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LETTER

Virtual nitrogen factors and nitrogen footprints associated with nitrogen loss and food wastage of China’s main food crops

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Keywords: nitrogen, nitrogen loss, virtual nitrogen factor, nitrogen footprint, China

Supplementary material for this article is available online

Abstract

A nitrogen (N) flow, divided into production, food supply, and consumption phases, was designed to calculate the virtual N factors (VNFs) and N footprints (NFs) of China’s main food crops. It covered four food groups—cereals, tubers, vegetables, and fruits—comprising 24 food crops. A meta-analysis of 4896 relevant examples from 443 publications was conducted to build a database on N availability and N loss rates during each stage. We calculated N loss from each food group during each phase, and estimated VNFs and NFs based on N loss. It was found that 39.2%–67.6% of N inputs were lost during the production phase, 6.6%–15.2% during the food supply phase, and 0.9%–6.7% during the consumption phase. VNFs for cereals, tubers, vegetables, and fruits were 2.1, 2.9, 4.1, and 8.6, respectively. To raise public awareness, we also calculated the NFs, which were 30.9, 6.7, 7.4, and 17.2 gN kg−1 for cereals, tubers, vegetables, and fruits consumed, respectively, equal to 9.3 kg N capita−1 yr−1 consumption for these four food crops in China. We concluded that policies and strategies to reduce N loss, especially N loss embedded in food loss, must be taken into account to improve the technologies, infrastructure, approaches, and social awareness in reducing nutrient loss during food production and consumption phases.

1. Introduction

To attain national food security, China’s crop production has increased by a factor of five over the last six decades (FAOSTAT 2016). However, it greatly depends on the overuse of synthetic fertilizers, especially N fertilizers, that account for one-third of global consumption (IFA 2016). For example, N fertilizers used for wheat and maize production were 326 and 263 kg N ha−1, respectively, during one crop season in the 2000s (Cui et al 2010), and excessive N fertilizer usage reached 735 kg N ha−1 for greenhouse vegetables during a similar crop season in China (Liang 2011). There is little doubt that the overuse of N fertilizers has introduced serious N pollution (Ju et al 2009, MEP 2010, Wang et al 2015).

Currently, most studies in China today focus on nitrogen use efficiency (NUE) and Nr (reactive N: all N species except N2) loss to the environment during the production stage (Cui et al 2014), while few studies have dealt with Nr loss embedded in food loss in China (Ma et al 2015). Food wastage includes both food loss and food waste, with the former referring to losses that occur through inefficiencies in infrastructure and logistics, inadequate technologies, and other unintentional losses, while the latter refers to discarded food meant for consumption (FAO 2013). These losses, in conjunction with the collateral Nr loss, are up to 1.3 billion tons per year, amounting to approximately one-third to one-half of global food production (Parfitt et al 2010, Gustavsson et al 2011).
To estimate N loss within supply chains, Leach et al (2012) introduced the concept of the nitrogen footprint (NF). It is defined as the total Nr loss to the environment from production to consumption, and was subsequently developed by the addition of a group of tools: N-Calculator, N-Institution, N-Label, N-Neutrality, and N-Indicator. These tools were introduced to increase the awareness of producers, consumers, and stakeholders and aid in decision making regarding offsets (Galloway et al 2014, Shibata et al 2017).

Owing to the shortage of local available data for the N-Calculator tools, Gu et al (2013) developed the N mass balance approach to simulate NF in China. Ma et al (2010) simulated N loss to the environment via nutrient flow in food chains in China, which included Nr loss during processing (crop to edible food) and food wastage (household kitchen loss) but without distinguishing between Nr loss during harvest, transport, and storage. Although these studies in China have been integrated using N budget estimations, virtual nitrogen factor (VNF) and NF techniques applied to different food categories could not be deduced.

In this study, we designed a N flow from production to consumption to calculate the per N consumed and per product VNfs and NFs of four food groups that make up the 24 main food crops grown in China, including three cereals, two tubers, thirteen vegetables, and six fruits. We conducted a comprehensive literature review and meta-analysis to quantify Nr loss during each N flow stage. In contrast to the available integrated estimations of NF in China, VNF and NF of each food crop group were calculated based on the results of Nr loss. Results from this study will not only raise awareness for stakeholders and policymakers regarding the importance of reducing both N fertilizers and food loss but will also educate the public in reducing food waste, which will help conserve food and promote a sustainable lifestyle in China.

2. Materials and methods

2.1. Nitrogen flow design

In contrast to food supply chains that only constitute food losses and wastage (Liu et al 2013), we designed the N flow from ‘cradle to grave’, which included three phases (production, food supply, and consumption) consisting of eight stages (crop, product, harvest, storage, transport, processing, distribution, and consumption), as well as the extra stage of human intake transfer to human waste (figure 1). For each stage, both available N and lost N were taken into account. Available N refers to N uptake by crops, N embedded in products, and N intake during consumption. Lost N refers to Nr losses in the form of nitrogenous compounds as well as N embedded in food loss and human waste. It should be noted that N₂ produced during production and sewage treatment (human waste) processes is returned back to the atmosphere as unreactive N, and is not considered Nr loss. Moreover, nitrogenous gas emissions from energy use during all phases were not taken into account in this study because of a lack of energy use data for cropping systems.

2.2. Data sources

Consistent with FAO standards, four groups, i.e. cereals, tubers, vegetables (including melons), and fruits, comprising 24 main food crops were considered, which respectively contribute 98%, 96%, 79%, and 82% of the total production of these four groups in China (figure S1) and account for 84% of N fertilizer usage in China (Wu 2014).

A meta-analysis method was used to obtain available N or N loss parameters during each stage. We applied a variety of keywords, e.g. ‘N uptake’, ‘N loss’, ‘N use efficiency’, ‘N balance’, ‘food losses’, and ‘food waste’, for the literature review from the Web of Science (ISI) and the China National Knowledge Infrastructure databases (CNKI), all based on studies in China. Publications from the 1980s through to the 2010s (4896 publications from 443 sources) were selected for the
final calculations. Data presented in tables or text were taken directly, and data presented in graphs were digitized using GetDATA software (version 2.22).

During the production phase, we analyzed available N fraction parameters in products (supplementary tables S1–S4; appendix 1, available at stacks.iop.org/ERL/13/014017/mmedia) instead of referring in detail to all the lost items (figure 1). Literature was selected with either the proportion of available N during the crop growth stage, or the available N proportion calculated by product of N content and yields or by product of N harvest indexes and total N uptake.

In place of the isolated N compounds released to the environment, N losses during the food supply and consumption phases were embedded in food loss. Therefore, food loss rates were defaulted as N loss rates during these phases. Total loss rates during each stage were analyzed instead of all possible loss paths (tables S5–S6; appendices 2–3). For limitation of N loss rates during the food supply and consumption phases, we merged loss rates of cereals and tubers (CT) and loss rates of vegetables and fruits (VF) during the food supply phase, and we merged loss rates of tubers and vegetables (TV) during the consumption phase.

2.3. Calculation of VNF and NF
The VNF is defined as the Nr released to the environment per unit of N consumed (Leach et al. 2012), indicating the environmental cost of different dietary structures. We calculated VNFs of food crops as follows:

\[ VNF = \sum_{i=1}^{9} \frac{N_{Li}}{N_c} \]

\[ N_{Li} = N_{Ai(-1)} \times L_i - N_{Ri} \quad \text{(2)} \]

\[ N_{Ai} = 100, \text{ when } i = 1 \]

\[ N_{R2} = N_{A2}(1 - NHI) \times R_{S2} \quad \text{ (when } i = 2 \) \]

where \( i \) is stage \( i \) with corresponding number as listed in figure 1; \( N_{Li} \) = Nr loss at stage \( i \); \( N_c \) = N consumed; \( L_i \) = the loss rate of N at stage \( i \); \( A_i \) = the available N at stage \( i \); A is the available rate of N; \( R_{i} \) = N recycled to stage \( i \); NHI = the N harvest index referring to the ratio of N in products to N in total biomass; \( R_{S} \) = the residual crop recycling rate; and \( N_{Li}, N_{Ai}, N_{Ri} \) and \( N_{R} \) are all in units of kg N ha\(^{-1}\) yr\(^{-1}\).

We also developed the per product VNF (=VNFc) using equation 5 to calculate the per product NF. NF in our study refers to N loss of per kg of a certain crop consumption, and it was calculated as follows:

\[ VNFc = \frac{\sum_{i=1}^{9} N_{Li}}{N_{Nc}} \]

\[ NF = VNFc \times N_{Nc} \quad \text{(6)} \]

\[ NF_p = \frac{\Sigma (NF \times C_s)}{Population} \quad \text{(7)} \]

where \( N_{Nc} \) is the N content of the consumed product, which was defaulted to equal the crop product N content without change after harvest; \( C_s \) is the domestic supply of the crop; \( NF \) is in units of g N loss kg\(^{-1}\) crop; \( NF_p \) is the per capita NF of all crops (in units of kg N capita\(^{-1}\) yr\(^{-1}\)); and \( N_{Nc} \) is in units of g N kg\(^{-1}\).

All average \( A_i, L_i, \) and NHI were obtained from the meta-analysis results (tables S1–S6), and available N or N loss rates during each stage were listed or plotted in tables 1 and 57 and figures 2 and 3. Residue recycling proportions \( (R_{S2}) \) for wheat, maize, rice, and tubers were 74%, 30%, 42%, and 13%, respectively (Gao et al. 2002, Bao et al. 2014, Fang et al. 2015). Crop residues of vegetables and fruits were not considered in this study since no residual products from them are typically recycled. Four percent of bran produced during processing was recycled into the cropping systems (Ma et al. 2010). Table loss recycling proportions were zero, because they were mostly mixed with municipal solid waste and burnt and moved to landfills (Liu 2013).

2.4. Presetting supplemental processes in N flow
We considered N deposition and denitrification in the N flow design owing to the high N deposition in China and the innocuous N \( N_2 \), which were also part of the advances made in the original framework for the VNF calculation (Leach et al. 2012). Sixteen units of N deposition were applied to CT groups (table S8); no N deposition was taken into account for VF groups because of the exorbitant usage of N fertilizers and multiple cropping systems, which resulted in a negligible fraction of N deposition relative to total N inputs. Moreover, greenhouse vegetables are not influenced by N deposition.

\( N_2 \) loss from denitrification during production was defaulted as the difference between N input and output, assuming N in soil remained balanced (table S8). We calculated the \( N_2 \) loss rate of tubers as the average data of dry-land cereal crops because of data limitations as well as the overlap distribution of wheat and maize (77%) in agricultural regions (China Statistical Yearbook 2016). The \( N_2 \) loss rate for the vegetable cropping system was set to 15.3%, which was taken from direct measurements (Cao et al. 2006). This percentage (15.3%) was also applied to the fruit cropping system because of a lack of data sources and its higher N fertilizer application comparative to the vegetable cropping system (Wu 2014).

Another \( N_2 \) release source was from sewage treatment. For most N consumed by well-fed adults...
transferred to waste with only 1% released as N$_2$O and NH$_3$ (Sutton et al 2000, Tallec et al 2007), human N intake can be defaulted to equal N in waste (Voegt and Voegt 2003). And approximately 27% of human waste is released as N$_2$ via sewage treatment (supplemental information).

## 3. Results

### 3.1. Available nitrogen during the production phase

An average of 4455, 22587, 27115, and 8180 kg products were harvested for cereals, tubers, vegetables, and fruits, respectively, in conjunction with their associative per 100 kg of N fertilizer applications. The average of the N uptake rates for each food group was 63.4%, 50.0%, 39.3%, and 17.1% for cereals, tubers, vegetables, and fruits, respectively (table 1). We found the highest available N rates in the cereal group with higher protein content in grains, while the lowest available N rates were in the fruit group with a smaller proportion of products relative to biomass. The greatest variation in available N rates were found in the vegetable group (table S7).

### 3.2. Nitrogen loss during the food supply phase

Losses of Nr during the food supply phase for the CT groups were 5.3%, 5.7%, 1.5%, 3.2% and 0.5% during the harvest, storage, transport, processing, and distribution stages, respectively; while food loss rates for the VF groups were 5.0%, 16.1%, 5.8%, 11.0% and 9.1%, respectively (figure 2). In general, loss rates of food N in CT were lower compared with VF for all stages with the exception of the harvest stage during the food supply phase (figure 2).

### 3.3. Nitrogen loss during the food consumption phase

Losses of Nr during the food consumption phase were on average 12.8%, 18.4%, and 8.2% for cereals, TV (tubers and vegetables), and fruits, respectively (figure 3). The TV had the highest Nr loss rate during the food consumption stage, while fruits had the lowest Nr loss rate during the same stage. We found a large variation in cereals with loss rates ranging from 1.1%−49.9%. This was followed by TV, which varied from 10.3%−46.5%. Less variation was found for fruits, which ranged from 6.5%−9.8%.
The virtual nitrogen factors (VNFs) and nitrogen footprints (NFs) of the main crops during both their separate phases and the total sum of nitrogen flow are shown in Table 2. The VNFs ranged from 2.1 to 14.7 g N loss kg⁻¹ food, while the corresponding total Nr losses were 14.7, 2.9, 13.2, and 30.9 g N kg⁻¹ food, respectively, while the corresponding total Nr losses were 44%, 22%, and 12% for cereals, vegetables, and fruits, respectively, during the food consumption phase. It should be noted that N flow in this study started from the production instead of the harvest stage. The Nr loss rates relative to total N inputs in each phase and the N uptake ratio (%) by crop products during the crop production phase are shown in Table 1. The Nr loss rates during the production phase (Cui et al. 2014), as well as food waste, can be greater than 50% in developed countries (FAO 2013). In our study, Nr loss rates were 12.7%, 18.4%, and 8.7% for cereals, vegetables, and fruits, respectively, during the food consumption phase. It should be noted that N flow in this study started from the production instead of the harvest stage seen in other studies. If only taking the food supply and consumption phases into account, Nr loss rates were 44%, 22%, and 12% for cereals, vegetables, and fruits, respectively, with cereal waste being significantly higher in both developed and developing countries (World Bank 2011, FAO 2013).

Food waste was the last but not the least factor on N loss, which further increased the inefficiency of the food supply chain. Globally, 30% of total N loss in the food supply chain can derive from table food waste, which can be greater than 50% in developed countries (FAO 2013). In our study, Nr loss rates were 12.7%, 18.4%, and 8.7% for cereals, vegetables, and fruits, respectively, during the food consumption phase. It should be noted that N flow in this study started from the production instead of the harvest stage seen in other studies. If only taking the food supply and consumption phases into account, Nr loss rates were 44%, 22%, and 12% for cereals, vegetables, and fruits, respectively, with cereal waste being significantly higher in both developed and developing countries (World Bank 2011, FAO 2013).

In contrast to previous studies that mostly focused on N loss during the production phase (Cui et al. 2014), VNFs and NFs in our study indicated that much of the Nr loss occurred during both food production and post-harvest processes. In our study, Nr loss during the food production phase contributed to half of

### Table 1. Harvest products per 100 units of nitrogen (N) fertilizer input and the N uptake ratio (%) by crop products during the crop production phase.

| Category | Harvest products (kg/100 kg N) | Percentages of N uptake (%) | N content (g N kg⁻¹) |
|----------|-------------------------------|-----------------------------|---------------------|
| Cereals  | 4455                          | 63.4                        | 14.7                |
| Tubers   | 22587                         | 30.0                        | 2.3                 |
| Vegetables | 27715                        | 39.3                        | 1.8                 |
| Fruits   | 8180                          | 17.1                        | 2.0                 |

Note: uptake ratio of applied N (%) = crop N/applied N × 100%; N content (g N kg⁻¹) = uptake ratio of applied N/harvest products × 1000; detailed values for all the 24 crops were listed in table S7.

### Table 2. Virtual nitrogen factors (per N consumed VNF) and nitrogen footprints (per product NF) of the main crops during both their separate phases and the total sum of nitrogen flow.

| Category | Production | Food supply | Consumption | Total |
|----------|------------|-------------|-------------|-------|
| Cereals  | 1.0        | 0.2         | 0.9         | 2.1   |
| Tubers   | 1.8        | 0.2         | 1.0         | 2.9   |
| Vegetables | 2.3        | 0.8         | 1.0         | 4.1   |
| Fruits   | 7.1        | 0.7         | 0.8         | 8.6   |

| Category | NF (g N loss kg⁻¹ food) | Production | Food supply | Consumption | Total |
|----------|-------------------------|------------|-------------|-------------|-------|
| Cereals  | 14.7                    | 2.9        | 13.2        | 30.9        |
| Tubers   | 4.1                     | 0.5        | 2.3         | 6.7         |
| Vegetables | 4.1                  | 1.5        | 1.8         | 7.4         |
| Fruits   | 14.2                    | 1.4        | 1.6         | 17.2        |

3.4. Nitrogen flow, virtual nitrogen factors, and nitrogen footprints

We developed N flow in each stage from production to human waste for the four crop groups (figure 4). On average, 46.7, 34.6, 19.5, and 9.5 units of N were consumed for cereals, tubers, vegetables, and fruits, respectively, while the corresponding total Nr losses were 96.2, 102.0, 79.6, and 82.1 units, respectively. VNFs (per consumed VNFs) and NFs (per product NFs) of these crops were calculated based on the N flow (table 2). The VNFs ranged from 2.1 to 14.7 with the lowest value found in cereals and the highest value found in fruits. This meant that 2.1–8.6 g N would be lost to the environment for every g of N taken up by consumers, and that N loss to the environment from fruits was higher than that of cereals.

Average NFs were 30.9, 6.7, 7.4, and 17.2 g N for every kg cereals, tubers, vegetables, and fruits consumed, respectively, and they were not consistent with VNFs because of variations in N content for the different crops. For example, cereals were the main source of protein intake under higher N content, while vegetables and fruits were not, which translates into higher VNFs but lower NFs compared to cereals. This meant that 6.7–30.9 g N would be released for every kg of crop products consumed. For the three different phases, VNFs and NFs were highest during the food production phases, in which fruits had the highest value and cereals the lowest. This was because of the relatively lower N fertilizer application (214 kg N ha⁻¹ yr⁻¹) used for cereal production compared to the higher N fertilizer application used for vegetable (735 kg N ha⁻¹ yr⁻¹) and fruit production (400–600 kg N ha⁻¹ yr⁻¹) (Liang 2011, Wu 2014, Wang et al. 2016).

From 6.6%–15.5% of N inputs were lost during food supply phases (figure 5) through spillage, damage, pests, peeling, degradation, and others. The higher water content in vegetables and fruits made them perishable, and N losses were because of both exogenous and endogenous (degradation) effects (Parfitt et al. 2010), while N loss from cereals was mainly because of exogenous (physical loss) effects. Generally, food loss rates have largely been attributed to industrial and logistic limitations pertaining to both technologies and infrastructure (FAO 2013).

4. Discussion

4.1. Distribution of nitrogen loss during different phases

Nr loss rates relative to total N inputs in each phase are shown in figure 5. The Nr loss rates were highest during the food production phases, in which fruits had the highest value and cereals the lowest. This was because of the relatively lower N fertilizer application (214 kg N ha⁻¹ yr⁻¹) used for cereal production compared to the higher N fertilizer application used for vegetable (735 kg N ha⁻¹ yr⁻¹) and fruit production (400–600 kg N ha⁻¹ yr⁻¹) (Liang 2011, Wu 2014, Wang et al. 2016).

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Food waste was the last but not the least factor on N loss, which further increased the inefficiency of the food supply chain. Globally, 30% of total N loss in the food supply chain can derive from table food waste, which can be greater than 50% in developed countries (FAO 2013). In our study, Nr loss rates were 12.7%, 18.4%, and 8.7% for cereals, vegetables, and fruits, respectively, during the food consumption phase. It should be noted that N flow in this study started from the production instead of the harvest stage seen in other studies. If only taking the food supply and consumption phases into account, Nr loss rates were 44%, 22%, and 12% for cereals, vegetables, and fruits, respectively, with cereal waste being significantly higher in both developed and developing countries (World Bank 2011, FAO 2013).

In contrast to previous studies that mostly focused on N loss during the production phase (Cui et al. 2014), VNFs and NFs in our study indicated that much of the Nr loss occurred during both food production and post-harvest processes. In our study, Nr loss during the food production phase contributed to half of
Figure 4. Nitrogen (N) flow for the main cropping systems from crop production to food consumption (A: cereals; B: tubers; C: vegetables; D: fruits) (grey boxes denote reactive nitrogen loss). The values represent relative values to the 100 units of applied N fertilizer (in the left-most box in each flow).

4.2. Comparison of VNFs and NFs between different countries

Comparisons of VNFs and NFs were conducted between China and other countries. The VNF of cereals in China was 43% higher compared with the United States (US), while it was 65% lower compared with Japan (figure 6). Taking a detailed analysis of comparative VNFs of maize in China and the SU as an example, N losses during the production, food supply and consumption phases were 35%, 5% and 32% of those in the US, respectively (Leach et al 2012), while the corresponding values in China were 39%, 15% and 13% (figures 4 and 5). This implied that the inefficiency of N fertilizer use in production and food supply phases were more responsible for the VNF in China while food loss and food waste were more responsible in the US. Similarly, the VNF of tubers in China were higher by a factor of 1.9 compared with the US, while only 48% of those in Japan. This was attributed to production efficiency, which was 50% and 65% in China and the US, respectively, but only 27% in Japan (Shibata et al 2014). The previous studies of the VNF in the US and Japan (Leach et al 2012, Shibata et al 2014) did not include the denitrification process to determine the VNFs during the food production phase (figure 1), suggesting that this difference in the definition of the total Nr loss before consumption (table 2). This means that the twofold N pollution effect should be reconsidered, including N loss embedded in food loss, which has been treated as municipal waste and further introduces nitrogenous pollution without recycling (He et al 2011, Lou et al 2017). Taking all post-harvest N losses into account, 2.1, 1.6, 1.8 and 1.2 times the N loss from cereals, tubers, vegetables, and fruits production, respectively, should be reevaluated as it pertains to environmental pollution from food production to consumption.
might be another source of the difference in VNF values between this study and previous reports (figure 6).

Trends in the VNF of vegetables were different from those of cereals and tubers. The VNF of vegetables in China was only 38% compared with the US, while it was similar to that of Japan. The Nr loss rates related to the VNF of vegetables were 85%, 25%, and 25% during food production, food supply, and consumption in the US, respectively, while the corresponding values in China were 45.4%, 39%, and 19%, respectively, showing that China’s vegetable VNF was half that of the US. However, the lower N loss rate during the production phase in China did not mean less N lost to the environment, and this was because of the higher absolute amount of N fertilizer applications and the possible residual effects of N in soil (Liang 2011). The higher Nr loss rate during the food supply phase in China indicated insufficient technology and infrastructure in storage and logistics. The highest VNF was found in the fruit group in China, but this result was attained without comparisons to the same categories from other countries because of a lack of available data. Shibata et al (2017) reported that the VNF for fruits tended to be higher than that of other crops in several countries.

4.3. Challenges and possible options for the Chinese agricultural system and society to reduce Nr loss to the environment

Increases in production and decreases in food loss have become a global problem under an increasing global population (FAO 2013). The European Parliament (2012) resolved to halve food loss and wastage by the year 2025 within the EU. It is also essential for China to reduce the VNFs and NFs not only during crop production stages in farmland but also during

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**Figure 5.** Available nitrogen (N) and reactive nitrogen (Nr) loss during each phase (numbers in parentheses are N available and N loss rates relative to available N that have passed through prior phases).

**Figure 6.** Comparison of virtual nitrogen (N) factors between different countries (data sources: China (this study); United States (Leach et al 2012); Japan (Shibata et al 2014)).
food supply and consumption phases, although, unlike the EU, no specific target has yet been established. In the pipe-and-hole model of N, it is impossible to achieve zero N loss (Oenama et al 2009). However, reducing N loss by improving NUE and reducing food loss is clearly feasible.

Here we discuss the challenges and possible options for the Chinese agricultural system to reduce Nr loss to the environment based on our analysis of the VNFs and NPs in this study. First, it is essential to reduce Nr loss during the crop production phase before the food supply and consumption phases. It is clear that increasing NUE and reducing N loss by integrated management is effective (Ju et al 2009, Cui et al 2014), but what is more important is to transfer the knowledge to farmers and encourage them to apply this knowledge. Initial efforts in farmer training by volunteer scientists and postgraduates have been very successful (Zhang et al 2016), however, nationwide support for both technology and finance should be launched, and professional technicians should be trained for sustainable agricultural services. At the same time, more attention should be paid to Nr loss during the food supply phases. Standardization should be implemented to improve infrastructure and technology from harvest to distribution. Strategies should also be put into place to encourage rural cooperatives with farmers not only during the crop production stage but also during each postharvest stage. Financial support should be provided to develop new technologies.

Second, it is important to reduce avoidable food waste ‘on the table’. It has been reported that 80% of food waste is preventable in the EU (Vanhan et al 2015). Although there were no available data on preventable food waste in China, statistics show that wasted food equates to approximately 50 million tons of grain per year, which could feed 200 million people per year (Xinhua News 2013). It is therefore extremely important to increase social awareness to reduce food waste, not only under economic and ethical perspectives but also under environmental and social perspectives. For example, promoting an environmentally sustainable lifestyle by ordering only enough food and asking restaurants to bag leftovers to bring home when eating out.

Finally, much more attention should be paid to N recycling initiatives, which could reduce both N pollution and N fertilizer applications. Currently, 80% of urban wastewater is treated, while half of the wastewater in China is produced in rural areas where only 10% of it is treated before discharge (supplementary information). Recycling of N from both table loss and human waste in China is almost zero (Liu 2013). More effort should therefore be focused on both effective technology development and applications to increase N recycling and its removal from the N flow chain. Both stakeholders and policymakers must be involved for this to happen.

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