented in tables S6–S15. The NUFER model also enabled the N footprint to be reported by N species, which is a new addition to the N footprint approach (table S1).

According to the methods used by Shibata et al (2014), the virtual N factors considering food trade (VNFf) are estimated as follows:

$$VNF_f = SSR \times VNF_{NT} + (1 - SSR) \times VNF_{Import}$$

where VNFNT is the VNF without considering food trade; VNFimport was based on the VNF of the food items from the US, one of China’s main agricultural trading partners; and SSR is the self-sufficiency rate of a specific food item, which describes how much food produced in-country contributes to total food supply (table S2).

3. Results

3.1. Virtual N factors of main food items

There are large differences among food items when examining VNF changes between 1961 and 2010 (table 1). VNFs of vegetables, fruits and roots (potatoes and sweet potatoes) increased continuously over the past five decades. Roots had the highest increase (198-fold), followed by vegetables (70-fold). The high rate of increase is due in part to the very low VNFs in the 1960s. VNFs of wheat, maize and rice increased from the 1960s to the 1990s, and then tended to decrease. In contrast, VNFs of soybeans decreased from 4.6 in the 1960s to 1.3 in the 2000s. Most meat items showed increasing VNFs from 1961–2010. VNFs of pig meat, beef and chicken increased throughout the whole period, while VNFs of eggs and milk decreased around the 1970s and the 1980s, but increased thereafter (table 1).

3.2. Per capita and national food N footprint

The per capita food N footprint increased from 4.7 kg N capita⁻¹ yr⁻¹ in the 1960s to 21.3 kg N capita⁻¹ yr⁻¹ in the 2000s (figure 1). For plant-derived food, the per capita N footprint increased over the last five decades for all crops except for maize and soybeans. Due to the dramatic decreases in per capita protein supply quantity of maize (29-fold) (table S2) and the VNF of soybeans (3.5-fold) (table 1), the per capita N footprint of soybeans decreased from 4.6 in the 1960s to 1.3 in the 2000s.
footprint of maize and soybeans decreased from 0.9 to 0.03 kg N capita\(^{-1}\) yr\(^{-1}\) and from 1.1 to 0.4 kg N capita\(^{-1}\) yr\(^{-1}\), respectively. The most dramatic increase occurred with roots, vegetables and fruits: the per capita food N footprint increased by 12, 33 and 82-fold, respectively. For animal-derived food, the per capita food N footprint increased continuously and significantly during the past five decades. Pig meat contributed 21% to the per capita N footprint in China in the 2000s, a seven-fold increase compared to the 1960s. The per capita food N footprint increased from 0.01 to 0.5 kg N capita\(^{-1}\) yr\(^{-1}\) (38-fold) and from 0.1 to 1.2 kg N capita\(^{-1}\) yr\(^{-1}\) (15-fold), respectively (figure 1).

The national food N footprint in China increased eight-fold during the past five decades, from 3.4 to 28.2 metric tons (MT) N yr\(^{-1}\) (figure 2). The increasing rate of the national food N footprint in China started to accelerate after the 1970s, and had the highest increase in the 1990s. The N footprint of plant-derived food increased from 2.2 MT N yr\(^{-1}\) in the 1960s to 13 MT N yr\(^{-1}\) in the 2000s. The N footprint of animal-derived food increased from 1.3 MT N yr\(^{-1}\) in the 1960s to 15.1 MT N yr\(^{-1}\) in the 2000s, and overtook the N footprint of plant-derived food in the 1990s. In the 2000s, animal-derived food contributed 54% to the national food N footprint.

3.3. Nitrogen losses from food production

The national N losses from food production increased from 3.0 MT N yr\(^{-1}\) to 27.2 MT N yr\(^{-1}\) over the past five decades. Emissions of NH\(_3\) and N\(_2\) are the main loss items, NH\(_3\) emissions increased from 1.3 MT N yr\(^{-1}\) in the 1960s to 9.6 MT N yr\(^{-1}\) in the 2000s. However, the contribution of NH\(_3\) emissions decreased from 42% to 35%. Due to increasing fertilizer application and biological nitrogen fixation (BNF) during the past five decades, N\(_2\)O emissions and N\(_2\) emissions increased from 0.04 MT N yr\(^{-1}\) to 0.3 MT N yr\(^{-1}\) and from 1.2 MT N yr\(^{-1}\) to 10.3 MT N yr\(^{-1}\),
respectively. The contributions of N₂O and N₂ emissions were relatively stable in the past five decades, accounting for nearly 1.5% and 38% of the total losses respectively. N losses to water increased from 0.5 MT N yr⁻¹ in the 1960s to 6.9 MT N yr⁻¹ in the 2000s. The contribution of N losses to water increased from 17% to 25% (figure 3).

4. Discussion

This study provides the first comprehensive analysis of the N footprint of food in China through the integration of the N-Calculator and the NUFER model. It analyzes the N flows of the main food items from production to consumption by humans, and it quantifies the virtual N factors using data on the NUE, recycling rate and losses at each stage of the whole food production to consumption chain from the 1960s to the 2000s. Large increases in the national food N footprint and Nr losses per capita were found over the past 50 years. NUFER provides N flows and environmental losses within the chain of food production to consumption, which were used to calculates VNFs of different food items, considering historical changes in food production and consumption in China. The NUFER model also makes the important connection to potential environmental impacts more feasible. The first N-Calculator N footprint calculation for food in China is presented here. This method can both help individual Chinese consumers better understand their food N footprint and improve the estimation of environmental impacts during food production in China.

4.1. Characteristics of the food N footprint in China

The increases in the per capita N footprint (by 4.5-fold) (figure 1) and population (by 1.8-fold) (NBSC 2015) between 1961 and 2010 have both contributed to the increase in the national food N footprint (by 8.3-fold) (figure 2). The per capita food consumption N footprint increased from 1.8 to 3.3 kg N capita⁻¹ yr⁻¹ (1.8-fold); however, its contribution to the total food N footprint decreased from 38% in the 1960s to 16% in the 2000s. The per capita food production N footprint increased from 2.9 to 18.0 kg N capita⁻¹ yr⁻¹ (six-fold); its contribution to the total food N footprint increased from 62% in the 1960s to 84% in the 2000s (figure S2). The contributions of the food production N footprint to the N footprint of plant-derived food increased from 48% in the 1960s to 82% in the 2000s. The food production N footprint contributed a relatively stable share of nearly 85% to the N footprint of animal-derived food in the past five decades (figure 2).

The main reason for the increase in the per capita food consumption N footprint was the increase in consumption of animal-derived food (figure S3). The food consumption N footprint of animal-derived food did not change much during the 1960s and 1970s, mainly because of the poor economic conditions in China at that time (Naughton 2007). At the beginning of the 1980s, along with the ‘reform and opening-up’ national policy, the average income increased quickly, the urban population increased from 18% in 1978 to more than 40% in the 2000s (NBSC 2015), and crop and animal production started to rise quickly (Zhang et al 2012, Ju et al 2009). These favorable conditions promoted the consumption of animal-derived food and increased the food consumption N footprint (figure S3).

The larger increase in the food production N footprint compared to the food consumption N footprint (six-fold versus two-fold) (figures S3 and S4) is because the VNFs increased substantially over the past five decades. Increased fertilizer N inputs in crop production, increased animal production and a low recycling rate of animal manure N were the main drivers of the increasing VNFs (Zhang et al 2012, Ma et al 2012, Zhang et al 2008, Bai et al 2016).

Not all food items had increasing VNFs. For example, the VNF of wheat increased from the 1960s to the 1990s, but then stabilized as the slight increase in fertilizer N input was compensated by an increase in harvested yield. Similar trends were observed for maize (table 1). Interestingly, the VNF of soybeans decreased over time for a number of reasons. First, due to the rapid development of breeding programs since
the founding of new China, many new cultivars with better productivity and quality have been released, which has stimulated the dramatic increase of soybean yield over the past five decades (Xue 2013, Liu et al 2008). Second, the increase of fertilizer N inputs was small relative to the increase of the soybean yield. Third, soybean imports have increased over the past two decades, and the VNF of soybeans is lower in exporting countries (including the US) than in China. The decrease of the eggs VNF in the 1980s and 1990s and the decrease of the milk VNF in the 1980s were also due to relatively large increases in yield and productivity (table S2).

Some food items with an increasing N footprint do not contribute a large proportion to the overall N footprint. For example, the per capita N footprint of fruits accounts for less than 4% of the per capita N footprint in China in the 2000s, but it increased 82-fold from the 1960s and the 2000s (figure 1). Pig meat contributed 21% to the per capita N footprint in China in the 2000s, but its increase (seven-fold) was relatively modest (figure 1).

4.2. Nitrogen losses associated with food production

The national N losses associated with plant-derived and animal-derived food production increased from 2.4 to 19.6 MT N yr\(^{-1}\) and from 0.6 to 7.5 MT N yr\(^{-1}\), respectively. The contribution of N losses associated with animal-derived food production increased from 21% in the 1960s to 28% in the 2000s. Increased fertilizer use and consumption of animal-derived food have become main drivers of the growing environmental costs of food systems (Tilman and Clark 2014, Xue and Landis 2010). N losses during feed crop production are merged into the total N losses of animal-derived food production. However, the total N losses were still dominated by plant-derived food production, which contributed 72% in the 2000s (table S16). This proportion is similar to the estimate provided in the study of Ma et al (2010).

The results of this study show that NH\(_3\) emission and N losses to water are the main N loss pathways of animal production in China (table S16), similar to the results of Ma et al (2010) and Bai et al (2016). Ma et al (2010) estimated the N losses from food production in 2005 at 38.5 MT N yr\(^{-1}\), which is much higher than the result of this study (27.2 MT N yr\(^{-1}\)) for the 2000s. This difference is mainly related to the difference in years and the numbers of food items; Ma et al (2010) included ten more plant-derived food items and five more animal-derived food items in their study compared to this study. Bai et al (2016) estimated total N losses from livestock production (including manure excretion, housing and storage) at 14.4 MT N yr\(^{-1}\) in 2010, which is much larger than the result of this study (7.5 MT N yr\(^{-1}\) in the 2000s) (table S16). This difference is related to the fact that our estimate is the average value from 2001–2010, while Bai et al (2016) estimated the N losses for 2010 (which are much higher than those in 2000). Also, Bai et al (2016) included sheep and goats, which are not included in this study.

N losses associated with vegetables, fruits and pig meat production increased after the 1980s, and accounted for 32%, 15% and 13% of the total N losses in China in the 2000s, respectively (table S17). N losses associated with the production of wheat, maize and rice reached a peak in the 1980s and then started to decrease. N losses associated with soybeans steadily decreased over the past five decades. N losses related to roots and animal-derived food items increased during the past five decades. Pig meat is the largest contributor to the N losses from animal-derived food (table S17).

4.3. Comparison with other countries

Most papers about N footprints are also based on the N-Calculator methodology (Galloway et al 2014, Leach et al 2012, Pierer et al 2014, Shibata et al 2014, Stevens et al 2014, Liang et al 2016, Shibata et al 2017, Hutton et al 2017), which facilitate comparison. Here, we compare only the N footprint of food, as we did not consider the N footprint related to energy consumption.

The per capita food N footprint in China was 21.3 kg N capita\(^{-1}\) yr\(^{-1}\) with food trade and 21.5 kg N capita\(^{-1}\) yr\(^{-1}\) without food trade in the 2000s (figure 4). This is higher than the food N footprint of Tanzania, Austria and Germany, close to that of the Netherlands, but lower than those of the UK, the US, Japan and Australia. The proportion of the food production N footprint to the food N footprint ranged from 77% in Tanzania to 95% in the Netherlands, which is mainly related to the amount of food N consumption and the level of sewage treatment (figure 4). The N footprint of plant-derived food is much higher in China than in some other developed countries, regardless of whether the total per capita food N footprint was higher in those countries. The US food N footprint is dominated by meat based animal-derived food items and that of the Netherlands is dominated by non-meat animal-derived food items (i.e. dairy, eggs and fish) (figure S5).

The VNFs indicate how much Nr is lost to the environment per unit of N in a food item consumed. The Chinese VNFs are generally higher than those of other countries, except for Japan. Japanese VNFs are especially high for meat products (pig meat, beef and poultry meat) (table 2), this is mainly related to the relatively low N use efficiency for feed crops and low feed conversion ratio for animals in Japan (Shibata et al 2014). A high chemical N fertilizer input and poor manure management in China caused a low NUE of crop and animal food production to consumption chain (Ma et al 2010, Zhang et al 2008, Yan et al 2014), which lead to high VNFs of food in China. For
example, the average apparent recovery efficiency of applied nitrogen (REN) for Chinese cereal (i.e. wheat, rice and maize) production was 26%–28% from 2001 to 2005, much lower than the global average value of 40%–60% (Zhang et al 2008). The N use efficiency of crop production in China was only 26% in 2005 (Ma et al 2010, which was much lower than the average level of Europe and the United States (Dobermann 2007, Oenema et al 2009, Howarth et al 2002). A low recycling rate of animal manure is the main driver of low NUE in animal production in China. Only 33% of the amount of N excreted in animal manure was recycled, which is much lower than in the US (75%) (Doering et al 2011) and the European Union (80%) (Leip et al 2011). The NUE of animal production in China was 11% in 2005 (Ma et al 2010), which is also lower than the world average level of 15% according to Zhang et al (2008).

4.4. Sources of uncertainty
In this study, we did not take energy consumption during food production into consideration when calculating the food N footprint. Developing a database of energy consumption related to food production and consumption should be included in future calculation in China, especially for food items which are highly dependent on international trade. However, previous studies in other countries have found that the energy portion of the food N footprint is very small (Leach et al 2012, Liang et al 2016, Shibata et al 2014).

We used the American VNF of fish & seafood data for China and assumed no temporal changes during the past five decades. Additionally, we used the VNFs for the US as representative for all countries exporting food to China because the US VNFs were the only ones available for major exporters to China. However,
Brazil is one of the most important soybean exporting country for China. The application of N footprint methods to more countries would benefit the estimation of the global N footprint.

We assumed there were no N losses from producing ‘other feed products’ (feed products except for maize and soybeans) because many of them are waste products (e.g. crop residue), this assumption underestimates the N footprint of animal-derived food items in China. We did not consider temporal changes in emission factors of N losses during plant-derived food production, which may cause uncertainties in food production N footprint and N losses results. Expanding the application of the N footprint methodology to a wider range of different specific food types and building a more complete emission factors database would also help to conduct a more accurate estimation of the N footprint and N losses of the food system in China.

5. Conclusion

This is the first study that combines the N-Calculator and the NUFER model to analyze the changes of the N footprint of food and to quantify specific N losses associated with food production in China during the last five decades.

Our analyses indicate that the per capita food N footprint in China increased by 4.5-fold from 1961 to 2010. This is related to the increasing food N intake, especially through animal-derived food consumption, and the increasing VNFs of most food items over the past five decades. NH₃ and N₂ emissions contributed a total of nearly 80% to the total N losses associated with crop and animal production. Contribution of animal-derived food to the total N losses increased over the past five decades.

The per capita food N footprint is higher for China than Tanzania, Austria and Germany, comparable to the Netherlands, but lower than those of the UK, the US, Japan and Australia. Over use of N fertilizer and poor reuse of manure are the main causes of the relatively high food N footprint in China.

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