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Impacts of urban expansion on nitrogen and phosphorus flows in the food system of Beijing from 1978 to 2008

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ABSTRACT

Rapid growth of metropolitan areas is associated with increased flows of nitrogen (N) and phosphorus (P) in the food production–consumption system. However, quantitative analyses of these flows during urban expansion and information about their controlling factors are scarce.

Here, we report on N and P flows in the food system of Beijing, which experienced a remarkable growth in population number between especially 1978–2008, using a combination of statistical data bases, surveys and the NUFER model (nutrient flow in the food system, environment and resource). The N (or P) cost of food is defined as the amount of 'new' N (or P) used in food production for the delivery of 1 kg N (or P) in the food entering household. 'New' N (P) includes fertilizer N (P), biological N fixation, atmospheric N deposition, and imports of N (P) via feed and food. Recycled N (P) includes N (P) in crop residues, manures and wastes.

We found that the rapid increase in temporary migrants greatly increased food imports to Beijing metropolitan areas and thereby led to an apparent decrease of the N and P cost of food. The input of 'new' N to the food system of Beijing metropolitan areas increased from 180 to 281 Gg, and for P from 33.5 to 50.4 Gg during 1978–2008, as a result of increases in population and changes in food consumption patterns per capita. The food and feed imports in per cent of total 'new' N and P inputs increased from 31 to 63% for N and from 18 to 46% for P during 1978–2008. The N and P cost of the food was relatively low compared to the mean of China, and decreased over time. About 52% of the new N input and 85% of the new P input was not recycled in 2008, it accumulated as wastes (in crop residues, animal excreta, and human excreta and household wastes). The N and P use efficiencies in crop and animal production were low, i.e., only 17% for N and 11% for P in 2008. Total losses of ammonia (NH_3) and nitrous oxide (N_2O) to air and of N to groundwater and surface waters increased by a factor of about 3, and losses of P to groundwater and surface waters increased by a factor of 37 in the period 1978–2008.

Key measures for decreasing N and P accumulation and losses are (1) developing satellite towns, (2) expelling animal production to rural areas, and (3) effective collection of the wastes and animal manure, and the utilization of these in rural areas outside Beijing. These findings may also portend changes in other metropolitan areas in China and elsewhere in the rapidly developing world.

1. Introduction

Urbanization is a primary driver for altering biogeochemical cycles (Grimm et al., 2008). This holds especially for nitrogen (N) and phosphorus (P), which are key elements for food production. Several studies have tried to link urbanization to socio-economic growth and national wealth (Bloom et al., 2008), and to changes in the cycling of N and P between urban and rural ecosystems (Deluca, 2009; Grimm et al., 2008). Urban areas are sinks for nutrients, and in an increasingly urbanized world, cities become 'hotpots' of N and P, which contribute to environmental effects (Marzluff et al., 2008).

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The global trend of urbanization has shifted from Europe and North America (first urban transition, 1750–1950) to Africa and Asia (second urban transition, 1950–2030) (Ramalho and Hobbs, 2012). Urbanization has resulted in the rapid centralization of population, economics, resources, and pollutions. Especially China has witnessed a rapid urban expansion during the last few decades, due to the rapid economic development and desire to live in cities (Bai et al., 2014). Both the economic development and urbanization had significant impacts on food consumption pattern. For example, mean food protein consumption went up from 9 to 26 kg capita^{-1} year^{-1}, and the percentage of animal-derived protein in the diet increased from 9 to 35% between 1961 and 2007 (FAO, 2010). These changes in food consumption had also large impacts on agriculture and food systems (Tara and Andreas, 2014; Westhoek et al., 2014). For example, (1) animal production increased through the establishment of large-scale confined animal feeding operations (Wang et al., 2010), (ii) the area used for vegetables and fruit production increased by 31% (FAO, 2010), and (3) intensive vegetable, fruit and livestock production increased near urban areas at the expense of cereal production (Wolf et al., 2003). These changes have also greatly increased demands for natural resources (Güneralp and Seto, 2008) and nutrient inputs to urban areas.

Beijing metro area, including central Beijing and its 14 counties, is a typical case of urban transition. A rapid urban expansion occurred between 1978 and 2008, facilitated by rapid economic growth (Fig. 1). During this period 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% (Fig. 1). The rapid urbanization and economic growth 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).

Urban metabolism is a concept used to quantify exchanges of water, energy and elements (including nutrients) in compartments of urban areas (i.e. food systems, industrials, water systems etc.) of urban areas (Bai, 2007; Kennedy et al., 2007), and has been applied in a number of studies. For example, Barles (2007) examined nitrogen flows in food system of Paris from 1801 to 1914 (historical perspective) (Barles, 2007). Forkes (2007) analyzed nitrogen balance of the food system of Toronto, Canada from 1990 to 2004 (Forkes, 2007). Færge estimated nutrient flows in the food system of the Bangkok province and monitored concentrations of

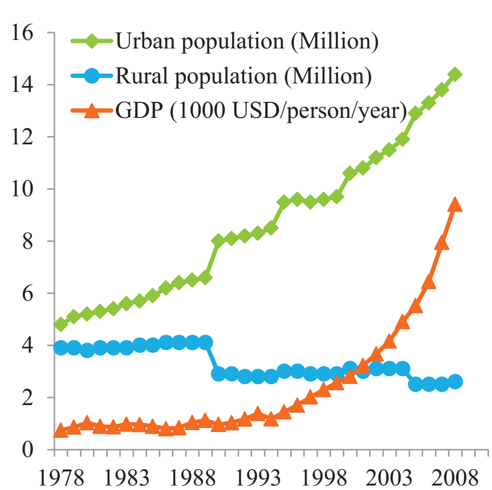

Fig. 1. Changes in the population of urban and rural areas, and in gross domestic production (GDP) of Beijing metropolitan between 1978 and 2008.

N and P in the inlets and outlets of main rivers in the region (Færge et al., 2001). Neset quantified the P flows in the food system of Linkoping, Sweden, for the years 1870–2000, as well as its influences on the regional ecosystem (Neset et al., 2008). Also, several cities in China (Li et al., 2011) have also been examined, including Beijing and Tianjin (Irie et al., 2013; Qiao et al., 2011), Shanghai (Gu et al., 2012), Hong Kong (Warren-Rhodes and Koenig, 2001) and Suzhou (Liang and Zhang, 2011). The N and P flows in the food system, as well as its influences on the regional ecosystem were quantified in these studies. For instance, Irie et al. (2013) analyzed the organic resource N flows in Beijing to establish an organic resources recycling model for Beijing. Qiao et al. (2011) focused on understanding the characteristics of P flows and stocks in Beijing and Tianjin. However, all studies considered the cities as static research objects; none of these studies addressed the driving forces for urban expansion and the resulting changes. Moreover, flows of N and P were analyzed separately. As a result, our understanding of the impacts of urban expansion on N and P flows and losses in the food system at sub-regional levels is still limited.

Here, we address the question 'how did urban expansion change the N and P flows in the food system of Beijing during the past 30 years'. We used a food system approach and the NUFER model (Nutrient flow in the food system, environment and resource use; Ma et al., 2010) to analyze the changes in N and P flows in the food system over time. The aims of this study are (1) to quantify the changes of the N and P flows and losses in the food system during the urban expansion period (1978–2008); and (2) to analyze the relationships between urban expansion, economic development and the N and P flows in the food system. Our research contributes to the understanding of the sustainability of growing centralizations or in many parts of the rapidly developing world.

2. Materials and methods

2.1. Description of Beijing metropolitan areas

Beijing in northern China is one of the twenty largest metropolitan areas in the world (Forstall et al., 2009). It is defined here by its administrative boundaries, and includes central Beijing and its 14 counties, with a total area of 1.6 million ha in 2008 (Fig. 2). Following the economic reforms in the 1970s and 1980s, the urban area of Beijing has expanded greatly. After the abolition of the food purchase policy, the prices of cereals, vegetables, meat and sugar became similar for residents and migrants. It leaded to a rapid influx of temporary migrants from rural regions to the urban and peri-urban areas of Beijing.

In 2008, about 21% of the total land area was urban and infrastructural area. Approximately 14% was used for intensive crop production (range 0–38% for the 14 counties), and this percentage has decreased dramatically in the past three deceases (Table S9 in the supplementary information). The main crops are maize, wheat, fruits and vegetables. A very high animal density in terms of biomass per hectare of cultivated land is found in some counties (i.e. Haidian, Shunyi, Daxing, Huairou, Pinggu, and Miyun) (Fig. 2). About 53% of the total land area of Beijing is a mixture of extensively used farm land and forest, and 12% of total land areas is non-utilized mountainous land (Table S8 in the supplementary information).

2.2. The food system of Beijing

The food system of Beijing is defined here as the whole food production–consumption chain, including the recycling of wastes from food production and consumption. The boundaries of the food system are defined by the geographic boundaries of Beijing (Fig. 2).