Journal of Cleaner Production 181 (2018) 416–425

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Enhanced nitrogen and phosphorus flows in a mixed land use basin: Drivers and consequences

Songyan Jiang [a, b], Hui Hua [a], Helen P. Jarvie [b], Xuewei Liu [a], You Zhang [a], Hu Sheng [a], Xin Liu [a], Ling Zhang [c], Zengwei Yuan [a, *]

[a] *State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, 210023, China*
[b] *Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK*
[c] *College of Economics and Management, Nanjing Forestry University, Nanjing, 210037, China*

ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form
18 January 2018
Accepted 1 February 2018
Available online 3 February 2018

Keywords:
Nutrient flow
N:P stoichiometry
Mixed land use basin
Basin nutrient management
Substance flow analysis

ABSTRACT

Rapid increase in accumulation of phosphorus (P) relative to nitrogen (N) has been observed in human-impacted regions, but the reasons are largely unknown. We developed an Integrated Nutrient Flow Analysis (INFA) model in order to assess the changes in nutrient flows of the Chaohu Lake basin from 1978 to 2015. Results show that the increase in total N input is slower than that of P (3.5-fold versus 4.2-fold) during 1978–2015, while total N loss increases much faster than that of P (3.1-fold versus 2.3-fold). We found a decline trend in the N:P ratio of nutrient input and accumulation since the mid-1990s. The decline in N:P ratio of nutrient loss to waterbodies in the basin is correlated ($p < 0.05$) with TN:TP of water concentration in Chaohu Lake, which may be related to the frequent algal blooms in the P-limited lake by supplying more P than N. Using an extended STIRPAT model, we found that nutrient use efficiency, urban rate, diet choice and population are key factors driving the change in nutrient flows, which contribute over 90% to the total change. This study confirms that human activities decrease N:P in regional environment and demonstrates the importance of P management to balance nutrient for improving water quality. The method in this study has a wide application for many other mixed land use regions to address nutrient flows imbalance problems and to explore nutrient management options.

1. Introduction

Human activities have dramatically accelerated the biogeochemical cycles of nitrogen (N) and phosphorus (P) especially over the last seven decades (Beusen et al., 2016), as a result of agricultural intensification, which relies on heavy inputs of N and P fertilizer (Powers et al., 2016). Increase in N and P availability has brought positive effects by boosting food production to feed more population (Tilman et al., 2011), but result in negative impacts on environment, i.e. excess N and P losses to surface waters, cause nuisance and harmful algal blooms, and thus impair aquatic ecology, biodiversity and water quality (Jarvie et al., 2015; Paerl and Otten, 2013). However, previous studies have shown that rapid increase in anthropogenic N inputs relative to P inputs is a widespread phenomenon at global scale (Peñuelas et al., 2012), as the sources of N are geographically widespread than P, and are also more mobile. As most terrestrial biomes have been proved to be N limitation (Camenzind et al., 2017), more N fertilization may be shifting this limitation, imposing negative effects on ecological diversity and climate change (Dashuan et al., 2016; Wieder et al., 2015). In contrast, in human-impacted areas, faster accumulation rates of P than N were observed in soils, lakes and streams (Peñuelas et al., 2012). For example, a recent study suggested that P accumulates faster than N in human-impacted freshwater ecosystems (Yan et al., 2016). It may exacerbate the impairment of water quality by altering the balance of N and P in receiving waters over long time scales, as P is the limiting nutrient for algal growth in freshwater ecosystems (Schindler et al., 2016). However, how humans influence the N and P flows and N:P stoichiometry is largely unknown in high-human impacted areas. To answer this question, it is necessary to examine historical changes in regional N and P flows from an integrated perspective.

Building a regional nutrient budget is an effective way to assess nutrient flows from different sources. Regional Phosphorus Flow Analysis (RPFA) is a substance flow analysis (SFA) based approach

---

* Corresponding author.
E-mail address: yuanzw@nju.edu.cn (Z. Yuan).

https://doi.org/10.1016/j.jclepro.2018.02.005
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

that facilitates quantitative evaluation on anthropogenic P cycles in socio-ecosystems. The PRFA was applied to basin and country scales and has been proved to be robust for assessing historical changes in P flows (Jiang and Yuan, 2015; Liu et al., 2016b). However, none of these studies take N into consideration to provide an integrated understanding of regional N and P flows. Recently, a mass-balance based modeling approach has been developed and applied to estimate N and P inputs to the northeastern United States and the southeastern Canada (Goyette et al., 2016; Hale et al., 2013). However, the studies only consider N and P inputs and do not provide understanding of nutrient flows from loss perspective, which is closely linked to water quality impairment. Hence, our ability to have a comprehensive understanding of the changes in N and P flows from both inputs and outputs perspective is still limited.

This study addresses the question “how human beings reshape regional N flows, P flows and N:P stoichiometry and what the drivers and consequences of the change are” by following steps shown in Fig. 1a. We first developed an Integrated Nutrient Flow Analysis (INFA) model and applied it to examine the changes in N and P flows and their stoichiometry in a basin of mixed land use (Chaohu Lake Basin, CLB) over the period of time from 1978 to 2015. Then, we used an extended STIRPAT model to quantitatively assesse the drivers of the changes. At last, we analyzed the relationship between the changes in N:P of nutrient loss and TN:TP concentration in waterbodies to demonstrate the potential consequence of the changes. The contribution of this paper lies in the adaption of the P-specific RPFA model into an integrated version for both N and P. The application of the adapted model in the CLB helps to demonstrate the changes in the N and P flows and their stoichiometry in the mixed land use basin. Furthermore, this paper performed the output of the integrated model in an extended STIRPAT model to analyze the drivers of the human-induced changes in N and P flows. The results are expected to support policy makers to design appropriate nutrient management measures for the CLB.

2. Material and methods

2.1. Study area

The CLB is located in the downstream area of the Yangtze River Basin in eastern China (30°87′-32°13′N, 116°40′-118°37′E, Fig. 2), covering a total area of 13 959 km^2. The basin falls within the boundaries of eight administrative regions (Hefei, Feidong, Feixi, Chaohu, Wuwei, Luajing, Shucheng and Hanshan). Chaohu Lake lies to the northwest of the Yangtze River, with an area of 760 km^2 and a storage capacity of 2.1 billion m^3 (at a water level of 8 m). Chaohu Lake is connected to the Yangtze River through the only outlet of the lake, the Yuxi River. Outflow from the lake has been artificial controlled since a dam was constructed in 1962. There are 32 rivers flowing into the Lake, and four of them, named Nanfei, Pai, Hangbu-Fengle and Baishitian are the most important, accounting for 90% of total water inflow.

The CLB is of particular interest because this basin is located within a major agricultural area in eastern China and encompasses the capital of Anhui Province (named Hefei), which has undergone a rapid urbanization (Fig. S1). As an important agricultural area, the land use of the CLB is dominated by cropland, followed by forest, accounting for 65.9% and 14.3% of the total area, respectively (Fig. 2). However, there has been large-scale land use change in the basin: Over the last 30 years, urban land area has increased by 6-fold—1168 km^2 (Fig. S1), with a corresponding rapid increase in population density, reaching 659 capita per km^2. Due to the increasing population, the per-capita water-resources availability in the basin has declined to 784 m^3, which is below the internationally-recognized water storage warning threshold (1000 m^3 $capita^{-1}$) (Pimentel et al., 1997). Meanwhile, since the 1980s, Chaohu Lake, the important water source for surrounding cities, has changed from oligotrophic to eutrophic, and is now one of the three most eutrophic lakes in China (Duan et al., 2017). Thus, it is a critical to quantify the changes in N and P flows within the CLB as a basis for mitigating eutrophication.

2.2. Estimation of nutrient flows

We developed an Integrated Nutrient Flow Analysis (INFA) model and applied it to quantify the N and P flows in the CLB over the past four decades. The INFA divided the socio-ecosystem into seven compartments: Crop farming, animal breeding, food processing, human consumption, waste disposal, loss to environment, and nutrient exchange through trade (Fig. 1b). Compared with the RPFA, the INFA considers some N-specific processes to estimate exchange of N between land and atmosphere. For example, we included biological N fixation by legumes crops and denitrification from fertilizer and manure. Specifically, the INFA considered four N and P inflows to the basin: (1) atmospheric deposition, (2) biological N fixation, (3) chemical fertilizer, (4) food/feed import; 6 outflows: (5) crop food export, (6) animal food export, (7) NH_3, N_2 and N_2O emission from fertilizer applied to the cropland and from manure storage; wind erosion for P, (8) erosion and runoff from cropland, (9) discharge to water via wastewater, (10) waste accumulation, and (11) soil accumulation; and 10 nutrient flows between compartment: (12) local crop animal feed (13) crop products, (14) animal products, (15) food consumption, (16) non-recycled crop straw, (17) non-recycled animal manure, (18) non-edible part of food, (19) human wastes, (20) straw and manure recycled to cropland and (21) straw recycled as feed. Here, we defined the flow (7), (8) and (9) as loss from the basin. All the calculations are based on the mass balance principle:

$$\sum_{1}^{n} In_i = \sum_{1}^{m} Out_j + \sum Stock$$

Detailed calculation methods of the flows can be found in the Supplementary Material (SM).

2.3. Assessment on drivers of changes

In this study, the STIRPAT model was used to assess the contributions of the factors to nutrient inputs. STIRPAT is a stochastic model for assessing the effect of humans on the environment, derived from IPAT (Impact = Population × Affluent × Technology) model (Dietz and Rosa, 1994; York et al., 2003). STIRPAT has been widely used to assess the anthropogenic driving forces on greenhouse gas emission and nutrient inputs (Cui et al., 2013; Wang et al., 2013). The standard STIRPAT model is:

$$I = aP^bA^cT^de \quad (1)$$

where a is the constant, e is the error term, and b, c, and d are the exponents of P, A and T, respectively.

As the standard STIRPAT model is a nonlinear multivariate equation, it is difficult to calculate the coefficients of a, b, c, d, and e. In the typical application, all the variables in Eq. (1) are often converted to logarithmic form to facilitate the calculation (York et al., 2003). We then obtained Eq. (2):