Journal of Hydrology: Regional Studies 11 (2017) 117–125

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Seasonal and annual fluxes of atmospheric nitrogen deposition and riverine nitrogen export in two adjacent contrasting rivers in central Japan facing the Sea of Japan

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ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
17 September 2015
Accepted 30 November 2015
Available online 2 January 2016

Keywords:
Atmospheric N deposition
Nitrogen saturation
Trans-boundary air pollution
Riverine N export
Coastal ecosystem

ABSTRACT

Study region: Kita and Minami River basins in Japan.
Study focus: The coastal watershed in central Japan along the Sea of Japan has suffered large amounts of atmospheric nitrogen (N) deposition from northeastern Asia. However, the quantitative influences of atmospheric N deposition onto forested watersheds in the two basins and riverine N export into coasts remain unclear. To evaluate the current contribution of atmospheric N deposition, N deposition rates from the atmosphere to both basins, and N export rates from the rivers to the sea were quantified.
New hydrological insight for the region: Deposition rates of bulk N in each basin exceeded 1000 mg m^{-2} $year^{-1}$, more than 60% of which was supplied from winter to early spring by westerly winds. Annual deposition rates in the two basins did not differ, but annual export rates of inorganic N from the Kita River were significantly higher than those from the Minami River. These results suggest that symptoms of N saturation in the Kita River forested watershed are more serious. Furthermore, recent increasing trends of riverine N concentrations may have caused shifts in the limiting nutrient for coastal primary production from N to phosphorous. We suggest reductions in nitrate exports from forests as a strategy to improve nitrate pollution to both downstream waters and coastal ecosystems; however such efforts would involve intercontinental-scale actions in reducing N emissions.

1. Introduction

Anthropogenic emissions of reactive nitrogen (N) due to fossil fuel combustion and modern agriculture practices have increased at a global scale (Galloway and Cowling, 2002; Gruber and Galloway, 2008). In particular, increases in N emissions in eastern Asia have been dramatic over the last decade (Akimoto 2003; Ohara et al., 2007; Liu et al., 2011). Increased deposition rates of atmospheric N can have impacts on N cycling in forest ecosystems (Aber et al., 1989; Vitousek et al., 1997). Chronic atmospheric N deposition can lead to N saturation of forests, resulting in excess nitrate export from forested

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http://dx.doi.org/10.1016/j.ejrh.2015.11.019

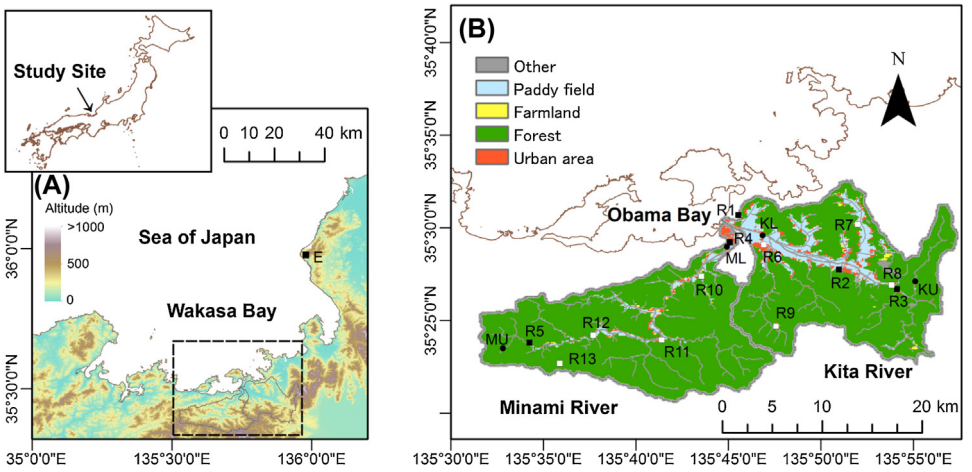

Fig. 1. (A) Study area and altitude. The closed square (Stn. E) indicates the monitoring site for acid rain by the Ministry of the Environment, Government of Japan. (B) Monthly sampling stations in the Kita and Minami River basins, including land use. Closed squares indicate the sampling sites (Stns. R1–R5) for bulk deposition of atmospheric nitrogen. Open squares are the monitoring site for precipitation by the Ministry of Land, Infrastructure and Transport (MLIT) and the Fukui Prefecture Government (FPG). Closed circles show monthly sampling stations of stream and downstream river waters in the Kita River (Stns. KU and KL) and the Minami River (Stns. MU and ML).

watersheds to stream water and ultimately coastal seas (Aber et al., 1989, 1998; Howarth, 1998). Therefore, N emissions caused by energy and food supply can induce water quality issues in local ecosystems.

In Japan, wet deposition rates of nitrate have increased during the last few decades by 2–5% year^{-1} (Morino et al., 2011). Particularly in the watershed along the Sea of Japan, large amounts of atmospheric N deposited onto forest ecosystems during winter, when the dominant direction of the movement of air masses is from the Asian continent toward Japan (Fukuzaki et al., 2001; Kamisako et al., 2008). Several studies have determined that N compounds originating from trans-boundary air masses have caused N saturation in forests and increased nitrate concentrations in stream and river water over the past few decades (Chiwa et al., 2012, 2013; Miyazako et al., 2015).

The coastal watershed along Wakasa Bay is one of the sites most affected by trans-boundary wet N deposition in Japan (Ministry of the Environment, 2015). The Kita and Minami Rivers are the adjacent waterways with the forested catchment located in the central part of Wakasa Bay (Fig. 1). Total N (TN) concentrations in the lower part of the rivers have been increasing from the 1980s to the present, while total phosphorous (TP) concentrations have not varied through time (Fig. 2). Because river discharge has not changed over the long term, N fluxes from both rivers into the coastal sea have likely doubled in the last few decades. Efforts have been made to reduce nutrient loads from point sources as well as nonpoint sources such as fertilizer; however, few changes in land use and population densities have occurred within the basins since the 1970s, suggesting that increasing trends of TN concentrations have likely been caused by chronic atmospheric N deposition. However, the quantitative influences of atmospheric N deposition on the forested watersheds and riverine N export into the coastal sea remain unclear.

To examine the linkage of atmospheric N input and riverine N export from the basin, a small-basin approach allows for the relatively precise estimation of chemical inputs and outputs (Johnson et al., 2000; Shibata et al., 2001). Although large-scale assessments can mask pronounced local variability among individual sub-basins, some large-scale patterns have indicated that riverine N export can be predicted by atmospheric N deposition rates (Howarth et al., 2002). A few studies have suggested that N-saturated forests may considerably degrade downstream water quality (Howarth et al., 2002; Tabayashi and Yamamuro, 2009; Chiwa et al., 2012).

The objective of the present study was to evaluate the contribution of the current level of atmospheric N deposition to N export in two adjacent contrasting rivers. To achieve this objective, atmospheric N deposition within the both basins and N export rates from the rivers to the coastal sea were quantified.

2. Materials and methods

2.1. Study sites

The Kita River system drains an area of 215.0 km^2 in the central part of Japan, facing the Sea of Japan (Fig. 1B). This river is short (length = 30.3 km) and steep (maximum altitude = 962 m), and mean river discharge is 12.7 m^3 s^{-1}. The overall land use in the drainage basin is mainly forest (80.5%) as well as agricultural lands including paddy fields and farmland (12.1%) and residential areas (3.9%). The Minami River system, which is adjacent to the Kita River, has a drainage basin of 215.4 km^2. This is also short (32.4 km) and steep (maximum altitude = 848 m), with an average discharge of 12.8 m^3 s^{-1}. The overall land use in the drainage basin is mainly forest (93.3%) as well as agricultural lands (2.6%) and residential areas (2.0%).