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Managing urban nutrient biogeochemistry for sustainable urbanization

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ABSTRACT

Urban ecosystems are unique in the sense that human activities are the major drivers of biogeochemical processes. Along with the demographic movement into cities, nutrients flow towards the urban zone (nutrient urbanization), causing the degradation of environmental quality and ecosystem health. In this paper, we summarize the characteristics of nutrient cycling within the urban ecosystem compared to natural ecosystems. The dynamic process of nutrient urbanization is then explored taking Xiamen city, China, as an example to examine the influence of rapid urbanization on food sourced nitrogen and phosphorus metabolism. Subsequently, the concept of a nutrient footprint and calculation method is introduced from a lifecycle perspective. Finally, we propose three system approaches to mend the broken biogeochemical cycling. Our study will contribute to a holistic solution which achieves synergies between environmental quality and food security, by integrating technologies for nutrient recovery and waste reduction.

1. Introduction

The urban proportion of the global population has already exceeded 50% and will continue to rise in the coming decades. As the principal socioeconomic entity for human habitation, cities have a distinct biogeochemical process and impose a huge ecological footprint on surrounding ecosystems, which provide their sustenance and receive their waste products (Luck et al., 2001; Kaye et al., 2006). For example, even though urban areas cover less than 3% of the global terrestrial surface, cities are responsible for 78% of carbon emissions, 60% of residential water use, and 76% of wood use at the global scale (Grimm et al., 2008). Urban ecosystems are dominated by the human population and the biogeochemical processes in urban and peri-urban areas are controlled by the complex interactions between society and the environment. Sustainable urbanization refers to the benign and efficient interactions between the urban socioeconomic system and biosphere, which are often considered to be two interdependent systems in co-evolution.

Urban metabolism has been defined as the socioeconomic driven materials and energy flows in a city (Wolman, 1965; Newman, 1999), which extracts resources from the biosphere to provide services for human life. However, lack of integrated management and wise utilization have resulted in negative metabolic processes including altered ground water levels, exhaustion of local resources, accumulation of toxic materials, summer heat islands, and irregular accumulation of nutrients (Kennedy et al., 2007). Great efforts are required to gain better understanding and characterization of the distinct urban biogeochemical processes to reduce environmental pressures and achieve sustainable urbanization.

Nitrogen (N) and phosphorus (P) are essential elements for life, and the availability of N and P controls many aspects of global biogeochemistry (Schlesinger and E.S.B., 2013). In natural ecosystems, N and P cycling is dominated by internal transfers between plants and various soil pools, and is coupled to a large global pool with relatively slow turnover. Currently, urbanization is accelerating N and P cycling, which is the major driving force for

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environmental deterioration (Kaye et al., 2006; Grimm et al., 2008; Cui et al., 2013; Grimm et al., 2004; Li et al., 2012). The impact of urbanization on N and P biogeochemistry has two aspects: one is human induced N and P fluxes and their socioeconomic metabolism; another is natural N and P biogeochemical changes induced by the urban physical environment, including urban nonpoint source pollution caused by impervious surface expansion (Goonetilleke et al., 2005; Al Bakri et al., 2008), soil erosion caused by urban land development and hydrological changes (Kaye et al., 2006; Leigh, 1982), and altered community structure and denitrification due to local climate or other environmental changes (Bettez and Groffman, 2012; Groffman and Crawford, 2003; Grimm et al., 2004; Johnson et al., 2013).

Although these physical alterations can affect the urban N and P influxes in multiple and complex ways, socioeconomic influxes (i.e. urban metabolism) normally dominate the nutrient biogeochemistry in the urban ecosystem.

To sustain the development of human society (urban metabolism), cities import natural resources from ecosystems and generate metabolites (i.e. wastes or pollutants) in the same way that heterotrophic organisms do (Zhang, 2013). Generally, the N and P fluxes into the urban ecosystem can be categorized as natural or human-induced inputs. The natural N inputs include wet deposition, surface water inflows and biological fixation. Since there is almost no significant gaseous component, the natural P inputs mainly come from surface water inflows. Human induced N and P inputs mainly come from food supply, energy use and non-food goods (i.e. N or P-containing chemicals) (Gu et al., 2013). Commonly, food supply and fertilizer application are major sources of urban nutrient metabolism. In some highly industrialized cities, fixation by combustion has become an increasingly important source (Fissore et al., 2011; Baker et al., 2001; Gu et al., 2012).

Currently, there is limited understanding of how to manage urban nutrient biogeochemical processes. Increased understanding of urban nutrient management will contribute to resolving not only nutrient derived environmental pollution such as water eutrophication and organic pollution, but also the recycling of urban wastes in agriculture and the problem of food security (Forkes, 2007; Faerge et al., 2001). In this paper, we firstly summarize the characteristics of urban nutrient cycling compared with natural ecosystem cycling. Then, the dynamic process of nutrient urbanization is explored using a case study of food consumption in Xiamen, China, and the concept of a nutrient footprint is introduced. Finally, we propose a system approach to mend the broken biogeochemical cycling, which includes material flow analysis, technological innovation and integration, and risk assessment.

2. Characteristics of nutrient cycling in urban ecosystems

A city is a special human and nature coupled ecosystem in which nutrient cycling is significantly different to that in a natural ecosystem. Four characteristics of urban nutrient cycling are summarized below.

2.1. High density

To feed the growing population and maintain a modernized urban lifestyle, cities significantly increase nutrient throughput and present a high N and P flux density. At the global scale, over the past century humans have contributed far more nutrients to the environment than all natural terrestrial processes (Schlesinger and E.S.B., 2013; Canfield et al., 2010). The natural N and P inputs into terrestrial ecosystems are about 839 kg N/yr.km^2 and 168 kg P/yr.km^2 (see “The global cycles of nitrogen and phosphorus” in Schlesinger and E.S.B. (2013); we consider only fixation by lightning and biological fixation as N inputs and mining for P inputs, divided by Earth’s total land area).

According to previous studies, the N and P inputs into cities are more than ten times larger than those of natural ecosystems (for example about 7946 kg N/yr.km^2 in Phoenix, USA (Baker et al., 2001), 15,974 kg N/yr.km^2 and 2364 kg P/yr.km^2 in Bangkok, Thailand (Faerge et al., 2001), and 55,376 kg N/yr.km^2 and 5000 kg P/yr.km^2 in Stockholm, Sweden (Burström et al., 1997)). Food and inadvertent imports with fossil fuels are the major components of human induced N and P fluxes (Baker et al., 2001; Gu et al., 2012; NILSSON, 1995). Moreover, intensive fertilizer application in urban green spaces, such as residential lawns, plays a comparable role in impacting urban nutrient cycles to agricultural fertilizer application in some low population density cities (Law et al., 2004).

2.2. Disrupted cycling

Nutrient flows in natural ecosystems follow the food chain and form a closed loop between the producers, consumers and decomposers. To some extent, the decomposers drive and maintain the nutrient cycling by transferring the waste (detritus) from producers and consumers into resources for producers. However, the connection between nutrient utilization and waste treatment is disrupted or nearly broken during urban nutrient metabolism because of a lack of effective nutrient recycling mechanisms in cities. This often results in a considerable amount of the induced N and P being discharged as a pollutant into the surrounding environment, while some is accumulated in the city system (Zhang, 2013; Fissore et al., 2011; Baker et al., 2001; Forkes, 2007; Faerge et al., 2001).

From a perspective of environmental capacity, sustainable urbanization can be understood as a development process which does not increase the throughput of materials beyond the biosphere’s capacity for regeneration and waste assimilation (Kennedy et al., 2007; Goodland and Daly, 1996). The disrupted nutrient cycling in urban areas has exerted great stress on natural N and P biogeochemistry, not only from nutrient resource exploitation but also from waste assimilation. Furthermore, discharged organic waste from urban ecosystems contains huge quantities of plant nutrients that should be recovered and reused to close the ecological nutrient cycle.

2.3. Human dominated

Most of the N and P fluxes in urban areas are controlled by human activities either inadvertently or advertently, particularly human induced nutrient. Taking food consumption as an example, consumer demand is the main driver of material production processes. Population growth and food consumption patterns will directly affect the N and P fluxes associated with food supply to the urban ecosystem. Meanwhile, consumption behavior will greatly influence the production of food waste. It is estimated that nearly one third of all food produced for human consumption is lost globally (FAO, 2013). In China, about 39% of the total dietary P in cities is exported through direct sewage discharge without treatment, while still containing large amounts of recoverable nutrient (Li et al., 2012).

In cities with poor waste treatment systems, rivers and coastal marine environments are the major acceptors for nutrient discharge. However, in some cities, modern waste treatment facilities can extract or separate discarded nutrients from one environment medium and consequently transfer them into another environmental medium (or the same environmental medium in a different place or time). For example, a sewage treatment plant extracts the N and P from waste water into sludge, which is finally buried in soil or combusted and emitted into the atmosphere through an incineration plant. However, only a minimal amount of nutrient is actually recycled.

2.4. Low eco-efficiency

In many respects, cities can be considered as a model of efficiency, due to their economies of scale and advantages of proximity. However, compared with natural ecosystems, urban ecosystems display a very low efficiency of nutrient recycling. In essence, ecological efficiency of urban metabolism is a cost-benefit indicator which refers to the amount of social services per unit resource consumption or per unit pollution discharge during the process of urban material metabolism (Liu et al., 2010; Zhang et al., 2009). Nutrient cycling in natural ecosystems is closed and highly efficient, because millions of years of evolution have allowed complex relationships to form among living organisms and between organisms and their environment, for example food networks. As a result, N can be absorbed by organisms so rapidly that little nitrogen remains in inorganic forms (Schlesinger and E.S.B., 2013).

In contrast, most of the nutrients entering the urban ecosystem are wasted (e.g. through food waste). The low efficiency of nutrient recycling in urban ecosystems is the combined result of high density fluxes and disrupted cycling. However, human management currently plays a rather weak role in enhancing urban nutrient efficiency. It is still a relatively new concept to consider cities as a coupled human and natural ecosystem (Collins et al., 2000; Pickett et al., 2011), and there is huge potential for scientists, planners and engineers to manage nutrient biogeochemical processes by moving misplaced resources into the right position to enhance the eco-efficiency of urban nutrient recycling (Fig. 1).

3. Nutrient urbanization

Urban ecosystems are unique in that humans are the major driving force of the biogeochemical processes. Therefore, along with the demographic movement into cities, there is a clear nutrient "urbanization". For example, in Shanghai, China, as a result of food structure changes, the food sourced N and P fluxes present a clear density gradient, with 19.36 g N and 1.80 g P in the urban central area, 16.48 N g and 1.52 g P in the newer urban districts, and 13.04 g N and 1.20 g P in the suburban area per person per day (Liu et al., 2013). According to the different sources, nutrient urbanization can be considered as two pathways, one advertent and the other inadvertent. The former refers to urban nutrient metabolism such as food consumption, while the latter means the altered biogeochemical processes in the urban environment such as nonpoint source pollution. Here, we focus on advertent urban metabolism to explore the dynamic causal chains of human driven nutrient urbanization processes, as shown in Fig. 2.

In general, urbanization means the urban population growth and lifestyle changes which will potentially drive the demand for nutrient consumption. At the same time, urbanization also promotes infrastructure development including waste treatment systems to achieve a better living environment. To satisfy nutrient consumption demand from the urban population, nutrient production and supply of food and other N or P-containing chemicals will increase, leading to increased waste production from nutrient consumption. Nutrient production will speed up the natural resource shortage, whilst waste discharge will cause environmental pollution when it exceeds ecological carrying capacity.

To maintain a suitable living environment, humans in the city will try to recover the ecosystem services by enhancing the waste treatment system and adjusting nutrient consumption behavior. Thus, a dynamic relationship between urbanization, nutrient consumption and ecological carrying capacity appears (see Fig. 2). Below we take Xiamen city as a case study to show the nutrient urbanization process through food consumption.

Xiamen is a coastal city in southeast China which has experienced rapid urbanization since becoming one of the first 'Special Economic Zones'. The population tripled between 1991 and 2010, and total food consumption increased at the same rate. Although per capita food consumption hovered around 300 kg per year, the food structure altered significantly reflecting residents' lifestyle changes (Fig. 3). During urbanization, the waste treatment system was improved and gradually collected more and more food waste and human excreta. However, the enhanced treatment system merely alters the nutrient discharges into different environmental media including air, water, and soil, and the amount of recycled food-sourced nutrients was limited or even decreased due to reduced farmland area and mechanization of agriculture. As a result of improvements in urban waste treatment, landfill has become an increasing stock for food waste and sludge from sewage treatment plants, with the city accumulating large quantities of nutrients (Fig. 4). The following equations show the dynamic mass balance of food sourced N and P during urbanization:

$$NP_{input} = NP_{output} + NP_{accumulated}$$

$$NP_{output} = NP_{air} + NP_{soil} + NP_{water}$$

$$NP_{accumulated} = NP_{human} + NP_{landfill}$$

where NP_{input} represents the total amount of N and P input to a city through food consumption in a given year; NP_{output} and $NP_{accumulated}$ represent the total N and P discharged from and accumulated in the urban ecosystem respectively; NP_{air}, NP_{soil}, and NP_{water}

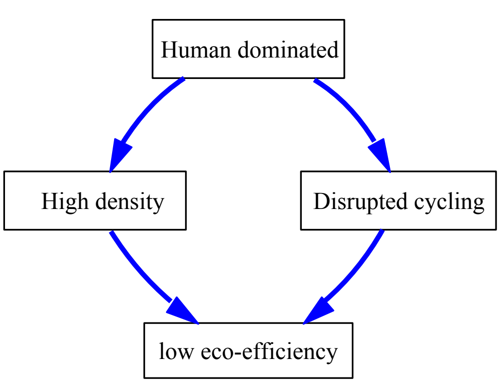

Fig. 1. Characteristics of urban nutrient cycling and their relationships.

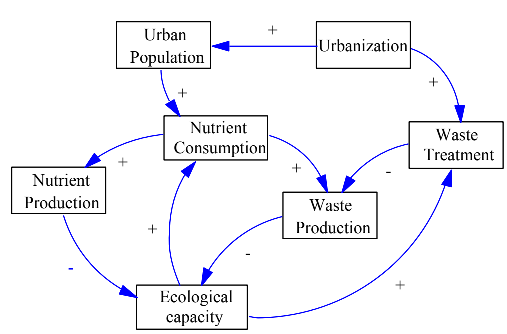

Fig. 2. Dynamic schematic diagram of nutrient cycling with urbanization. Note: + represents positive feedback, − represents negative feedback.

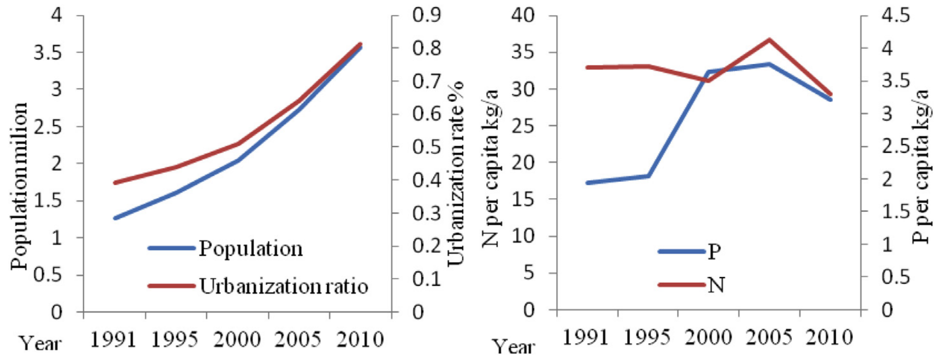

Fig. 3. Food sourced N and P consumption with rapid urbanization in Xiamen city, 1991–2010.
Data source: Xiamen Statistics Bureau

represent the N and P outputs into air, soil, and water environments respectively; NP_{human} and $NP_{landfill}$ represent the NP accumulated in human bodies and landfill areas respectively.

4. Nutrient footprint and its calculation

Understanding of urban nutrient cycling heavily depends on how the city boundary is defined, as shown in Fig. 5. From a perspective of material cycling or mass balance, a city is a heterotrophic super-organism consisting mostly of impervious surfaces, if the city boundary is defined as the human settlement (built up) area. On the other hand, a city is an unbalanced ecosystem with consumption far in excess of production if we combine the human settlement with the surrounding natural ecosystem. However, a city can be a mass balanced ecosystem with humans driving all material cycling and energy flows if we connect the urban area with its footprint area (the area required to meet the demands of the urban population in terms of consumption and waste accumulation, and the area affected by urban pollution and changes in climate) (Churkina, 2008; Lin et al., 2013). Theoretically, a mass balance always exists between a city and its footprint area. Unfortunately, current management of urban metabolism always neglects the potential to imitate biogeochemical processes in natural ecosystems, and results in many kinds of environmental pollution.

In addition to material balance analysis, the ecological or environmental footprint method is becoming a popular analysis tool in urban metabolism study (Barles, 2010). The N footprint model was first developed in 2010 by Galloway and Leach, who defined N footprint as the total amount of N released to the environment as a result of an entity's resource consumption (Leach et al., 2012). Taking a lifecycle approach to nutrient supply for a city, the nutrient footprint can be calculated by the following equations:

$$NP_{fp} = \sum\sum N_i \times L_j$$

$$NP_{fpr} = \sum\sum N_i \times L_j \times R_{ij}$$

where N_{fp} is nutrient footprint, which represents all nutrients lost to the environment during the lifecycle of a good, expressed in total units of N or P; j represents different stages of the lifecycle, including mining, production, transportation, consumption and waste treatment; L_j is the amount of nutrient released in different life stages; N_i represents the consumption of different goods which contain N and P in a city; i represents different types of goods including food and nonfood goods; R_{ij} is the release factor of good i into different environments including air, water, and soil at life stage j; N_{fpr} represents the amount of nutrient release of a good into different environments r, which represent air, water, or soil environment.

In fact, nutrient losses occur at each step of the nutrient supply chain and greatly depend on economic and climatic conditions, production and infrastructure systems and market and consumption features. Even the same kind of production may have different nutrient footprints as their lifecycles vary. The per capita N footprint in China increased 68% during the last three decades and the N input to China's cropland has increased far beyond the optimal fertilization rate (Gu et al., 2013). However, much of the nutrient is lost before actually being consumed: for example, N loss from food production and consumption accounts for 70% of the nitrogen

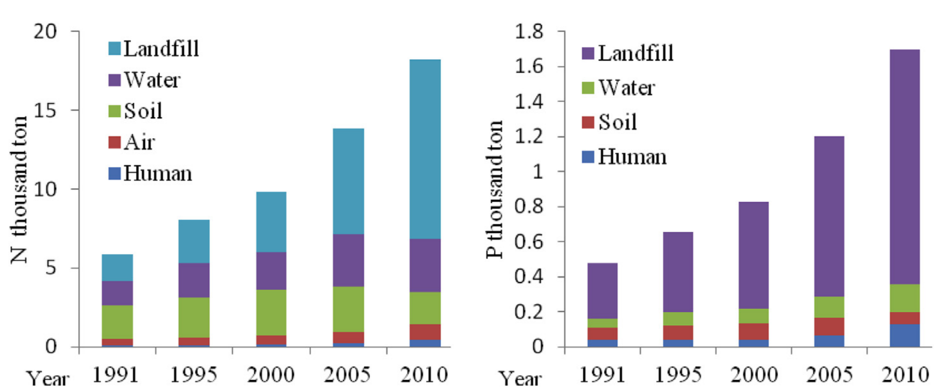

Fig. 4. Fates of food sourced N and P with rapid urbanization in Xiamen city, 1991–2010.

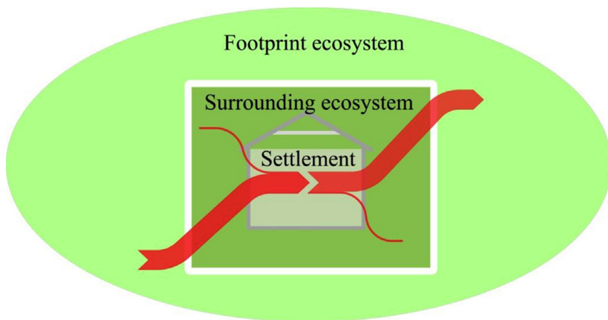

Fig. 5. Urban ecosystem boundary and material balance. Arrows represent the material fluxes.

footprint (Gu et al., 2013) and only 18% of P entering the food supply chain exits as food for humans (Wang et al., 2011).

Meanwhile, people living in suburban or rural areas, which traditionally consider crop products as major dietary sources of food, now show a preference for increasing the intake of animal-derived as well as processed foods, which will inevitably enlarge the N and P footprint from human diets (Liu et al., 2013). Systematically evaluating the life cycle N and P flows for urban utilization will contribute to identifying the inefficient uses and leaks to the environment, and enable more effectively targeted policymaking for managing urban nutrient biogeochemistry (Forkes, 2007; Wang et al., 2011).

5. Mending the broken nutrient biogeochemical cycling

Coupling nutrient consumption in the urban area with production and supply chains in the footprint area is necessary to realize balanced nutrient cycling. Food supply and consumption are fundamental for a city to sustain urban development and trigger urban nutrient metabolism. Agricultural ecosystems are the typical footprint ecosystem for urban food consumption, and one of the worst consequences of urbanization is breaking the traditional nutrients link between food consumption and production. Food waste and sewage sludge from the urban waste treatment system are the largest sources of nutrients which remain unused today and should be returned to agricultural land (Nilsson, 1995).

In rapidly urbanizing China, human food consumption has significantly increased the input of N and P into the urban ecosystem, causing the typical agro-ecosystem to become more dependent on chemical fertilizers (Liu et al., 2012). Some nutrient recycling practices have been established among agriculture and aquaculture activities (Cucarella et al., 2012; Heeb et al., 1996; Granstedt, 2000). However, without considering the nutrient supplies for cities, these kinds of recycling are incomplete. Producing food closer to where it is consumed represents a closed-loop approach to resolve the current nutrient problems of cities and agriculture. Furthermore, it is a practical solution for urbanization coupled with poverty issues (Abdalla et al., 2012; Zezza and Tasciotti, 2010).

Here, we propose systems approaches to mend the broken biogeochemical cycling including: (1) material flow analysis to reveal the source and fate of N and P in the urban system; (2) technology innovation and integration to recover/recycle nutrients from urban waste streams and reduce the urbanization footprint; and (3) risk assessment to ensure appropriate technologies to remove toxic chemicals before recovery and recycling can be implemented. Taking food supply as an example, we design a sustainable food sourced nutrient cycle in a coupled urban and peri-urban ecosystem (Fig. 6).

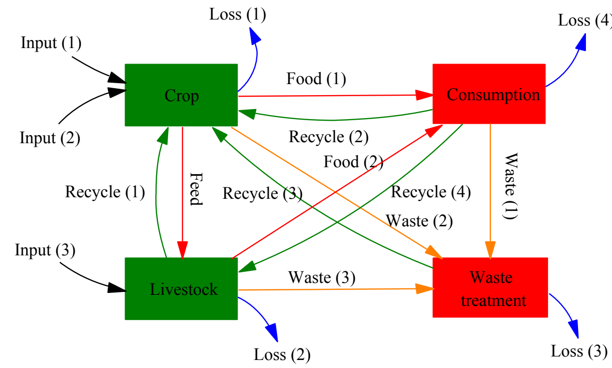

Fig. 6. Sustainable food sourced nutrient cycling in a coupled urban and peri-urban ecosystem. Note: Red and green boxes mean the processes of food consumption, waste treatment, livestock and crop production, which take place in urban (red) and peri-urban (green) areas respectively. Input (1) is natural nutrient input such as N deposition; Input (2) is fertilizer application; Input (3) is extra feed input; Loss (1) is nutrient leaching and runoff; Loss (2) is nutrient loss from livestock's excreta; Loss (3) is reclaimed water discharge and landfill; Loss (4) is food waste discharged directly (not entering waste treatment); Food (1) is plant derived food such as wheat, vegetables; Food (2) is animal derived food such as egg, pork; Waste (1) includes food waste and human excreta; Waste (2) includes crop residues and runoff nutrients; Waste (3) includes animal excreta and carcasses; Recycle (1) is the recycled use of animal excreta as fertilizer; Recycle (2) is the recycled use of human excreta as fertilizer; Recycle (3) is the recycled use of food waste and sludge as fertilizer; Recycle (4) is the recycled use of food waste as feed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.1. *Nutrient budget (material flow analysis)*

In the coupled urban and peri-urban ecosystem, the crop system is the fundamental footprint ecosystem of food supply for a city, since it provides food for people as well as feed for livestock. The waste treatment system should play a critical role in nutrient recycling due to its capacity to transfer waste from the crop, livestock and consumption systems into fertilizer for food production. As the four subsystems are spatially adjacent, we can minimize the nutrient loss from processing, storage and transportation within the system. The recovered nutrients from food waste and sewage sludge will replace, at least in part, the chemical fertilizers imported from outside of the system. Thus, the nutrients lost within the system are nearly equal to the inputs from the outside in the long run. The detailed nutrient budget description can be seen in Fig. 6.

5.2. *Technology integration and innovation*

Technologies for sustainable nutrient cycling in the coupled system can be categorized as loss reduction technology and recycled use technology. Loss reduction technology aims to minimize the nutrient loss in the four subsystems including reducing crop residues and mitigating non-point source pollution in the peri-urban area, increasing food waste collection and enhancing the nutrient removal rate during waste treatment in the urban area. In a stable cycling system, the total nutrient loss is compensated by inputs from outside the system. Thus, the reduction of nutrient loss within the system leads to decreased nutrient input in the form of fertilizer and imported feed. Recycling technologies aim to form direct and indirect recycling loops between the four subsystems.

The key functions in the direct and indirect recycling loops are 1) efficiently collecting waste from crops, livestock, and consumption systems and 2) transferring waste into organic fertilizer for food production systems. Loss reduction technology and recycling technologies should be integrated into the urban and peri-urban coupled system. Furthermore, technological innovation will contribute to efficient integration. For example, Ray et al. (2013) introduced cyanobacteria and microalga to accumulate polyphosphate and then used them as biofertilizers to substitute for inorganic phosphorus fertilizers and curb environmental P pollution (Ray et al., 2013).

O'Neal and Boyer (2013) used a hybrid anion exchange resin containing hydrous ferric oxide coupled with chemical precipitation reactions to accumulate and recover nutrient from different types of wastewater and to minimize environmental impacts of excess nutrient on receiving waters. In addition, electrodialysis was found to be an effective way to achieve nutrient recycling by integration with struvite precipitation (Zhang et al., 2013). Wan et al (2013) found that co-digestion of food and garden waste or waste paper materials in a new single stage rotary anaerobic reactor can enhance the recovery of ammonium-N and simultaneously produce energy (biogas). Because it produces additional energy during the waste treatment process, Wan's approach could be a cost-effective alternative to treat food wastes and other organic wastes after landfill (Wan et al., 2013a,b).

5.3. Risk assessment

Capturing nutrients from waste sources may be cost-effective (Qiao et al., 2011) but their safe use should be carefully evaluated. For example, sewage sludge and animal waste have been reused in agricultural land, because the nutrients and organic constituents they contain can improve plant growth as well as provide beneficial soil conditioning properties. However, sewage sludge and animal waste often contain elevated concentrations of residual chemicals and bio-hazardous substances, such as metals, pharmaceuticals and personal care products (PPCPs), pathogens and antibiotic resistance genes (ARGs) (Werner, 2000; Zhu et al., 2013). Therefore, direct application of sewage sludge and animal waste on farmland could result in public health concerns. For example, Zhu et al. (2013) found diverse and abundant ARGs in swine manure and elevated concentrations of ARGs in manure-applied farmland, which also pose potential health risks due to the possible spread of antibiotic resistance to human pathogens (Zhu et al., 2013).

Consequently, it is necessary to develop suitable techniques to monitor the release of contaminants in the environment and their uptake by crops after the application of recovered nutrients from urban waste to farmland, to provide information for further risk assessment and evaluation of applicability. For example, Huang and his colleagues conceptualized food waste management through the use of a Food Recycling Index (FRI) to assess recyclability within a food system and improve urban food safety (Lin et al., 2009; Huang, 2010). In addition, development of effective technologies to remove hazardous substances or minimize their release before and after application will be beneficial for sustainable nutrient recycling from urban waste. For example, Khan et al. (2013) found that turning sewage sludge to biochar and using it as a soil amendment in peri-urban agriculture can reduce the availability of contaminants to the soil and crops (Khan et al., 2013). Currently, more research is needed to assure the safe use of recovered nutrients from urban waste streams for agricultural purposes.

6. Conclusion

In conclusion, urban ecosystems maintain a greater amount of nutrients than any other natural ecosystems on the Earth to sustain the high density of human population and intensive socioeconomic activities. The nutrient cycling in the urban ecosystem is dominated by human but tightly connected to natural biogeochemical cycling in a larger scale, presenting distinguished characteristics. With increasing urbanization, more and more nutrients (N and P) are imported into cities leading to potential environmental pollution (e.g. lakes or rivers) and wastage of resources. However, our understanding on the urban nutrient cycling is still limited and the existing management methods are unsustainable. It is proposed that for sustainable urbanization, it is critical to mend the broken nutrient biogeochemical cycling with a life cycle perspective, such as recycling the nutrient between urban human population and peri-urban food production systems. Thus, a nutrient budget analysis is necessary to track the flows in the coupled urban and footprint ecosystems. It also suggested that technologies should be improved to make sure that nutrient cycling is implemented safely and efficiently. We suggest that nutrient flow analysis, technology innovation and integration, and risk assessment should be foci for future urban nutrient cycling studies that will require trans-disciplinary collaboration among urban planners, ecologists, engineers, social scientists and managers.

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