Ecological Modelling 337 (2016) 29–38

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Modelling urban nitrogen metabolic processes based on ecological network analysis: A case of study in Beijing, China

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ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form 24 May 2016
Accepted 2 June 2016

Keywords:
Urban ecology
Nitrogen cycles
Metabolism
Ecological network analysis
Ecological relationship
Beijing

ABSTRACT

The consumption of food, energy, and industrial products in cities results in large quantities of excess nitrogen circulating in socio-ecological systems. However, details about how nitrogen flows and transforms within urban systems are unclear. In this study, we analyzed the nitrogen processes of Beijing considering the influences from human activities and nature under the framework of urban metabolism. Ecological network analysis was used to track the integral (direct + indirect) flows and to compare the contribution of direct and indirect flows at both the scale of each component and of the whole urban system during the period from 1996 to 2012. We found that Atmosphere, Household, and Industry had the most interactions with other nodes in the network. The integral flow from Industry to Atmosphere, which was consistently at 200 Gg, was the largest at five time points; the flow from Household to Sewage treatment grew fastest, and in 2012, increased to 5.9 times its 1996 value; the flow from Industry to Farmland decreased most obviously, and in 2012, it decreased to 12.9% of the value in 1996. Moreover, the indirect effects were dominant for the whole system in Beijing with a ratio of indirect to direct flow equal to 1.2. Surface Water and Forest had the strongest indirect effects maintaining a ratio of almost 2. Meanwhile, exploitation and competition relations were most frequent and their proportions were much larger than the proportion of mutualism relations. Through our results, integral flows were found to identify accurately the crucial process of nitrogen metabolism and our results showed how these ecological relationships influence the urban nitrogen flows within the system.

1. Introduction

Beijing, as the capital of China, has experienced unprecedented urbanization, and this inevitably results in a dense population and a large quantity of nitrogen (N) input and output. In particular, the increase of Beijing's population gave rise to the increase of food consumption and vehicle ownership. The population in Beijing in 2012 was 1.6 times the value in 1996, during the same period, the consumption of farm products and animal products in Beijing have increased to 2 and 3 times, respectively (BMBS NBS, 2013). And, vehicle ownership of Beijing in 2012 was almost 6.5 times the number in 1996 (BMBS NBS, 2013), which caused that energy consumption by transportation increased 4.6 times (by standard coal) (NBS DES, 2013). The increasing food and energy consumption inevitably elevated the nitrogen input into the city. From 1996 to 2012, the amount of household sewage discharge changed from 0.9 Mt to 1.5 Mt (NBS MEP, 2013; NBSC, 2013), and the contents of nitrogen and other nutrients in the sewage led to water eutrophication. Moreover, in 2012, 48% of the days in Beijing missed the air quality targets from the *Report on the State of China's Environment in 2013.* The emission of nitrogen oxides (NOx) from fossil fuel combustion is one of the key pollutants that cause air quality problems. To solve the problem, specific emission reduction targets of ammonia nitrogen and NOx had been proposed in the *Beijing's 12th Five-Year Environment Protection Plan.* In this context, it is urgent to study nitrogen cycle processes influenced by human activities in the urban areas, introduce the theory of urban metabolism, clarify nitrogen inputs, destinations, flow paths, and outputs, quantify the direct and indirect flows of nitrogen, and then identify the vital flows among urban metabolic processes.

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http://dx.doi.org/10.1016/j.ecolmodel.2016.06.001
0304-3800/

The early study of nitrogen balance was to estimate nitrogen output at estuaries and explore the reason of its increase after the invention of Haber-Bosch nitrogen fixation (Jaworski et al., 1992; Howarth et al., 1996; Boyer et al., 2006). With the inheritance and development process of nitrogen cycle research from catchment to urban scale, Baker et al. (2001) studied nitrogen balance for the Central Arizona–Phoenix (CAP) Ecosystem and then extended research from the urban to the regional urban-agglomeration, national, and global scales. Most of them concentrated on national and global scales. Galloway et al. (2004) established a nitrogen balance model at the global scale excluding denitrification in 1860 and forecasted its development tendency in 2050. Based on the study of Galloway et al. (2004), Schlesinger (2009) developed a balance of nitrogen input and output term list including denitrification also at the global scale. Early national-scale nitrogen cycle case studies were conducted for Brazil (Filoso et al., 2006) and New Zealand (Parfitt et al., 2006). Singh and Bakshi (2013) incorporated the biogeochemical cycle of nitrogen into the 2002 input–output model of the U.S. economy and quantified the direct and indirect impacts or dependence of economic sectors on the nitrogen cycle. There are fewer studies at urban and urban agglomeration scales. Deng et al. (2007) studied the nitrogen sources and sinks in the Yangtze River Delta economic region which is an urban agglomeration in China, but focused only on nitrogen fixation related to fertilizer use and agriculture. For urban areas, Han et al. (2011) estimated net anthropogenic nitrogen accumulation (NANA) as an index of nitrogen pollution potential in the Beijing. But in their accounting terms, energy consumption was not considered. For another two Chinese cities, the Hangzhou study focused on developing an accounting process that could account for the complexity of the nitrogen cycle (Gu et al., 2009), whereas the Shanghai study paid more attention to the influence of urbanization on the nitrogen cycle and to the key drivers (Gu et al., 2012). Recently, long time series and spatial distribution analyses were developed at the national scales, such as China (Ti et al., 2012; Cui et al., 2013) and the United States (Sobota et al., 2013).

Because rapid socioeconomic development and dramatic population increases have raised the standard of living, these changes have increased the demand for nitrogen as a component of human food, particularly due to increased consumption of animal products. Accordingly, the percentage of the total nitrogen input accounted for by food nitrogen is increasing, thereby affecting the global biogeochemical nitrogen cycle (Lassaletta et al., 2014). Leach et al. (2012) found that food nitrogen was the largest single component of the calculated nitrogen footprints of the United States and of the Netherlands. The food supply, the most decisive nutrient flow between the urban system and the waste recycling back to the agriculture were evaluated for Bangkok (Faerge et al., 2001) and Paris (Barles, 2007). Ma et al. (2010) developed the model NUFER (NUtrient flows in Food chains, Environment and Resources use) for China, on this basis, Ma et al. (2012) provided an integrated assessment of the N and P utilization efficiencies and their losses in the chain of crop and animal production, food processing and retail, and food consumption at a regional scale in China in 1980 and 2005. Besides, Ma et al. (2013) explored scenario analyses on possible changes in the food chain structure, improvements in technology and management, and combinations of them on food supply and environmental quality in China in 2030. Lin et al. (2014) and Ma et al. (2014) studied food nitrogen flows under urbanization processes in Xiamen and Beijing, respectively. Gierlinger (2015) also studied the food and livestock feed supply and the waste-disposal patterns of Vienna, Austria. All of these urban studies paid special attention to the influence of rapid urbanization on the nitrogen cycle of cities, and they both reflected and highlighted the high density and low ecological efficiency of nutrient cycling in urban areas.

On the basis of nitrogen input, output, and cycle process, tracking nitrogen circulation from a metabolic perspective was another objective. Urban nitrogen metabolism is one of the foci of urban metabolism research. Because of the high concentration of humans in cities, they are subject to large quantities of nitrogen flowing through them. The key concept guiding this research is that cities can be simulated as if they were analogous to living organisms, in the sense that they are open systems that require material and energy flows to maintain them and generate waste products that must be expelled from the system boundary. In this manner, we investigate urban flows and processes analogous to biological metabolism. Then, by simulating these flows, it becomes possible to analyze the metabolic role of nitrogen in the processes involved in the uptake, circulation, and emission of nitrogen. Urban metabolism proposed by Wolman (1965) was considered to be an effective way to solve urban metabolic disorders. In the 21st century, many researchers paid more attention to metabolism of human nutrition in the urban food system. When analyzing the nitrogen balance for the urban food metabolism in Toronto, Canada, Forkes (2007) focused on the available food input, food wastes output, and recycled wastes. However, Barles (2007) added food processing and retailing steps, and specified the recycle processes in the food metabolism of Paris, France. Villarroel Walker and Beck (2012) and Villarroel Walker et al. (2014) started to focus on the socioeconomic sectors within an urban area and adopted multi-sectoral analysis to calculate the flow of materials and elements among five industrial sectors. During the same time period, Wang and Lin (2014) and Lin et al. (2014) studied metabolic paths and metabolism-related flows of nutrients within the food system of Xiamen, China.

In the study of the nitrogen cycle, most researchers paid more attention to the chain of nitrogen flow processes, but did not emphasize the nitrogen network processes that the components interweave with each other. In addition, most researchers considered the natural environment which can provide resources and receive wastes in the urban system as external environment, but did not emphasize the importance of the natural components. Ecological network analysis (ENA) is applied mainly by abstracting the ecosystem into a network of nodes, paths between nodes, and flows along those paths. Integrating this structure within a model makes it possible to analyze the paths and flows related to each node in the network, and this can then provide a systematic and overall view that reflects the structure and function of the system (Fath and Patten, 1999). Min et al. (2011) have used four common parameters based on ENA to validate indirect effects on nitrogen biogeochemical cycling of 5 cities and 22 natural ecosystems. However, the network model of Min et al. (2011) did not involve the sectors of energy consumption and the flow of chemical products. Energy consumption is an important resource of nitrogen input for cities which connects with other sectors. So the network model of Min et al. (2011) has not been a complete system. Hannon (1973) first applied economic input–output analysis (the Leontief model) to simulate the structural distribution of ecosystem components and the interrelationships among trophic levels. In recent years, this approach has been widely applied to study natural systems such as bays (Christian and Luczkovich, 1999; Baird et al., 2009), estuaries (Whipple et al., 2007; Christian et al., 2009), saline ponds (Dame and Christian, 2008), near-shore bodies of water such as straits (Jordán et al., 2009), and wetlands (Heymans et al., 2002). It has also been used to study human systems such as cities (Zhang et al., 2009), industries (Bailey et al., 2004a,b; Chen, 2003), fisheries (Walters et al., 1997; Pauly et al., 1998), energy (Zhao, 2006), and utilization of water resources (Bodini and Bondavalli, 2002; Li et al., 2009). However, there have been few studies that used ecological network analysis to study socioeconomic systems (Trotter, 2000; Costea, 2006; Zhang et al., 2009) and an urban metabolism (e.g., Zhang et al., 2009, 2012).