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Driving forces and impacts of food system nitrogen flows in China, 1990 to 2012

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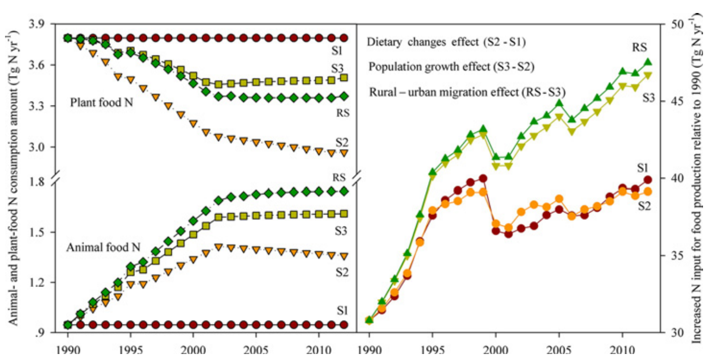
HIGHLIGHTS

- Urban-rural difference in per capita plant- and animal-food N (AN) was studied.
- One demands 0.3–0.5 kg more AN yr^{-1} when he moved to cities from a rural area.
- 17% increased AN was caused by rural-urban migration between 1990 and 2012.
- Dietary changes no significant contribution to N increase over the past two decades.
- Urban food-sourced N losses to soil and water bodies are 3 folds of rural area.

GRAPHICAL ABSTRACT



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ABSTRACT

Food nitrogen (N), which includes animal-food (AN) and plant-food N (PN), has been driven by population growth (PG), dietary changes associated with income growth (DC) and rural-urban migration (M) over the past three decades, and these changes combined with their N cost, have caused some effect on N use in China's food system. Although there is an increasing literature on food N and its environmental impacts in China, the relative magnitude of these driving forces are not well understood. Here we first quantify the differences in per capita AN and PN consumption in urban and rural areas and their impacts on N input to the food system during 1990–2012, and then quantify the relative contributions of DC, PG and M in the overall N change during this period. Our results show that a resident registered as living in city required 0.5 kg more AN yr^{-1} and 0.5 kg less PN yr^{-1} than one living in a rural area, in 2012. DC, PG and M accounted for 52%, 31% and 17% of the total AN increase, respectively. These three factors caused 46% of the increased N use for food production over the past two decades. Another 54% was mainly caused by the declining in N use efficiencies of the food system. Food-sourced N loss intensity in urban and rural areas were 502 and 162 kg N hm^{-2} in 2012, a three-fold difference due to the increasing amount and a linear rural-urban flow of N input, and inadequate N recovery via solid waste and wastewater treatment in cities. Our study highlights China is facing higher risks of environmental N pollution with urbanization, because of the high demand for AN and higher food-sourced N loss intensity in urban than in rural areas.

1. Introduction

Nitrogen (N) is an essential and irreplaceable element, which can sustain food production and global population after it is converted

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into reactive N (Nr) species (Galloway et al., 2004). But the imbalances and overuses of N have caused large Nr losses to the environment, resulting in a cascade of negative effects on natural resources and environmental quality, including soil acidification, eutrophication of aquatic systems, coastal dead zones, biodiversity loss, stratospheric ozone depletion, and an enhanced greenhouse effect as well as human health effects, all of which have become the focus of research in areas with large populations and intensive agriculture (Liu and Diamond, 2005; Schlesinger, 2009; Robertson and Vitousek, 2009; Sutton et al., 2011). An understanding of the correlation between human socioeconomic activities and N flows at local, regional, national, and global scales is essential to improving the N use efficiency (NUE) and to balancing food production with the aim of minimizing damages to environmental systems (EPA, 2012; Cui et al., 2013).

At the global scale, the Nr rate has already transgressed the planetary boundaries and seriously affected global sustainability (Steffen et al., 2015; Liu et al., 2015), and this trend may continue in the coming decades, driven by the rapidly increasing world human population and the concomitant increase in prosperity (Tilman et al., 2011). The human diet is transitioning to higher animal-food consumption, especially in emerging economies (Tilman et al., 2001), and the share of animal-food N (AN) to total food N is higher in urban diets than in rural ones (FAO, 2013; Tilman and Clark, 2014). These dietary changes are expected to continue, as some 2 billion more people move into cities in the wave of global urbanization, especially in China, India, southeast Asia and Africa (UN-Habitat, 2010), and the shift from traditional diets to those higher in AN will cause serious health and environmental problems (Tilman and Clark, 2014).

As the largest Nr producer and consumer, the most populous country in the world, and the one undergoing the greatest urbanization during the last few decades (Yang, 2013; X.M. Bai et al., 2014), China is an interesting case that demonstrates how population growth, dietary changes, rural-urban migration, and N management practices can affect long-term trends in N use and loss from the food production and consumption system, in an emerging economy. In crop production, large quantities of synthetic-fertilizer N have been used to increase crop yields, with the total amount reaching 30.6 Tg by 2012, up from 17.5 Tg in 1990 (NBSC, 2013). If current trends continue, total Nr input to China by 2050 will be more than double the 48.0 Tg in 2010 (Gu et al., 2015), accounting for 33–40% of the global increase in fertilizer N demand, from 2005 to 2050, driven by the increase in food demand (Tilman et al., 2011).

Furthermore, the continuing Chinese dietary shift to animal foods, which has driven the rapid intensification and specialization of animal-food production, has significantly increased the demand for animal feed (Chen et al., 2014), and caused serious environmental pollution because of the poor management of animal wastes (Ma et al., 2012; Hou et al., 2014). All these pressures, taken together, will increase the total demand for AN, and consequently the amount of N imported into the Chinese food system.

Rapid urbanization is indeed the most critical component of the increase in agricultural N demand, in China. Most of the high-AN food is consumed in urban settings (Lin et al., 2013; Hou et al., 2014). Yet the higher the urbanization rate, the lower the efficiencies of nutrient recycling, because an urban ecosystem is a combination of high nutrient density fluxes and disrupted N cycling (Grimm et al., 2008; Lin et al., 2013; Ma et al., 2014). The blocked recycling of N from cities to rural areas will cause large amounts of N to be stranded in urban environments after consumption (Marzluff et al., 2008). Thus, the rapid urbanization in developing countries will cause even more severe resource and environmental problems than have been previously suffered in developed countries (Lin and Grimm, 2015). One limitation to assessing and solving Nr-driven problems is the scarcity of detailed analyses on N stock and N losses to the environment in both urban and rural settings in China.A substantial literature has been undertaken to analyze the dietary transition per capita (Wei et al., 2008; Cui et al., 2016), quantify the budgets of N at the national scale in China (Ti et al., 2011; Cui et al., 2013; Gu et al., 2015) and the inputs or flows of N in the Chinese food chain system (Ma et al., 2012; Hou et al., 2014; Cui et al., 2016). However, these researches have mainly focused on analyzing the historical trends in per capita food consumption (Cui et al., 2016), and on quantifying N balances, losses at the national scale (Cui et al., 2013; Gu et al., 2015; Cui et al., 2016), nutrient use efficiency, and nutrient cycling in the different food chain sectors: crop and animal production, food processing, and food consumption (Ma et al., 2012). There is a lack of research quantifying the relative impacts of the specific drivers behind the changes in budgets and flows of N, or any comparison of N losses to the environment from food systems in urban and rural areas during the period in which China has experienced rapid urbanization. Although Hou et al. (2014) found that the food N consumption in China's urban settings increased about fivefold from 1980 to 2010, while decreasing in rural settings after the 1990s, they neglected to further analyze the impacts of population growth, dietary changes and the changes in food N consumption in urban and rural areas on the N input to the Chinese food system, and ignored the effect of rural-urban migration on food N consumption and N input.

This study aimed (i) to analyze the historical trends in per capita food N consumption and the differences in per capita food N consumption between urban and rural areas from 1990 to 2012; (ii) to estimate the changes in AN and PN consumption, driven by population growth, dietary changes associate with income growth and rural-urban migration; (iii) to quantify the contributions of the above key drivers to inputs of N through the food system; and (iv) to compare the intensities of food-sourced N losses to the environment in urban and rural areas.

2. Methods and data

2.1. Description of the Chinese food system

The material flow analysis approach was adapted for quantifying the flows of N in the Chinese food system, which is defined as the entire food production–consumption chain, including the recycling of wastes from food production and consumption. The system boundaries followed the geographic boundaries of China, and excluded Taiwan, Hong Kong and Macao because of limited data availability. In this study, the food system was divided into five categories (Fig. 1): crop production, animal-food production, food processing, household consumption (including both urban and rural households), and waste disposal. The crop-production category includes 19 crops (rice, wheat, maize, millet, sorghum, other cereals, beans, potatoes, peanuts, canola, sesame, cotton, flax, sugarcane, sugar beets, tobacco, fruit trees, vegetables, and green fodder). These crops accounted for >95% of the total area sown in China (NBSC, 2013). The animal-production category included 12 animals (hogs, sows, dairy cattle, beef cattle, draft cattle, laying hens, broilers, sheep, horses, mules, donkeys, and rabbits); fish and seafood were viewed as N input from other systems to the food system. The food-processing category included storage, transportation, processing, packaging, and retail sectors. We supposed that the difference between food N supply and final consumption by residents was the N stock in some stages and N loss in food processing, because we lacked information on Nr loss data at these sector levels (Ma et al., 2010). The household-consumption category included rural and urban household diets. The division between rural and urban households was based on national statistical information (NBSC, 1991–2013), and we further distinguished migrants who were living in cities but not registered in the urban population, and quantified rural-urban migration (Fig. S1, see SI for details). Here the imported and exported foods were included in the calculation of household food consumption. The waste-disposal category included human and animal excreta, food processing wastes, kitchen wastes, crop residues and sludge. Distinctions were made among: new N imported from outside the food system via chemical fertilizers, biological N_2 fixation (BNF), atmospheric deposition, irrigation,