Urban Nitrogen Metabolism in Xiamen City, China

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Abstract
Urban settlements, as highly concentrated areas for human production and consumption activities, have become important components in the alteration of regional and even global nitrogen (N) cycle. This study, by using substance flow analysis (SFA), establishes an urban N metabolism model and quantifies a detailed N mass balance for Xiamen, a rapidly urbanizing city in China, in 2008. The results show that the total N input into Xiamen was 103.2 kt in 2008, including 64% through products and 36% from the environment. The total N output was 99.6 kt, with 12% as products exported to other regions and 88% released to the environment. Fossil fuels ranked first of the N inputs, contributing 78% of N to the atmosphere. About 50% of N inputs were retained within the urban ecosystem. N use efficiency in the food chain was only 11%. Several interventions are suggested to improve N efficiency and reduce N environmental impacts, including municipal solid waste composting, reduced fossil fuel consumption, fuel N removal and integrated watershed management.

Keywords
nitrogen metabolism, substance flow analysis, urban ecosystem, regulatory measures, China

Introduction
Increasing amounts of reactive nitrogen (Nr) have been created through food production and consumption as well as through fossil fuel combustion, which have resulted in excessive N loading to the environment and a series of ensuing environmental problems, such as water eutrophication, acid rain, photochemical smog, and climate change (Galloway et al. 2008). Especially in developing countries, the demand for Nr is expected to increase, due to both agricultural demand and increased consumption of industrial products. Cities consume increasing amounts of natural resources and generate increasing amounts of wastes, which in turn cause environmental problems at local, regional and global levels (Bai 2007, Grimm et al. 2008). Urbanization hence has a significant impact on global biogeochemical cycles, including nutrient enrichment in urban areas, especially in rapidly urbanizing countries. Human-driven increase in Nr affects both human health and the environment in urban ecosystems. Therefore, N flow pathways and quantities in urban ecosystems need to be understood properly in order to effectively control the Nr creation and its impact on the environment and human beings. China's rapid urbanization, industrialization and associated changes in lifestyle and consumption have led to fast-growing anthropogenic creation of Nr from 18.3 Tg in 1980 to 53.9 Tg in 2010 (Gu et al. 2015). In this study, we constructed a comprehensive urban N metabolism model in Xiamen city. Xiamen is a coastal city located in southeast of China, with a population of 2.49 million. We quantified the N input, output, loss to the environment and retention within the urban ecosystem, providing insights into regulatory measures to improve N use efficiency and reduce environmental impacts.

Methods
Brief Review on Urban N Metabolism
A great majority of scientific debates have focused on N flows on the regional, national, and global scales. In recent years, N flows on the urban scale are gaining more attention and have been studied for Bangkok, Stockholm and Central Arizona-Phoenix (CAP) (Baker et al. 2001). The studies of N flows in urban food metabolism have been attempted for Paris and Toronto, as well as focus on the urban household ecosystem for the Minneapolis-Saint Paul. More recently, cities in China such as Beijing, Shanghai have also started to characterize the urban N metabolism (Ma et al. 2014). These studies, however, have not covered all N flows throughout an urban region.

N Metabolism Model for Xiamen City
Figure 1 shows the urban N metabolism framework model used in this study. The N input into the city consists of two parts: imported products containing N, and N from the environment. Humans consume some

of the N. In terms of the N output, some of it is transformed into loss and waste and released to the environment (mainly into the soil, the inland waters, the sea, and the atmosphere), some of it is exported to other regions through trade, and the rest is retained in the city.

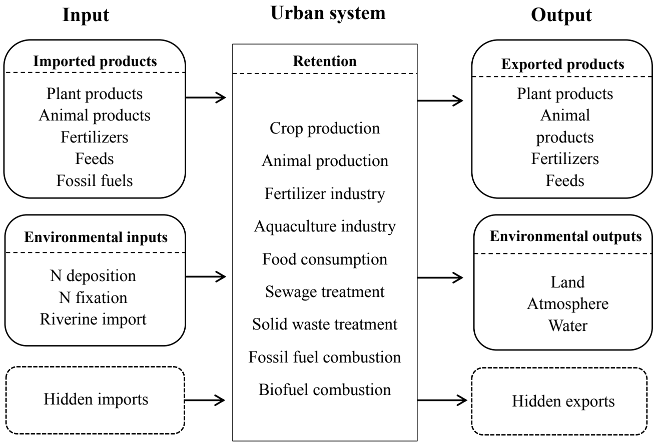

Figure 1. Analytical framework of common urban N metabolism

A full N balance based on SFA, which both investigated N cycling in different ecosystem components and the magnitude of major fluxes across the boundary of the ecosystem, was conducted for Xiamen city in our study. This study is based on large activity data and N cycling parameters, including statistical data, survey data, and published literatures. We excluded N in industrial products other than from the fertilizer or food industries, because of the complexity of industrial products and lack of information. The component level method was used to compute N retention within the city by summing up fluxes accumulating within different functional and environmental components. The formula to calculate N use efficiency is as follows:

$$NUE = \left[\left(Ih_{Plant\ food} + Ih_{Animal\ food} + If_{Export} - If_{Import}\right)/\left(Ic_{Fertilizer} + Ic_{Irrigation} + Ic_{Deposition} + Ic_{BNF} + Ic_{Seed} + Ia_{Grass} + Ia_{Residue} + Ia_{Feed}\right)\right]\times 100\%,$$

where *Ih*= N input to household, *If*=N input to food processing, *Ic*= input to crop production, *Ia*= input to animal production, and *BNF*=biological N fixation.

Results and Discussions

N Sources and Inputs to Xiamen

The imported products contributed 65.9 kt of N input into the urban system. Due to lack of mineral resources, the energy supply of Xiamen relies entirely on imports. Of the total N input from imported products, 62% was from fossil fuels. Coal utilized for the power sector and industrial production accounted for over half of the supply of fossil fuels. Agricultural products comprised 13% of the total N input. The contrast between land resource shortage and large population size in Xiamen leads to dependency of food products on imports.

N inputs from the environment accounted for a total of 37.3 kt in 2008. Xiamen is located at the estuary of the Jiulong River, and much of this river-born N input into Xiamen is N discharged by upstream cities and regions. Up to 76% of the total N input from the environment was brought from the Jiulong River, while the rest was from the atmosphere through N deposition and N fixation.

Collectively, the total N inputs to Xiamen amounted to 103.2 kt in 2008, which was equivalent to 22.5 times the N applied to Xiamen's farmland in the same year. The per capita N input in Xiamen was 58.5 kg N for the year 2008. Compared with other city scale studies, a common feature for urban systems is the large dependency on imported products. N in imported food and feed contributed 17.4%, 13.4%, 26% and 19.6 % to total N input in Xiamen, Beijing (Han et al. 2011), Shanghai (Gu et al. 2012) and CAP (Baker et al. 2001), respectively.

N Sinks and Outputs from Xiamen

The results show that 88.2 kt of N were released to the environment. The urban environment became the largest sink of N inputs into Xiamen city. Of the total N released to the environment, 48% entered the atmosphere. 78% of the N released into the atmosphere was from energy use, far exceeding the N lost from crop and animal production. Reduction of fossil fuel consumption and use of low-N fuels (e.g. natural gas and nuclear energy instead of coal and oil products) are key measures to reduce atmospheric N. Moreover, technologies for removing N from fossil fuels (e.g. staged combustion method in coal combustion) for both domestic and industrial use can make a difference. Seawater is another major N sink in Xiamen, accounting for 39% of the environmental N loading. This has led to eutrophication and it is likely to co-influence the frequent incidence of red tides with other elements.

The total N output from Xiamen to other regions was 59.4 kt—11.5 kt transferred to other regions as products and 47.9 kt via air and water. The estimated N accumulating in the atmosphere was 20.0 kt, and N accumulation in seawater was estimated to be 8.4 kt, accounting for 25% of the N inputs to the sea. Figure 2 shows the N inputs and outputs of Xiamen urban system in 2008.

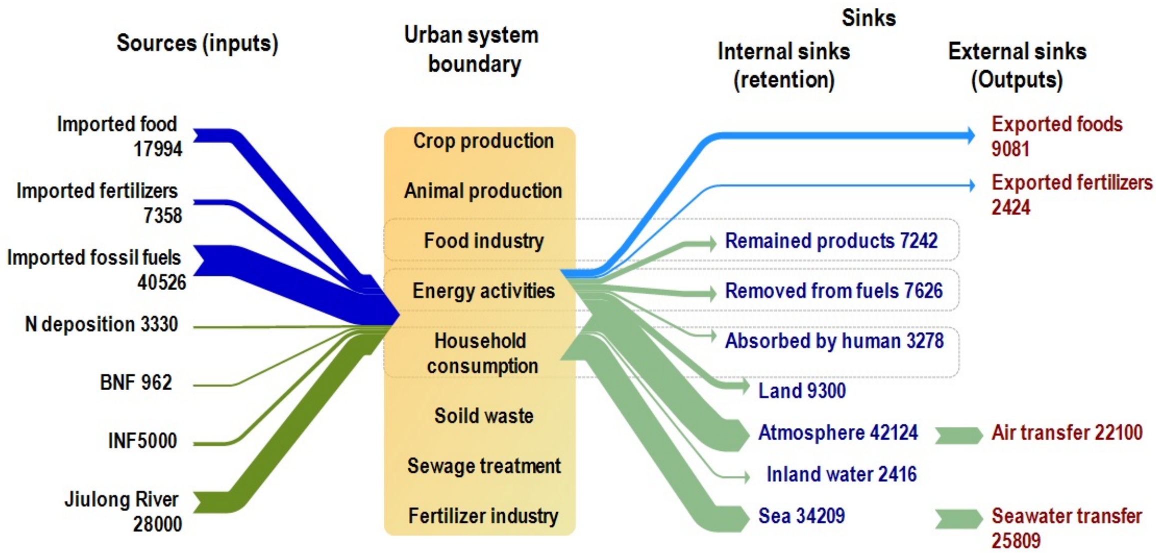

Figure 2. Comparison of N sources and sinks of Xiamen in 2008 (Unit: t). BNF, biological N fixation; INF, industrial N fixation.

Urban N Retention

For coastal cities, N which enters into the environment can be transported out of cities by water and air, combined with the N transported through exported products, the remainder is N retention in urban system. The total N retention based on the component level method in Xiamen city was 52.3 kt in 2008, which was equivalent to 26 t km^{-2} yr^{-1} N—51% of the total input. Of the total N retention, 68% was finally accumulated in urban environment; the rest 32% was retained in products or human bodies. The detailed urban N metabolism model is illustrated as Figure 3. Our result of N retention rate was comparable to the previous studies. The reported N retention in the Beijing metropolitan region accounted up to 88% of total N input during the period 1991-2007 (Han et al. 2011), which was much higher than that of Xiamen. That might be because Xiamen is a coastal city, and seawater is a significant sink for N—a geographical situation different from inland city Beijing.

N Use Efficiency

It is estimated that the N use efficiency in the food chain in Xiamen was only 11% in 2008, a little higher than the national average N use efficiency 8.9% (Ma et al. 2010). The major reasons are the intensification of crop and animal production and the lack of N recycling between urban and rural settlements. In addition to low N use efficiency, N waste in household food consumption remains a serious problem. About 25% of the N consumed by households became kitchen waste and ended up in landfills in 2008, leading to a substantial quantity of N squandered and finally accumulated in the soil. If the kitchen waste and food processing waste could be composted and then applied to crop production, the N use efficiency would increase to 14%.

Conclusion

Based on the results, there are several possible measures to enhance N use efficiency and reduce N retention. First, the use of low-N fuels and the progress in the N-removal technologies for fossil fuels are key measures for reducing atmospheric N accumulation. Second, limiting N input into crop production and improving the use efficiency in agricultural ecosystem is significant. Third, reducing the N load to the seawater is not achievable by Xiamen city alone, but workable through integrated watershed management programs partnered with upstream cities. Finally, reducing food waste via consumer behaviour changes and a comprehensive approach to solid waste management, will help reduce total N use in agriculture and N load into the environment.

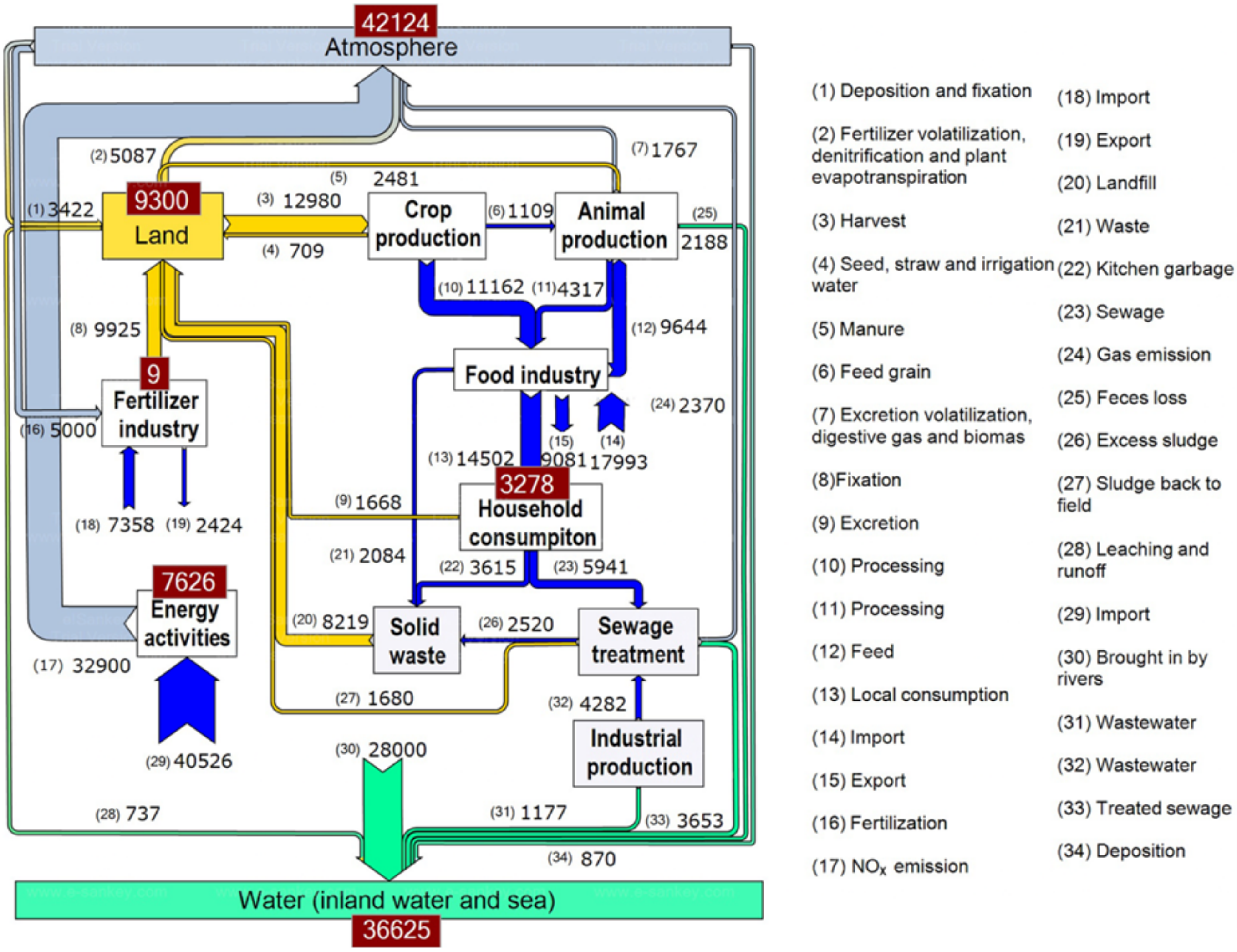

Figure 3. Systemic N metabolism in Xiamen in 2008 (unit: t). The arrows with yellow, light blue and green colours represent the N flows to land, atmosphere, water, respectively. The figures in the red boxes represent the volume of N accumulation (i.e. the difference between N inputs and outputs) of each N pool.

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