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# Changes in nitrogen and phosphorus flows and losses in agricultural systems of three megacities of China, 1990–2014

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ABSTRACT

Urban expansion is a crucial process altering nutrient cycles in agro-ecosystems, often accompanied by negative impacts on the environment. Quantitative analysis of nutrient flows in agricultural systems of megacities and their interactions with urbanization is still lacking. This study reports on changing patterns in inputs, outputs, losses and cycling of nitrogen (N) and phosphorus (P) in agricultural systems in three of China's megacities–Beijing, Shanghai and Chongqing during 1990–2014, using the substance flow analysis method. Results show that changing patterns of nutrient flows varied among cities. With rising urbanization rate in Chongqing, nutrients were increasingly imported to agricultural systems to sustain food demand, which led to increased nutrient losses. An opposite trend occurred in Beijing and Shanghai with high urbanization levels (over 80%) since the early 2000s, resulting from a decline in cropland and livestock numbers, and stricter enforcement of environmental laws. Mineral fertilizers and livestock husbandry both contributed largely to ammonia emissions from agriculture. Losses of nutrients to water bodies in Beijing were sourced mainly from the livestock sector, while derived from overuse of mineral fertilizers in Chongqing, suggesting that priority management practices need to be designed differently among regions. Increased intensity of nutrient losses from agriculture was significantly correlated with increased mineral fertilizer input, livestock density and feed import and with reduced recycling ratio of manure. Integrated management for better use of nutrients in fertilizers, feed and manure are urgently required at regional scales. Our findings can serve as basis for policy decisions for sustainable agricultural systems in megacities.

## 1. Introduction

Nitrogen (N) and phosphorus (P) are essential nutrients for plant and livestock growth, holding an important role in sustaining food security. China has made great achievements in increasing crop productivity to feed its growing population, which is in part attributed to increases in the use of mineral fertilizers since 1980s (Zhang et al., 2011). However, owing to improper and excessive use of fertilizers in recent decades, excess nutrients have become a threat to the environment. Moreover, intensification and specialization of livestock farms is taking place in many regions of China, in response to the increasing demand for animal products. In such process, livestock farms have become great contributors to anthropogenic N and P losses, which can be explained by poor manure management practices and decoupling of geographical regions specialized in intensive livestock farming and intensive crop production. (Bai et al., 2014; Hou et al., 2013). Nitrogen in mineral fertilizers and animal manure is vulnerable to losses via emissions of ammonia ($NH_3$), nitrous oxide ($N_2O$) and nitrogen oxides ($NO_X$) to the atmosphere and via leaching of nitrate ($NO_3$) and other soluble N forms to groundwater and surface waters. These emissions cause eutrophication of ecosystems, soil acidification and loss of biodiversity (Guo et al., 2010; Liu et al., 2011). Moreover, $NH_3$ may form fine particulate matter (PM) in the atmosphere, which can be transported over large distances and may negatively affect human health. Nitrous oxide is a potent greenhouse gas and an important cause for the depletion of stratospheric ozone. Mineral P fertilizer production mainly relies on exploiting fossil phosphate rock that is a finite and non-renewable resource. On the other hand, losses of P from agricultural

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production practices comprising fertilizer application, manure collection and handling have created considerable damages to aquatic ecosystems in China. It is apparent that sustainable N and P resource management in crop and livestock production systems is urgently needed to ensure food security and safety and improve environmental quality in China.

More than half of the global population lives in urban areas, with a higher growth rate of urbanization in developing countries. China has experienced rapid urbanization since the start of the reform and opening-up policy in 1978, and the urbanization rate of the total national population amounted to 56% in 2014 (National Bureau of Statistics of China (NBSC, 2014). Urbanization has been identified as a principle driver for enhancing N and P flows and losses in China's food production and consumption chain over the past decades (Hou et al., 2013). The process of urbanization tends to alter biogeochemical process in surrounding agro-ecosystems that provide their sustenance (Lin et al., 2014). Nutrient-rich resources are increasingly imported into agricultural systems in urban and peri-urban areas to maintain nutrient demand for food consumption. At the same time, most of these cities in China, especially 'megacities', are facing severe environmental problems.

Intensification and agglomeration of livestock production are progressively taking place in China, driven by increasing demand of animal products due to population growth, urbanization and economic development (Ma et al., 2013). Concentrated animal feeding operations (CAFOs) are mainly located in the peri-urban region of megacities and coastal cities. Intensive livestock farms are generally characterized by high livestock production and limited cropland area, which largely rely on feed import from other regions or abroad and have little connections with nearby crop farms (Wang et al., 2010). This decoupling of crop and livestock production poses difficulties to the recycling of manure generated in CAFOs. On croplands, mineral fertilizers are increasingly applied on specialized crop farms, exceeding crop demand in most cases. These intensification/specialization-related changes causes massive problems to agricultural soils in peri-urban areas (Heimann et al., 2015). Environmental legislation has been adopted in some Chinese cities to reduce manure-sourced environmental pollution by reducing or reallocating livestock production. On the other hand, since agricultural land may shrink for reasons of growing built-up areas (National Bureau of Statistics of China (NBSC, 2014), livestock density can still remain at a high level, with a high risk of environmental pollution. There is a need for an increased understanding of detailed nutrient dynamics over multiple years in food production systems for formulating better management strategies (Chowdhury et al., 2014), in particular for urbanized regions.

Nutrient flow analysis has been conducted for some megacities of China, varying in research objects, system boundaries and timeframe. For example, Irie et al. (2014) estimated changes in organic resource N flows in Beijing for three specific years. Qiao et al. (2011) focused on exploring the stocks and flows of P through food consumption in Beijing and Tianjin in 2008. Li et al. (2010) investigated anthropogenic P cycling in Hefei, Anhui province, in 2008, and its contributions to local water pollution. Analyses with focus on changes in nutrient flows along time series are still scarce. Gu et al. (2012) investigated N flows in combined natural, agricultural and industrial systems in Shanghai during 1952–2004. Ma et al. (2014) conducted a substance flow analysis of N and P flows in the food system of Beijing during 1978–2008. There is still a lack of understanding of long-term variations in nutrient flows in agricultural systems, and their interactions with urbanization during recent years when environmental laws were increasingly tightened. Moreover, since these types of studies focused on specific areas and nutrient elements, and used different approaches and scopes, it makes them very hard to compare and draw consistent conclusions.

The objectives of this study are to reveal how nutrient(N and P) flows and losses in agricultural systems vary on a temporal scale in megacities of China over the past 25 years (1990–2014), using uniform method and database, and to examine the relationships between agricultural nutrient losses and some crucial agricultural management decisions, in terms of fertilizer application rate, livestock density, supply of animal feed and recycling of animal manure. To fulfill these objectives, a deterministic and static model - NUFER (NUtrient flows in Food chains, Environment and Resources use) model was employed in this study (Ma et al., 2010), with the update of activity data and model parameters. We also attempt to explore the possible influence of urbanization-induced changes on the key nutrient inflows and losses, and to suggest some necessary management measures to attenuate environmental impacts in this regard. Beijing, Shanghai and Chongqing, as representatives of megacities in China, were selected as case study locations.

## 2. Materials and methods

### 2.1. Study area and system boundary

The boundaries of the agricultural systems analyzed in this study refer to the geographical borders of Beijing, Shanghai and Chongqing, three of China's four direct-controlled municipalities (the fourth being Tianjin) that have been experiencing rapid economic development and urbanization in the past decades. The direct-controlled municipalities were established as economic and political demonstration zones for their surrounding regions. In China, a municipality is often not in the usual sense of the term (i.e., a large continuous urban settlement and generally lack of agricultural farming), but instead an administrative unit comprising, typically, a main central urban area and also a much larger surrounding rural area containing a number of districts, towns and villages where agricultural production is performed to provide food products mainly consumed by citizens of these municipalities. It is worthy to prioritize the analysis of nutrient flows in agricultural systems of the municipalities. The temporal scope of our analyses was 25 years, namely from 1990 to 2014. The urbanization rates have increased from 67.3%, 60.8% and 22% in 1990 to 89.6%, 86.4% and 59.6% in 2014 for Shanghai, Beijing and Chongqing, respectively. Beijing, the national capital is located in northern China (39°24′–41°36′ N; 115°42′–117°24′ E) and has been serving as political, economic and cultural center. Shanghai is one of the most developed and urbanized cities in China, located on the eastern coast of China (30°40′–31°53′ N, 120°51′–121°12′ E). Chongqing is a major city in southwestern China (28°10'–32°13' N, 105°11'–110°11' E), which has been established as a direct-controlled municipality in 1997. Beijing, Shanghai and Chongqing hold a total population of 20.7, 23.8 and 29.4 million in 2014, and have the total land area of 1.641, 0.634 and 8.237 million ha, respectively, in which 13.4%, 29.7% and 29.8% were occupied by arable land. The gross domestic product (GDP) per capita in Beijing (102869 Yuan RMB) and Shanghai (97370) were about 2.1–2.2 times of the national average (47203), while Chongqing has similar GDP per capita (47850) to the national average.

Agricultural systems considered in our study comprised both crop and livestock production sectors. The main nutrient fluxes in agricultural systems were taken into account for the estimates of nutrient budgets (Fig. 1). Nutrient inputs to cropping system included mineral fertilizers, biological nitrogen fixation and atmospheric deposition, as well as the recycling of livestock manure from livestock systems and crop residues incorporated into the field. Output items of cropping system referred to crop main products and crop residues, as well as losses of nutrients to the atmosphere via emissions of $NH_3$, $N_2O$ and $N_2$, and to surface waters and groundwater via leaching, runoff and erosion. As to livestock systems, feedstuffs to livestock were considered as input items, which can be produced by local crop farms or imported from other regions. Nutrient output items from livestock system consisted of animal products (live weight gains, milk, eggs etc.) and the fate of nutrients in livestock manure, such as losses during livestock housing and manure storage to the atmosphere (via $NH_3$, $N_2O$ and $N_2$) and water bodies (mainly via