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Analysis of nitrogen metabolism processes and a description of structure characteristics

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ABSTRACT

As excessive consumption of food and energy, etc. in cities results in severe nitrogen pollution, this research analyzed the process of nitrogen metabolism in Beijing, calculated total input reactive nitrogen in Beijing from 1995 to 2014 using empirical coefficient method, and further delved into characteristics of consumption structure of food and energy categories, followed by an analysis on the influence of consumption structure change of food and energy categories in Beijing on the quantity of input nitrogen to look for important nitrogen element emission reduction sectors and main emission reduction substances. The result shows that: as a whole, during 1995–2014, the total input of reactive nitrogen in Beijing increased from 516.8 Gg in 1995–616.1Gg in 2014. Seen from the inputting sources of reactive nitrogen, mainly the consumption of food and energy contributes to the increase of general input. Seen from natural and anthropogenic reactive nitrogen, the proportion of anthropogenic reactive nitrogen is above 88%. Meanwhile, the total transferred quantity from external environment in the total quantity of anthropogenic reactive nitrogen produced, i.e. proportion of Z_0 increased from 62.9% to 74.3%. Secondly, the consumption structure of food and energy which are two most important sources for increase of input quantity of reactive nitrogen also changed. In the food consumption system, the proportion of the meat products with high nitrogen content was building up. In the energy consumption system, the total energy consumed of traffic sector which has the largest nitrogen oxide emission factor increased about 9.5 times, while kerosene which is the energy category with the largest nitrogen oxide emission factor was its most principal energy consumption category, with the proportion of consumption increasing from 58.2% to 74.2%. This research can provide theoretical basis for formulation of nitrogen emission reduction policy and reference for other cities with similar nitrogen activities.

1. Introduction

Beijing, as the capital of China, is a typical case of urban transition and has experienced unprecedented urbanization, and this inevitably results in a dense population and a large quantity of nitrogen (N) input and output. Urban systems have been compared to organisms or ecosystems that have a metabolism. Urban metabolism proposed by Wolman (1965) was considered to be an effective way to solve urban metabolic disorders. Kennedy et al. (2007) defined this urban metabolism as the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and waste. A rapid urban expansion was facilitated by rapid economic growth (Ma et al., 2014). During 1978–2008, the population nearly doubled, but about 90% (7.5 million in 2008) of the incoming population were temporary migrants from rural areas working in industry and construction. The percentage of 'urbanized' population in Beijing increased from 55 to 85% (Ma et al., 2014). The rapid urbanization and economic growth had significant impacts on food consumption pattern (Ma et al., 2014) and the consumption of fossil fuel based energy (Zhang et al., 2015) have led to a range of environmental problems, that are threatening human health and human well-being, through especially depletion of water resources, degradation of water quality, traffic jams, smog, and sandstorms (Liang et al., 2013; Qi et al., 2007; Wang et al., 2013; Zhang et al., 2007).

In the 21st century, many researchers paid more attention to metabolism of human nutrition in the urban food system. When analyzing the nitrogen balance for the urban food metabolism in Toronto, Canada, Forkes (2007) focused on the available food input, food wastes output, and recycled wastes. However, Barles (2007)

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added food processing and retailing steps, and specified the recycle processes in the food metabolism of Paris, France. Villarroel Walker and Beck (2012) took the Upper Chattahoochee Watershed as an example to identify the importance of energy and material flows (water, nitrogen, phosphorus, and carbon), as they pass through an anthropologically manipulated metabolic system. The five industrial sectors in the system include water, forestry, food, energy and waste management. Based on this, Villarroel Walker et al. (2014) took London, England as examples to reveal the synergies and antagonisms resulting from various combinations of water-sector innovations and estimating the economic benefits associated with implementing these technologies, from the perspective of fertilizer and energy production, and the reduction of greenhouse gases. Wang and Lin (2014) tracked the main paths that involved in "food consumption", "waste treatment", then explored the same path among them and clarified the metabolic paths, metabolic flows, and the difference among their influencing factors of three elements. Lin et al. (2014) analyzed the characteristics of nitrogen and phosphorus metabolism that were influenced by rapid urbanization, and calculated a nitrogen and phosphorus footprint dissipated to the environment during a product lifecycle.

The early study of nitrogen balance was to estimate nitrogen output at estuaries and explore the reason of its increase after the invention of Haber-Bosch nitrogen fixation (Jaworski et al., 1992; Howarth et al., 1996). They noted that the main nitrogen inputs included nitrogen fixation by leguminous crops, inputs in fertilizer, sewage discharge, net imports of agricultural products, and atmospheric deposition, whereas outputs only included river exports, exports in harvested crops, and denitrification. Valiela et al. (1997) added the accounting term of nitrogen fixation in forest, considered the nitrogen storage and other ways of loss in the study of Waquoit Bay Land Margin Ecosystem. Related to watershed system, Baker et al. (2001) studied nitrogen balance for the Central Arizona–Phoenix (CAP) Ecosystem and then extended research from the urban to the regional urban-agglomeration, national, and global scales. Most of them concentrated on national ((Filoso et al., 2006; Parfitt et al., 2006)) and global scales (Galloway et al., 2004; Schlesinger 2009; Singh and Bakshi 2013). There are fewer studies at urban and urban agglomeration scales. Deng et al. (2007) studied the nitrogen sources and sinks in the Yangtze River Delta economic region which is an urban agglomeration in China, but focused only on nitrogen fixation related to fertilizer use and agriculture. For urban areas, Han et al. (2011) estimated net anthropogenic nitrogen accumulation (NANA) as an index of nitrogen pollution potential in the Beijing. But in their accounting terms, energy consumption was not considered. For another two Chinese cities, the Hangzhou study focused on developing an accounting process that could account for the complexity of the nitrogen cycle (Gu et al., 2009), whereas the Shanghai study paid more attention to the influence of urbanization on the nitrogen cycle and to the key drivers (Gu et al., 2012). Recently, long time series and spatial distribution analyses were developed at the national scales, such as China (Ti et al., 2012; Cui et al., 2013) and the United States (Sobota et al., 2013). Because rapid socioeconomic development and dramatic population increases have raised the standard of living, these changes have increased the demand for nitrogen as a component of human food, particularly due to increased consumption of animal products. Accordingly, the percentage of the total nitrogen input accounted for by food nitrogen is increasing, thereby affecting the global biogeochemical nitrogen cycle (Lassaletta et al., 2014). Leach et al. (2012) found that food nitrogen was the largest single component of the calculated nitrogen footprints of the United States and of the Netherlands. The food supply, the most decisive nutrient flow among urban system and the waste recycling back to the agriculture were evaluated for Bangkok (Faerge et al., 2001) and Paris (Barles, 2007). Ma et al. (2010) developed the model NUFER (NUtrient flows in Food chains, Environment and Resources use) for China, on this basis, Ma et al. (2012) provided an integrated assessment of the N and P utilization efficiencies and their losses in the chain of crop and animal production, food processing and retail, and food consumption at a regional scale in China in 1980 and 2005. Besides, Ma et al. (2013) explored scenario analyses on possible changes in the food chain structure, improvements in technology and management, and combinations of them on food supply and environmental quality in China in 2030. Lin et al. (2014), Ma et al. (2014) and Firmansyah et al. (2017) studied food nitrogen flows under urbanization processes in Xiamen and Beijing, respectively. Gierlinger (2015) also studied the food and livestock feed supply and the waste-disposal patterns of Vienna, Austria. All of these urban studies paid special attention to the influence of rapid urbanization on the nitrogen cycle of cities, and they both reflected and highlighted the high density and low ecological efficiency of nutrient cycling in urban areas.

This study analyzed the process of nitrogen metabolism in Beijing, calculated total input reactive nitrogen in Beijing from 1995 to 2014 using empirical coefficient method, and further delved into characteristics of consumption structure of food and energy categories, followed by an analysis on the influence of consumption structure change of food and energy categories in Beijing on the quantity of input nitrogen to look for important nitrogen element emission reduction sectors and main emission reduction substances, and to provide theoretical reference for formulation of nitrogen emission reduction policy.

2. Methods and data

2.1. Nitrogen metabolic processes

The main concept is that the natural and socioeconomic components of an urban system can be abstracted as nodes in a network, and that the exchanges among these nodes can be treated as paths. Direct flows between nodes, which do not pass through any intermediate nodes, and indirect flows, which pass through at least one intermediate node, can then be identified and quantified. Based on the available data and a rational classification of the key transfer processes in an urban nitrogen metabolism, we defined 16 nodes in Beijing's metabolic system. The first 11 nodes relate to socioeconomic sectors of the system and represent the major sectors that generate anthropogenic nitrogen: Household (node 1), Industry (node 2), Animal Husbandry (node 3), Crop Cultivation (node 4), Aquaculture (node 5), Forestry (node 6), Services (node 7), Construction (node 8), Transportation (node 9), and Sewage Treatment (node 10). The remaining 5 nodes represent the predominantly natural sectors of the system: Surface Water (node 12), Atmosphere (node 13), Forests (node 14), Grassland (node 15), and Farmland (node 16). All of these nodes are within Beijing's municipal administrative boundary, and we treated areas outside of Beijing's municipal administrative boundary, including both socioeconomic and natural systems, as the external environment (node 0). Most of the natural components receive the wastes created by the socioeconomic components of the system, though they also engage in at least some level of natural metabolic processes. Compared to the production sectors, which tend to generate nitrogen-containing outputs, Beijing's consumer sectors are nitrogen importers. In addition to the rapidly increasing urban population, a growing number of pets had greatly increased demands for pet food. In addition, we subdivided the agriculture sector into three nodes (Crop Cultivation, Animal Husbandry, and Aquaculture) that reflect differences in their nitrogen recycling activities and in human consumption of different types of nitrogen-containing food. In addition to the mass consumption of nitrogen in food, urban energy consumption