Continental Shelf Research 88 (2014) 140–150

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Different contributions of riverine and oceanic nutrient fluxes supporting primary production in Ishikari Bay

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ARTICLE INFO

Article history:
Received 26 December 2013
Received in revised form
18 July 2014
Accepted 25 July 2014
Available online 5 August 2014

Keywords:
Nutrients
Oligotrophic
Primary production
Coastal
Estuarine circulation.

ABSTRACT

We computed a ratio of riverine nutrient flux (RNF) to bottom nutrient flux (BNF) to determine the relative importance of oceanic and riverine nutrient fluxes on primary production dynamics in Ishikari Bay, which is composed of oligotrophic subarctic coastal water. Across spring, summer and autumn, the RNF:BNF ratio (R:B ratio) was significantly greater than 1.0, especially in spring and autumn for DIN and $Si(OH)_4$, suggesting that riverine nutrients mostly supported primary production. A strong inverse relationship ($r = -0.927$) between Chl *a* and salinity in autumn and a corresponding increase in the apparent utilization of DIN and primary production indicated that the contribution of DIN from the Ishikari River on primary production was maximal in autumn. However the R:B ratio for PO_4 was significantly less than 1.0, especially in summer (0.1) and autumn (0.3), suggesting a larger contribution of bottom upwelling nutrient sources. In spring, when the ratio was close to 1 (0.8), PO_4 supply from both bottom (upwelling) and surface (river) was equivalent, since PO_4 concentration of river end-member was the lowest. Although riverine nutrient fluxes were a major source of DIN and $Si(OH)_4$ nutrient supply in the bay, oceanic nutrient contribution from bottom upwelling and horizontal advection was a major source of PO_4. While riverine nutrients significantly fuel primary production, the estuarine circulation process may contribute significantly to compensating for the inadequate supply of riverine PO_4 in an oligotrophic system like Ishikari Bay. Also, unlike the usual estuarine system in which nutrient concentration at a deeper layer is high due to the regeneration of nutrients at depth, concentration in Ishikari Bay was very low due to an influence of oligotrophic waters. We conclude that riverine nutrient flux contributes a large portion of the total flux in Ishikari Bay.

1. Introduction

Primary production is dependent on the presence of the appropriate combination of nutrients to support and sustain their activity (Brzezinski, 1985; Barber et al., 2001; Kristiansen and Hoell., 2002; Kudo et al., 2005). Rivers are a critical link in the global cycling of elements, and dissolved inorganic nutrients from rivers to ocean system are obviously of great importance in a discussion of the interactions of these compounds in estuarine and adjacent coastal zones. Also, massive transport of nutrients from the deeper nutrient-rich layers to the impoverished euphotic zone occurs when intense vertical mixing or upwelling processes are observed. Such short and cataclysmic events have a pronounced influence on the biogeochemical fluxes in the ocean because they accelerate the completion of nutrient transport to upper layers, which would take much longer under “ordinary” conditions. However, it is difficult to evaluate these fluxes due to significant seasonal fluctuations and human activities that perturb the natural fluxes. One of the objectives in this study is to determine the possible sources of nutrients, and ultimately the fate of nutrients that are drawn from the Ishikari River into the adjacent shelf of Ishikari Bay, the northwestern North Pacific, Japan (Fig. 1).

Unlike the Pacific coastal region, which is influenced by the subarctic ocean current (Oyashio) with its high nutrients, Ishikari Bay receives few nutrient fluxes from oligotrophic subtropical (Tsushima) warm currents (Yoshida et al., 1977) and receives a nutrient flux from the Ishikari River, the second largest river in the catchment area in Japan. Thus, the bay is characterized as an oligotrophic subarctic coastal water with a considerable influence of riverine discharge from the Ishikari River (Agboola et al., 2010). Earlier studies on the seasonal change in riverine nutrients and distribution of chlorophyll *a* at 26 gridded sampling stations in Ishikari Bay have been reported (Agboola et al., 2009, 2010). Also,

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http://dx.doi.org/10.1016/j.csr.2014.07.013
0278-4343/

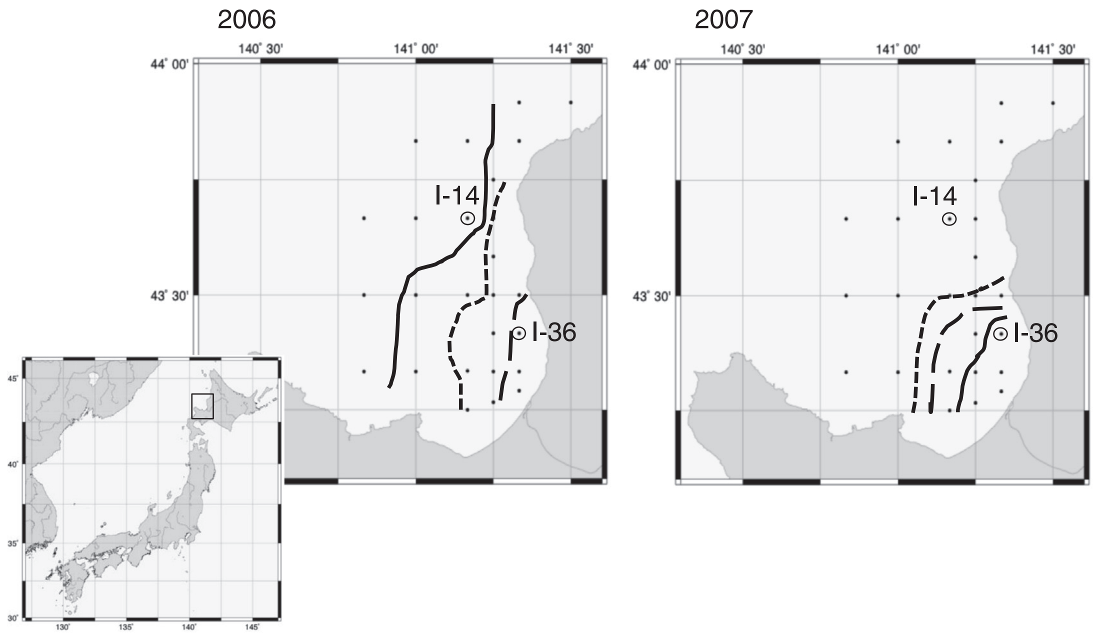

Fig. 1. Sampling stations in Ishikari Bay indicating boarder of Plume for 2006 and 2007. Bold line, spring; broken line, summer; and dashed line, autumn.

Agboola et al. (2013) reported on a 16-month time-series study on seasonality and the environmental drivers of biological productivity (primary productivity and chlorophyll biomass) in Ishikari Bay. However, studies on influence of estuarine circulation and oceanic nutrient fluxes as well as coupled riverine nutrient flux on phytoplankton biomass and production dynamics are scarce in this region of the Pacific. The present study is the first attempt to document the dynamics of nutrients and phytoplankton biomass and productivity in Ishikari Bay. We further quantified the relative contribution of bottom nutrient (upwelling) flux through estuarine circulation and horizontal advection from the oceanic region into Ishikari Bay.

Lastly, this paper aims to provide the answers to some hypothetical questions. Firstly, can the Ishikari River discharge supply the required nutrients for phytoplankton biomass and production build-up in Ishikari Bay oligotrophic system? Secondly, in considering the relative importance of estuarine circulation, is there any significant bottom nutrient upwelling flux to the euphotic zone which could possibly fuel primary production in the bay? Analysis of seasonal and inter-annual variations in the river Plume and Out-Plume areas (see Agboola et al., 2009) will not only help to establish possible relationships between these variables, but will also test and validate our hypothesis that the Ishikari River discharge contains nutrients to significantly fuel primary production in Ishikari Bay. If it does, and assuming a steady state, then the river Plume area receiving a higher nutrient flux should have a higher production, and this will enable us to predict the major source of nutrients and other possible factors fueling or limiting production in this oligotrophic system.

2. Materials and methods

Eight cruises were carried out in Ishikari Bay on board the TS *Oshoro-Maru* and the TS *Ushio-Maru* of Hokkaido University in spring (April, May), summer (July, August) and autumn (October, November) of 2006 and 2007. The study area, approximately 4370 km^2, lies between 43°10′N and 44°00′N and stretches between 140°00′E and 141°22′E (Fig. 1). Ishikari Bay is located in the northwest coast of Hokkaido within the subarctic regions, which is defined as a vertical 34.0 isohaline from the surface to ~200 or 400 m in summer and autumn (Dodimead et al., 1963; Dodimead, 1967). The boundary is located around 42°N in the North Pacific Ocean and divides the ocean roughly into the subtropical and subarctic regions.

2.1. Sampling

Routine samplings for nutrients and chlorophyll *a* were carried out at all 26 gridded sampling stations using a Sea Bird 911 CTD system equipped with a carrousel multi-sampler of 12 2.5-L Niskin bottles to collect discrete samples for macronutrients, Chl *a* and other biogeochemical variables in the water column (down to 5 m above the sea floor) at each sampling station. Six stations (representative stations of Plume and Out-Plume areas) were assigned for a detailed observation of nutrient and phytoplankton biomass and productivity.

2.2. Nutrients

Sub-samples for nutrients (NO_3^-, NH_4^+, PO_4^- and $Si(OH)_4$) were collected in duplicate in 10 ml spit tubes and were stored frozen at −30 °C until laboratory analysis (Parsons et al., 1984). Concentrations of the dissolved inorganic nutrients were determined using a continuous flow analyzer (QuAAtro, BRAN+LUEBBE). Detection limits were estimated at around 0.01 μM based on three times the standard deviation of the lowest concentration of samples.

2.3. Quantification of nutrient fluxes

In order to determine the nutrient fluxes to the bay we considered the influence of Ishikari River nutrient discharge and bottom nutrient upwelling through estuarine circulation using vertical and spatial profile data of salinity and nutrients. These distinct perspectives were deployed and related to phytoplankton biomass and productivity across space and time to determine the source and fluxes of the nutrients fueling primary production in this oligotrophic system.