Phosphorus inflow into agricultural and urban soil: the perspective from food production and consumption in China

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Abstract
In this study, phosphorus (P) concentration in 201 types of food consumed daily by urban households was collected to calculate P inflow into urban soil through food consumption over the period of 1985-2006 in China. It indicates that 3.87 million tonnes of dietary P have been accumulated in urban soil over the 1985-2006 period, which accounted for 53.53% of total dietary P inflow. Further analysis shows that it is of low efficiency of P utilization in food chain process from field to Table, including: (1) to produce 1 kg food P (edible part) will cost 9 kg mineral P fertilizer input into agricultural soil; (2) Among this 1kg food P, about 0.6 kg flow into urban area through food consumption, in which 0.3 kg will be disposed and the other o.3 kg will be recycled in urban area, mainly in urban soil, i.e. 50% food P inflow through urban food consumption eventually remained in urban area.

Key Words
Phosphorus recycling, food consumption, phosphorus utilization efficiency, urban geochemistry.

Introduction
The migration of large population into cities suggests food consumption is increasingly concentrated in the urban area, implying more phosphorus(P) are being imported into urban area through food consumption. Part of the imported P is then released into peri-urban environments through wastewater discharge and sludge disposal. Other part is enriched in urban soil and aquatics. Currently, global annual consumption of P is approximately 12 Mt, of which 90% is for food production (Smil 2000). Consequently, about 0.27 Mt P from food consumption per year might be imported into urban area globally based on our estimation (UN-DESA 2008; Cordell *et al.* 2009; Chen *et al.* 2008; Gao *et al.* 2009). It appears the amount of P flow into urban area is marginally comparable to P storage in agricultural soil and outflow into ocean. However, the environment consequence can be very significant since urban area occupies only less than 3% of the global terrestrial area (Grimm *et al.* 2008). The increasing dietary P inflow into urban area could be a very significant factor contributing to the increasing eutrophication in urban soil in China (Zhang *et al.* 2007; Yuan *et al.* 2007). In this study, the flow and mass balance of urban dietary P in China were analyzed at national scale (excluding Hong Kong, Macao, and Taiwan). Our purpose was to manifest the spatio-temporal trend of dietary P consumed by urban household and the accumulative amount remained in urban built-up area during the urbanization process.

Methods
Data
The key datasets are from first-hand national food consumption survey and related official statistics and reports. The data on urban dietary P flow analysis were obtained from various sources and subjected to rigorous cross checking before analysis.

Method
The dietary P flows into urban system from natural ecosystem through urban household consumption and out of urban system through waste disposal (Figure 1). P flow in food import and export has been considered.

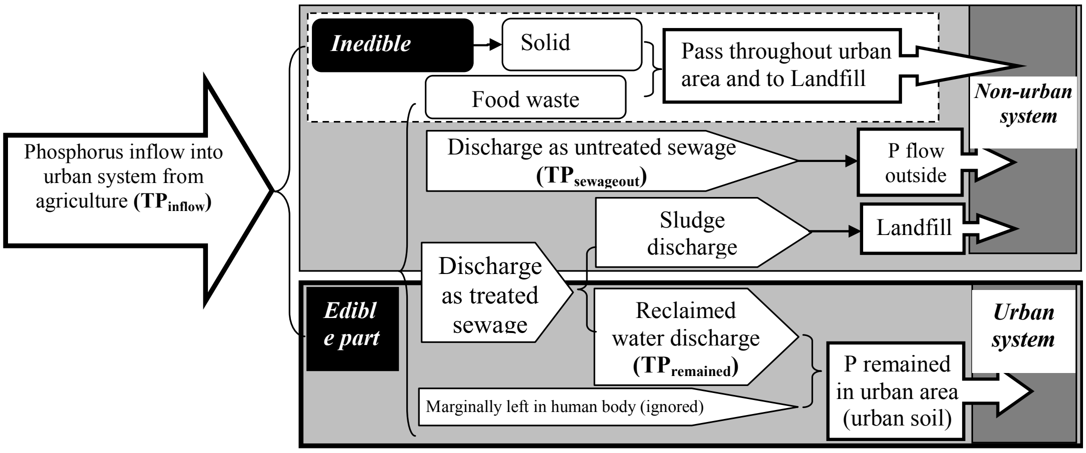

Figure 1. Conceptual model of urban dietary P flow into and out of urban area.

According to the conceptual model illustrated in Figure 1, the following formulas were established to determine the amount of urban dietary P flow into and out of urban area:

$\mathbf{TP}_{remained} = \mathbf{TP}_{inflow} - (\mathbf{TP}_{sewageout} + \mathbf{TP}_{sludgeout}) * f$ Eqs.(1)

Where, $\mathbf{TP}_{remained}$, $\mathbf{TP}_{inflow}$, $\mathbf{TP}_{sewageout}$, and $\mathbf{TP}_{sludgeout}$ are illustrated in Figure 1. f (50%) is the fraction of household sewage in municipal sewage drainage system (Yang *et al.* 2006).

$\mathbf{TP}_{inflow} = N_{up} * P_{cd} * 365$ Eqs. (2)

Where, N_{up} is the total urban population (10000 persons), P_{cd} is the per capita daily dietary P consumed by urban household (g P_2O_5/d/capita), which is calculated as

$P_{cd} = \sum(Q_{cd} * C_{Pfood})$ Eqs. (3)

Here, Q_{cd} is the per capita daily consumption of a certain group of food by urban household (g edible part/capita/d), and C_{Pfood} is the P concentration in edible part of a certain group of food (g P_2O_5 / g edible part of food).

$\mathbf{TP}_{sewageout} = D *(1-R)* C_{untreated}$ Eqs. (4)

Where, D is the discharge volume of urban household sewage per annum (10000 tonnes), R is the urban household sewage treatment rate per annum (%), and $C_{untreated}$ is the P concentration in untreated urban household sewage (mg/L).

$\mathbf{TP}_{sludgeout} = D * R * (C_{untreated} - C_{allowed})$ Eqs. (5)

Where $C_{allowed}$ is the maximal P concentration allowed in discharged reclaimed water after treatment (mg/L) and $C_{untreated}$ is the P concentration in untreated discharge (mg/L).

Results

Dietary P consumption by urban households

In average, 3.68 g P_2O_5 was imported into urban area by per urban capita per day through food consumption during 1985-1992. The number slightly decreased to 3.45 g P_2O_5 per urban capita per day in 1993-2006 (Table 1), which is mainly due to the change in P concentration in food and food consumption structure.

Table 1. P concentration and consumption of each group of food

	C_{Pfood} (P_2O_5 g /100g edible part)		Q_{cd} (g/capitaday^{-1})		P_{cd} (P_2O_5 g/capitaday^{-1})		Q_{cd}in HK (g/capita/d) (A)
	1985-1992	1993-2006	1985-1992	1993-2006	1985-1992	1993-2006	1997
Cereals	0.48	0.33	432.00	356.50	2.07	1.18	303.8
Potato tubers	0.08	0.14	56.00	30.50	0.04	0.04	n.a. (B)
Vegetables	0.22	0.10	310.50	259.50	0.68	0.26	206.3
Fruits	0.05	0.05	74.00	73.50	0.04	0.04	292.9
Animal meat	0.47	0.40	61.13	61.50	0.29	0.25	352.3
Poultry meat	0.37	0.35	20.38	23.50	0.08	0.08	
Milk products	0.55	0.82	23.00	73.50	0.13	0.60	231.8
Poultry eggs	0.47	0.41	22.50	192.50	0.11	0.79	n.a.
Fishes	0.74	0.59	33.00	36.00	0.24	0.21	160.0
Sum					3.68	3.45	

(A) calculated according to Warren-Rhodes *et al.*(2001); (B) n.a. means not available;

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Mass balance of dietary P flow in urban area

The annual inflow of P (calculated as P_2O_5, thereafter) by urban dietary consumption increased from 218.23×10^3 tonnes in 1985 to 491.29×10^3 tonnes in 2006 for China (Figure 2). In total, 7225×10^3 tonnes of dietary P through urban household consumption has been imported into urban area in China during 1985-2006. About 3873×10^3 tonnes of dietary P, i.e. 53.60% of total dietary P from urban household consumption, have been eventually remained in urban area over the 1985-2006 period.

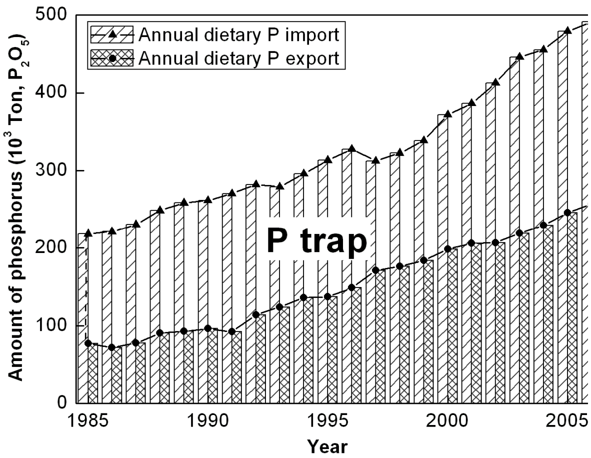

Figure 2. Annual dietary P import into and export from urban area and hence the formation of P-trapping island in urban area in China.

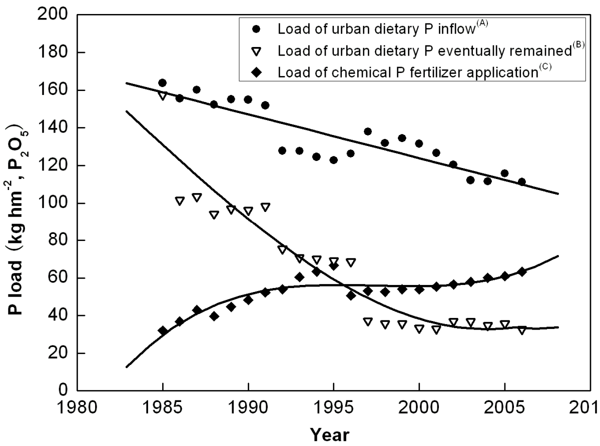

Figure 3. Comparison of per unit area load of urban dietary P in urban area to that of P fertilizer application in agricultural land. (A) Load of urban dietary P inflow on per unit of urban built-up area; (B) Load of urban dietary P eventually left on per unit of urban built-up area; (C) Load of chemical P fertilizer on per unit area of cultivated land.

Temporal trends of dietary P inflow intensity

Figure 3 indicates that inflow intensity of urban dietary P was much higher than that of chemical P fertilizer application on agricultural soil in China over the period of 1985-2006, suggesting that urban ecosystem was heavily burdened by the considerable inflow of dietary P. For instance, in 2006, the total dietary P inflow into cities is 0.06 times as much as the P fertilizer consumption, in contrast, the urban built-up area is only 0.02 times as large as the agricultural land area.

Low efficiency of P utilization in food chain system

The production efficiency of food P is defined as input amount of fertilizer P to produce per unit food P. From Figure 4, to produce 1 kg food P_2O_5 will cost 9 kg mineral P fertilizer input, suggesting the food production efficiency of P is only 11% in China's food production systems. Low efficiency of fertilizer P to produce food suggests to increase the risk of environmental eutrophication by P in food production process. For example, to produce 1 kg food P_2O_5 will cause the of 1 kg P_2O_5 released into aquatic environment, 2 kg P_2O_5 lost (crop discard) into natural environment, and another 5 kg P_2O_5 reserved in agricultural soil.

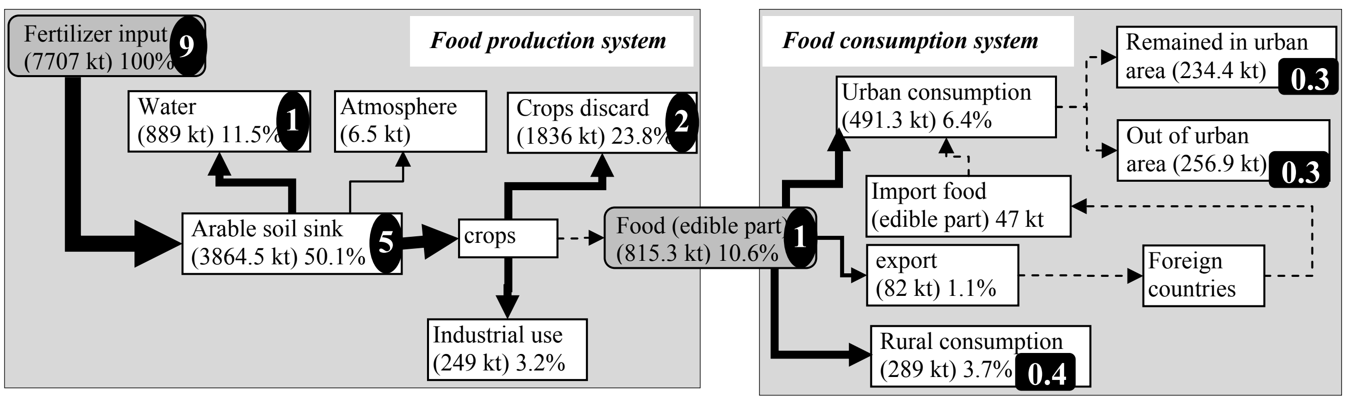

Figure 4. Phosphorus flow from chemical fertilizer to food in 2006 in China. note: (1) Unit: kt (kilo ton) P_2O_5; (2) Dash line means the source and the fate of flow. Solid line means the flow amount of P; (3) The number in black box means the relative value to the amount of food P consumption

The recycling efficiency of food P after consumption means the ratio of the amount of food P consumed by urban population and then recycled to agricultural soil as waste to the total inflow of food P into urban area. In China in 2006, about 60% of food P_2O_5 is consumed in urban area, in which about half was remained in urban area, mainly in urban soil. For instance, about 234.4 kilo tons of P_2O_5 was remained in urban soil in China in 2006. Therefore, it's really necessary to find ways to increase utilization efficiency of P in food production process and recycling rate of food P in urban system.

Conclusion

It's concluded that the heavy P accumulation in urban area of China, which results in the "P Island" at regional and national scale. The accelerating urbanization in the coming decades means more dietary P will be imported into urban soil, which will exacerbate a series of environmental problems. The key problem is the low efficiency of P use in the whole food chain process from field to Table. The potential solutions are to increase P use efficiency in food production process and develop techniques to increase extracting rate of P from household sewage and make fertilizer products from the extracted P.

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