Agriculture, Ecosystems and Environment 221 (2016) 145–155

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Modeling forest/agricultural and residential nitrogen budgets and riverine export dynamics in catchments with contrasting anthropogenic impacts in eastern China between 1980–2010

Dingjiang Chen[a,b,*], Minpeng Hu[a,c], Yi Guo[a], Randy A. Dahlgren[d]

[a] College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, China
[b] Key Laboratory of Environment Remediation and Ecological Health (Zhejiang University), Ministry of Education, Hangzhou 310058, China
[c] Zhejiang Provincial Key Laboratory of Subtropical Soil and Plant Nutrition, Zhejiang University, Hangzhou 310058, China
[d] Department of Land, Air, and Water Resources, University of California, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form 21 January 2016
Accepted 25 January 2016
Available online 5 February 2016

Keywords:
Nitrogen
Nutrient budget
Legacy nutrients
Land use
Climate change
Atmospheric deposition

ABSTRACT

This study quantified the long-term response of riverine total nitrogen (TN) export to changes in net anthropogenic nitrogen inputs to forest/agricultural ($NANI_{FA}$) and residential ($NANI_{R}$) systems across three catchments affected by low (LD), medium (MD), and high (HD) human impacts in eastern China. Annual $NANI_{FA}$ increased by 63–87% in 1980–1999, followed by 0% (LD), −23% (MD) and −40% (HD) changes of $NANI_{FA}$ in 2000–2010, resulting in a net increase of 56–78% in $NANI_{FA}$ in 1980–2010. Annual $NANI_{R}$ increased by 101–152% in the three catchments in 1980–2010. Land-use showed a 58–65% increase in developed land area (D%) and a 96–108% increase in agricultural lands with improved drainage systems (AD%) over the study period. In response to changes in $NANI_{FA}$, $NANI_{R}$ and land-use, riverine TN flux continuously increased 3.0- to 6.1-fold in the three catchments over the past 31 years. For each catchment, an empirical model incorporating annual $NANI_{FA}$, $NANI_{R}$, water discharge, D%, and AD% was developed ($R^2 = 0.93 - 0.97$) for predicting and quantifying sources of annual riverine TN fluxes. The model estimated that $NANI_{FA}$, $NANI_{R}$ and other N sources (e.g., natural background, legacy, and industrial N sources) contributed 27–90%, 0–45%, and 10–28% of riverine TN fluxes, respectively. Model results were consistent with spatio-temporal changes of riverine chloride, ammonium, nitrate, dissolve oxygen and pH, as well as changes in available N levels in agricultural soils. In terms of N source management, reduction of $NANI_{FA}$ in catchment LD and $NANI_{R}$ in catchment HD would have the greatest impact on reducing riverine TN fluxes. Furthermore, changes in land use and climate as well as legacy N should be considered in developing N pollution control strategies.

1. Introduction

Human activities associated with food and energy production have greatly elevated nitrogen (N) bioavailability to an extent that exceeds the assimilative capacity in many terrestrial ecosystems, often leading to large increases in N fluxes to waters (Kopáček et al., 2013; Wang et al., 2014). Enrichment of N leads to eutrophication of surface waters causing degradation of aquatic ecosystems, such as toxic algal blooms, low dissolved oxygen, depletion of fish populations, and loss of aquatic biodiversity (Kettering et al., 2012; Vogt et al., 2015; Hofmeier et al., 2015). To effectively guide watershed management to control N pollution, it is essential to quantify the response of riverine N export to changes in sources and levels of anthropogenic N inputs (Hayakawa et al., 2009; Chen et al., 2014a).

Nitrogen budgets are useful for evaluating impacts of human activities on the N cycle by relating anthropogenic N inputs to outputs (Hayakawa et al., 2009; Kettering et al., 2012; Wang et al., 2014). Net anthropogenic nitrogen input (NANI) is a budgeting approach that sums annual N contributions from atmospheric deposition, fertilizer application, agricultural fixation, seed input, and net import/export in feed and food (Hong et al., 2013; Han et al., 2014). The NANI approach has been applied to many watersheds across Asia (Hayakawa et al., 2009; Han et al., 2014; Chen et al., 2014a; Huang et al., 2014; Gao et al., 2014, 2015; Swaney et al., 2015), America (McIsaac et al., 2001; Boyer et al., 2002; Han et al., 2009; Hong et al., 2013), and Europe (Billen et al., 2009; Kopáček et al., 2013). It is a simple yet powerful approach to evaluate net N inputs

* Corresponding author at: College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, Zhejiang Province, China.
E-mail address: chendj@zju.edu.cn (D. Chen).

http://dx.doi.org/10.1016/j.agee.2016.01.037
0167-8809/

from anthropogenic sources to terrestrial ecosystems, as well as an effective tool to explain among-watershed or among-year variations in riverine N exports. However, the relationship between NANI and riverine N export is additionally influenced by variations in hydroclimate and land management activities, as well as progressive N saturation of terrestrial ecosystems (McIsaac et al., 2001; Han et al., 2009; Howarth et al., 2012; Swaney et al., 2012; Kopáček et al., 2013; Chen et al., 2014b; Huang et al., 2014). It is commonly observed that years with higher precipitation or river discharge export a higher fraction of NANI via rivers than drier years (Han et al., 2009; Howarth et al., 2012). Furthermore, the export fraction of NANI via rivers can be enhanced by improved agricultural drainage systems (e.g., tile drainage, McIsaac and Hu, 2004; Kopáček et al., 2013). Previous studies also demonstrate a larger fractional export of NANI by rivers when NANI exceeds some threshold value (e.g., 10.7 kg N ha^{-1} yr^{-1}, Howarth et al., 2012), which corresponds to NANI exceeding the N assimilative capacity of terrestrial and aquatic ecosystems (McIsaac et al., 2001; Han et al., 2009; Chen et al., 2014b; Gao et al., 2014). As a result, changes of climate, land management, and the degree of N saturation have a strong potential to enhance riverine N export (McIsaac et al., 2001; Huang et al., 2014; Øygarden et al., 2014). Importantly, the influence of climate change, land-use change and progressive N saturation is difficult to detect from short-term (several years) records, instead requiring a long-term (several decades) record of NANI and riverine N export dynamics.

For a watershed, the NANI components of chemical fertilizer, atmospheric deposition, biological fixation and seed input are the primary N inputs to forest and agricultural systems, while residential systems mainly receive N from human and animal wastes. In terms of N delivery pathways, N exports from forest and agricultural landscapes to the river network are mainly via diffuse runoff and leaching (non-point sources) (Chen et al., 2009), while a portion of N from residential systems enters the river network via direct sewage discharge (point sources) (Gao et al., 2014; Huang et al., 2014). In addition, the greater impervious surface area in residential systems further enhances N delivery efficiency (Groffman et al., 2004; Kaushal et al., 2008). As a result, residential systems have a higher potential to export NANI than forest/agricultural systems. This is especially true in developing countries where agricultural subsurface drainage and efficient treatment of residential wastewater are both often lacking (Yan et al., 2011; Chen et al., 2013). Therefore, it is valuable to separate watershed forest/agricultural and residential N budgets to effectively identify their contrasting export fractions and relative contributions to riverine N fluxes.

Based on extensive data collection for three adjacent catchments subjected to low, medium and high levels of anthropogenic impacts in eastern China, this study provides a long-term (1980–2010) analysis of the response of riverine TN export to changes in forest/agricultural and residential N budgets, land use and climate. Specifically, this study (i) examines temporal and spatial variations of NANI to forest/agricultural ($NANI_{FA}$) and residential ($NANI_R$) systems, (ii) addresses temporal and spatial variations of riverine N fluxes; (iii) develops empirical models for linking $NANI_{FA}$ and $NANI_R$ to riverine TN fluxes, and (iv) identifies individual contributions from $NANI_{FA}$, $NANI_R$ and other sources (e.g., natural background, legacy and industrial N sources) to the riverine TN flux. This study improves the NANI budgeting methodology to separately estimate watershed $NANI_{FA}$ and $NANI_R$ budgets and identifies of their contributions to annual riverine TN flux. Such quantitative knowledge is essential for managers to determine which systems and sources should be targeted for N reduction.

2. Materials and methods

2.1. Study catchments

The three catchments in this study are located in the rapidly developing Taizhou region of Zhejiang Province, China (Fig. 1). The three rivers are tributaries of the Jiaojiang River, which is the third largest river of Zhejiang Province and flows into Taizhou Estuary and the East China Sea, a coastal area that commonly experiences hypoxia (Gao and Zhang, 2010). The climate is subtropical monsoon having an average annual temperature of 17.2 °C and

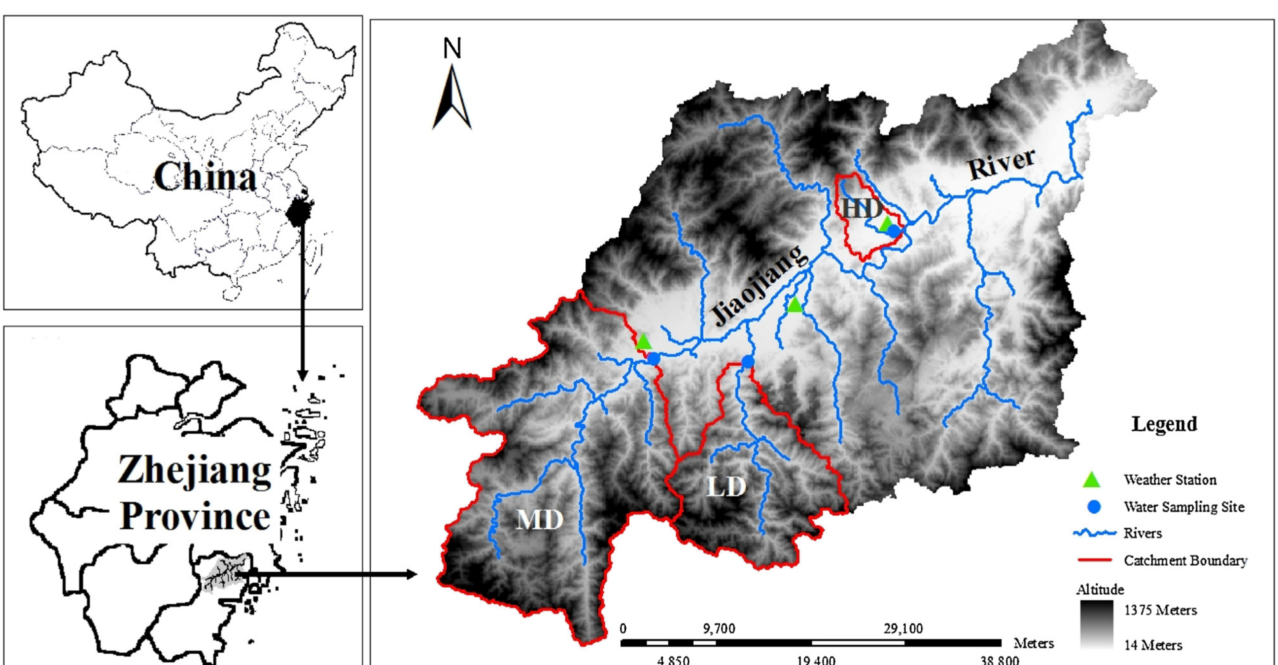

Fig. 1. The location of the three catchments affected by low (LD), medium (MD), and high (HD) levels of anthropogenic disturbance in Jiaojiang watershed in Zhejiang Province in eastern China.