



Assessing responses of the Hiroshima Bay ecosystem to increasing or decreasing phosphorus and nitrogen inputs



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ABSTRACT

The Japanese Government is seeking an appropriate level of nutrient load from the land to maintain the highest possible estuarine fishery production and water transparency simultaneously. To provide a scientific basis for the governmental inquiry, we conducted sensitivity analyses using an ecosystem model of Hiroshima Bay in order to assess the ecosystem's responses to phosphorus and nitrogen inputs. Load levels of phosphorus (Case P), nitrogen (Case N) and both phosphorus and nitrogen (Case NP) that were different from the average loading recorded during 1991–2000 ($\pm 25\%$, $\pm 50\%$, and $\pm 75\%$) were applied. The results showed that phosphorus had a significantly greater impact on the primary production of the bay than nitrogen. Case P+25 increased the primary production but led to N-limitation. However, it was found that Case NP at the levels over +25% could bring the Hiroshima Bay ecosystem back to its eutrophic state of 30 years ago.

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1. Introduction

Hiroshima Bay, located in the western part of the Seto Inland Sea in Japan, is known as a eutrophied semi-enclosed coastal sea due to increasing anthropogenic activities such as industrialization and urbanization that have occurred since the 1960s. Another important causative factor of the eutrophication of Hiroshima Bay is oyster culturing, which has been intensively conducted for a long time. In fact, fisheries statistics have indicated that ca. 60% of the total annual oyster production of Japan comes from Hiroshima Bay, which amounts ca. 20,000 tons per year as oyster meat production (Hirata and Akashige, 2004).

Measures to reduce phosphorus loading have been implemented since 1980 and are continuing under the “Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea”

(Yamamoto, 2003). These measures have clearly resulted in a decrease in the phosphorus concentration in the Ohta River, which empties into Hiroshima Bay, as observed in the long-term monitoring data (Yamamoto et al., 2002b). Phosphorus is required by every kinds of plants, and in contrast to nitrogen, it can be manipulated easily. In the case of nitrogen, its gaseous forms are involved in the cycling processes in ecosystems, and its fixation would interfere with the reduction measures. However, several studies have pointed out that the reduction of only phosphorus will lead to an imbalance in the ratios between phosphorus and other elements and could alter the composition of phytoplankton species in coastal seas (Tilman et al., 1982; Lee et al., 1996; Yamamoto et al., 1999; Yamamoto et al., 2004a).

The drastic decrease of oyster production in Hiroshima Bay since the 1990s could be due to changes in the phytoplankton species as well as to a decrease in primary production, especially the dwindling of the supply of diatoms, which are regarded as important food for oysters (Yamamoto et al., 1999; Yamamoto et al., 2002b; Hirata and Akashige, 2004). Thus, the decline in primary production in Hiroshima Bay could be one of the causes responsible for the drastic decrease in oyster production since the 1990s (Yamamoto et al., 2004b).

The present study aims to evaluate the response of phytoplankton growth and the increase/decrease in the amount of detritus due to different loading levels of phosphorus and nitrogen, which affect the growth of cultured oysters in Hiroshima Bay. In addition, the present study also aims to investigate how the Hiroshima Bay ecosystem would react to changes in phosphorus and nitrogen levels. The results of this study will be useful for coastal managers

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in determining the levels of nutrient loads that could sustain oyster production while also keeping the ecosystem of Hiroshima Bay healthy.

2. Materials and methods

The pelagic and benthic ecosystem coupling model of Hiroshima Bay, which was developed in a previous paper (Kittiwanih et al., 2007), was used in the present study. Based on the geological structure of the bay (Fig. 1), the bay was horizontally divided into two areas, namely the northern bay (NB) and southern bay (SB), and vertically divided into four layers, namely the upper (u) and lower (l) layers of the water column and the oxic (ox) and anoxic (an) layers of the sediment. The depth at which the layer of the water column was divided was 5 m according to the stratification situation of the water column in summer (cf. Yamamoto et al., 2000, 2002c). The ecological structure of the model showing the phosphorus and nitrogen cycles through the major organic and inorganic compartments is illustrated in Fig. 2. There are three major compartments for living organisms (phytoplankton, PHY; zooplankton, ZOO; and oyster, OYS), three compartments for the state variables of the different forms of phosphorus (detritus, DET-P; dissolved organic phosphorus, DOP; and dissolved inorganic phosphorus, DIP), and four compartments for the state variables of nitrogen (detritus, DET-N; dissolved organic nitrogen, DON; ammonium, NH_4^+ ; and nitrate, NO_3^-). Regarding the external forces, physical processes such as advection and diffusion as well as biogeochemical processes and parameters were also used in the present model (Yamamoto et al., 2002a; Kittiwanih et al., 2007). The dynamic model was developed using the software STELLA (version 8.0), running with a time step of 0.02 days by the fourth-order Runge–Kutta method.

The calculation was carried out using different loading levels of phosphorus and nitrogen with reference to the loading levels from 1991 to 2000 as the standard averages. The model outputs for the phosphorus and nitrogen cycles in the pelagic and benthic ecosystems of Hiroshima Bay have already been reported in a previous paper (Kittiwanih et al., 2007). The results revealed that the internal regeneration of materials is an important source of bio-available nutrients for phytoplankton growth. In particular, the sediment functions as a source of dissolved phosphorus and nitrogen for phytoplankton in the pelagic system; the release rates of dissolved phosphorus and nitrogen from the sediment exceeded 100% of the total phosphorus (TP) and total nitrogen (TN) loadings in the southern area. As for the northern area, which is known to have significant loading via the river, the release rates were found to be up to 56% of the TP and TN loadings. With regard to the denitrification process, the results revealed that 48% and 37% of the NO_3^- produced by nitrification was denitrified in the northern and southern areas, respectively. These amounts accounted for more than 10% of the total nitrogen loaded in the northern area and more than 14% of that loaded in the southern area, respectively. Because almost all phosphorus in the sediment is remineralized, it subsequently returns to the pelagic system and is repeatedly utilized for the growth of phytoplankton. The model used, therefore, provides a basis and tool for describing the dynamics of the phosphorus and nitrogen cycles in Hiroshima Bay.

In the present study, the levels of the phosphorus and nitrogen loads have changed as follows. In Case P, the load levels of phosphorus were changed by -25% (P–25), -50% (P–50), -75% (P–75), $+25\%$ (P+25), $+50\%$ (P+50) and $+75\%$ (P+75). In Case N, the load levels of nitrogen were changed by -25% (N–25), -50% (N–50), -75% (N–75), $+25\%$ (N+25), $+50\%$ (N+50) and $+75\%$ (N+75). In Case NP, the load levels of both phosphorus and

nitrogen were changed by -25% (NP–25), -50% (NP–50), -75% (NP–75), $+25\%$ (NP+25), $+50\%$ (NP+50) and $+75\%$ (NP+75).

The effects of the increase/decrease in the phosphorus and nitrogen loads were evaluated in terms of the increase/decrease in phytoplankton biomass and detritus stock in the water column and in the filtering rate of oysters cultured intensively in the bay. The resulting increase/decrease in the phosphorus and nitrogen flux and the accompanying increase/decrease in sediment stocks were also evaluated. In particular, the seasonality of the phytoplankton biomass and the detritus, which mainly contains phytoplankton decomposed matter, was evaluated, because phytoplankton growth apparently depends on the seasonal change in riverine NP loads due to the effect of monsoonal rain that usually occurs in spring and autumn. These targeted parameters, namely phytoplankton biomass, detritus stock, oyster filtering rate, and P and N content in the sediment, are the most important parameters to measure in order to sustain oyster production while maintaining good water and sediment quality.

3. Results

3.1. Responses of the pelagic system to NP loads

The responses of the respective compartments and relevant processes under the various nutrient load level conditions of $\pm 25\%$, $\pm 50\%$ and $\pm 75\%$ to the standard rate are shown in Table 1. The results indicated that the change in phosphorus loading levels (Case P) strongly influenced the phytoplankton biomass and the amount of detritus in the water column, while the change in nitrogen (Case N) did not have much effect. The increases in the nitrogen load of $+25\%$, $+50\%$ and $+75\%$ did not affect the growth of phytoplankton at all, not only in NB but also in SB. The decrease in nitrogen load also showed no effect on the phytoplankton biomass in SB.

The effect of the simultaneous change in phosphorus and nitrogen (Case NP) was similar to that of Case P, indicating that phosphorus is the key element controlling the ecosystem. The NB area was more sensitive to changes in the load levels than the SB area, especially in the upper layer of NB (NBu), where nutrient load was directly discharged from the Ohta River. Judging from the record of transparency during 2000–2009 (5.3 m on average; Yamamoto et al., 2011), the NBu, which was defined as the layer above a depth of 5 m, had light conditions suitable for the photosynthesis of phytoplankton.

The phytoplankton growth rate in NBu was particularly sensitive to the phosphorus loads (Case P and Case NP) as shown in Fig. 3, while it was not sensitive to the nitrogen loads (Case N). In the NB area, the output of Case P+25 (a 10% increase in phytoplankton growth rate) was not much different from the output of Case NP+25 (an 11% increase). The phytoplankton growth rate was enhanced by 23% and 34% in Cases NP+50 and NP+75, respectively, which were clearly large when compared to those in Cases P+50 and P+75 (16% and 19%, respectively).

Linearity was observed in the relationship between the increase in the nutrient load and the growth rate in Case NP in NBu as shown in Fig. 3, while it was not found in Case P. This indicated the absence of nitrogen limitation on the phytoplankton growth in the higher region of Case NP.

The pattern of seasonal change in the phytoplankton biomass in NBu was likely affected by the nutrient loads. Although in Case P+25 the phytoplankton biomass increased by 25% all year round except in winter, further increases in phosphorus (Cases P+50 and P+75) led to increased biomass only in spring (Fig. 4a). On the other hand, the increase in nitrogen concentration (Case N) had almost no impact on the phytoplankton biomass, with a slight suppression of the biomass due to

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