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Nitrogen budget at two artificial tidal flats along the coastal area of Osaka Bay, Japan

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Abstract

Budgets of nitrogen, suspended solids and chlorophyll *a* were studied in September 2000 and June, August, September and October 2001 at the north pond of Nanko Bird Sanctuary and at an artificial tidal flat of Hannan Second District, Osaka Bay, Japan. At the north pond of Nanko Bird Sanctuary, the output of suspended solids to coastal water exceeded its input to the pond, while chlorophyll *a* was intercepted within the pond through the tidal exchange. Dissolved inorganic nitrogen imported into the pond was temporally incorporated into the biomass and was then exported in the form of dissolved organic nitrogen. Particulate nitrogen was abundant as a resource of nitrogenous nutrients to coastal water in the summer of 2001. These phenomena are thought to be correlated with biological activities such as feeding, fixation and decomposition by benthic animals, seaweeds and microalgae. At the artificial tidal flat of Hannan Second District, the net exchange of nitrogen significantly changed between 2000 and 2001. In October 2000 only five months after its construction, nitrogen was released from the artificial tidal flat to the adjacent waters at a rate of 5.39 kg N/day. In contrast, the artificial tidal flat functioned as a site of sink for nitrogen in relation to the growth of seaweeds in October 2001. As a result, nitrogen uptake by the dominant species of seaweeds reached 2.51 kg N/day which accounted for 72% of the total dissolved nitrogen fixed at the artificial tidal flat within one day.

1 Introduction

Osaka Bay, about 1500km^2 in area, is one of the most eutrophicated estuaries in the temperate areas of Japan. Especially in the north part of Osaka Bay, red tides and hypoxic bottom waters are frequently observed in summer due to the nutrient load from the Yodo and Yamato rivers which contain a large quantity of domestic sewage and industrial waste water. Therefore, citizens and the local government of Osaka Prefecture have put great concern on the environmental restoration of the coastal area of Osaka Bay.

Reduction of the nutrient load to the sea is thought to be the most important measures to restore the coastal environment in the vicinity of urban areas. In addition to this, we consider that the construction of artificial tidal flats and salt marshes help ecological remediation since natural tidal flats and salt marshes are well known as areas for seawater purification, nursery habitats for larval fish and crustacean and places for shell and algal production. Tidal flats and salt marshes are closely related to nutrient recycling in the shallow waters because they are excellent in the decomposition of organic substances, fixation of nutrient salts and filtration of suspended particles.

There are so far some research on the structure and function of natural tidal flats and salt marshes [1,2] but only a few on those of artificial ones. Therefore, we started field surveys from 1999 at the artificial salt marsh of Nanko Bird Sanctuary and at the artificial tidal flat of Hannan Second District, both of them being constructed near an urban area of Osaka Prefecture.

In the present paper, we discuss the input and output of suspended solids, chlorophyll *a* and nitrogen through the tidal exchange at Nanko Bird Sanctuary and Hannan Second District to clarify the role of shallow areas in eutrophic Osaka Bay.

2 Methods

2.1 Nanko Bird Sanctuary

A lagoon-type salt marsh, the Nanko Bird Sanctuary opened at the innermost coast of Osaka Bay in 1983 (Fig.1a). Although this sanctuary is a man-made salt marsh, it is said to be important as a transit area of migratory birds like dunlin, common greenshank and little ringed plover. The field survey was conducted at the north pond of Nanko Bird Sanctuary (ca. 42000m^2 in area) where seawater flowed in or flowed out to Osaka Bay through six sluice pipes (each 74cm in diameter) with the tidal exchange. The depth of the north pond is less than 1m and its bottom almost entirely emerges at low water of spring tides.

Measurements were done near the sluice pipe for one or two tidal cycles at 1 min intervals with an Aleck ACM210-D type electromagnetic current meter for current velocity and at 1 hour intervals with an Aleck ACL200-PDK type fluorometer for chlorophyll *a* measurements in August 8-9 and October 17-18, 2001. Water samples were taken at the same site with chlorophyll *a* at 1 hour intervals and suspended solids (SS), ammonium (NH_4-N), nitrite and nitrate (NO_2+NO_3-N), dissolved organic nitrogen (DON) and particulate nitrogen (PN) were analyzed.

2.2 Hannan Second District

The experimental tidal flat (ca. 8000m^2 in area) of Hannan Second District was constructed off the coast of Kishiwada City, Osaka in May 2000. This artificial

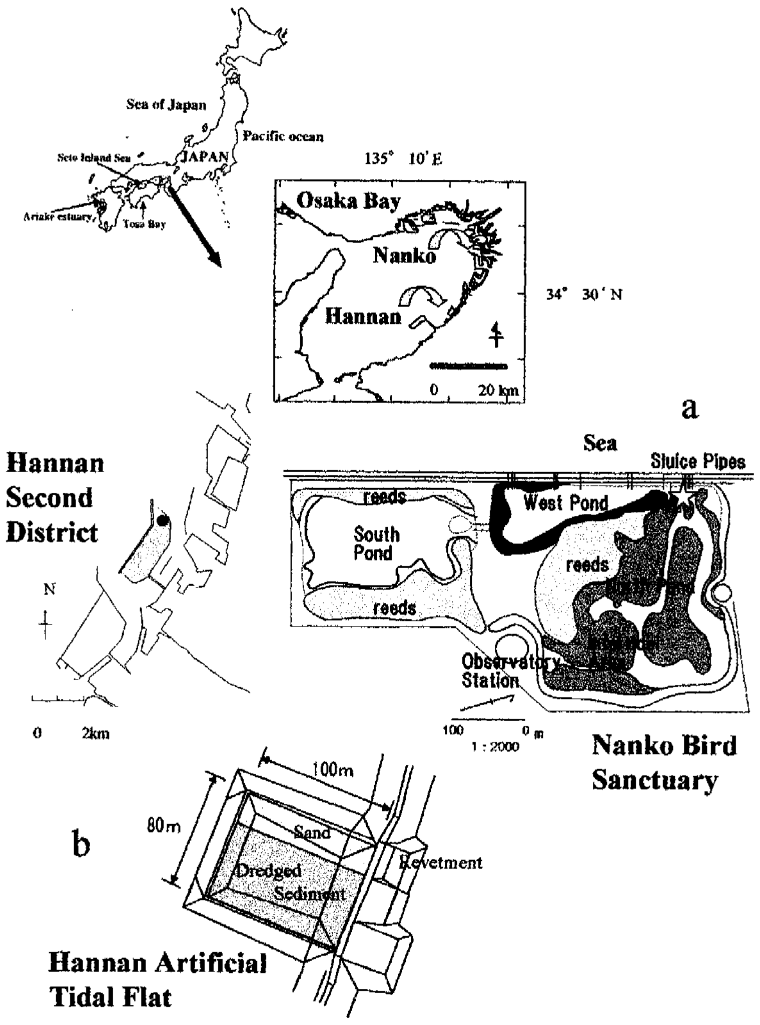

Fig. 1 Nanko Bird Sanctuary and the artificial tidal flat of Hannan Second District in Osaka Bay. ☆ : a sampling station at Nanko Bird Sanctuary, ● : location of the artificial tidal flat of Hannan Second District.

tidal flat was surrounded with a rubble revetment, two rubble jetties and a submerged mound. A quarter of the tidal flat (20m x 100m) was capped with sand at 1m thickness on the dredged sediment, while the rest of the tidal flat (60m x 100m) was only covered with the dredged sediment (Fig.1b). The slope of the bottom sediment was 3/100-5/100. There is little influence of fresh water or sediment discharge from rivers or groundwater since this tidal flat was located ca.1km off the coast. When the artificial tidal flat was constructed, the silt and clay content (grain size: less than 63 μ m) of the surface layer of the bottom sediment was 2-25% for the sand area and 1-71% for the dredged sediment area. In the present paper we regarded the intertidal area and its adjacent shallow area (less than 3-4m depth) as the tidal flat because they are quite different from the outside of the tidal flat which is 9-10m in depth.

Field surveys were carried out at 8-12 stations in September 25-26, 2000 and September 20-21, 2001. Water samples were collected at low and high tides for two tidal cycles and were analyzed for chlorophyll *a*, SS, NH_4-N, NO_2+NO_3-N, DON and PN. Dense growths of seaweeds (*Ulva pertusa, Ulva fasciata, Ulva* sp. and *Gracilaria vermiculophylla*) were observed at shallow areas of the artificial tidal flat one year after the construction. We sampled these seaweeds at 136 stations of the tidal flat with a 50cm x 50cm quadrate on November 29-30, 2001 and estimated the total biomass of the dominant seaweeds inside the tidal flat. Budgets of chlorophyll *a* and nitrogen at the artificial tidal flat were calculated from the following equation by Matsukawa and Sasaki [3].

$$\Delta(V \cdot CV) = Q \cdot CA + A0 \cdot K \cdot T \cdot \Delta C/\Delta L + QC + P \quad (1)$$

Where V is the volume of the tidal flat, CV is the mean concentration inside the tidal flat, $\Delta(V \cdot CV)$ is the difference of standing stock between the high tide and low tide inside the tidal flat, Q is the difference of volume of the tidal flat between the high tide and low tide, CA is the mean concentration in the marginal section of the tidal flat, $A0$ is the area of marginal section, K is the horizontal dispersion coefficient, T is time between the low tide and high tide, $\Delta C/\Delta L$ is the mean horizontal gradient of the concentration across the marginal section, QC is the load from the land, and P is production or loss of substance at the tidal flat.

3 Results and discussion

3.1 Nanko Bird Sanctuary

Concentrations of suspended solids (SS) of seawater near the sluice pipe were ca.1.5 times higher in ebb tide than the flood tide at the north pond of Nanko Bird Sanctuary. As a result, the output of SS per tidal cycle surpassed its input with a net loss of 29.3 kg on August 8, 2001 and of 24.8-26.7 kg on October 17-18, 2001. In contrast, the chlorophyll *a* concentration was high during the flood tide compared to the ebb tide in August but almost the same between the flood tide and ebb tide in October. The input of chlorophyll *a* over one tidal cycle basis exceeded its output at values of 0.028 kg in August but no marked difference was observed in October 2001. These findings indicate that (1) the chlorophyll *a* concentration decreases owing to the predation of phytoplankton by benthic

Table 1 Budget of suspended solids, chlorophyll *a* and nitrogen at the north pond of Nanko Bird Sanctuary on August 8, 2001 and October 17-18, 2001.

Date	Time	Substance	Input (kg)	Output (kg)	Net exchange (kg)
August 8, 2001	11:51-19:54	SS	55.2	84.5	-29.3
October 17, 2001	2:11-14:22		106.3	131.1	-24.8
October 17-18, 2001	14:23-1:26		79.4	106.2	-26.7
August 8, 2001	11:51-19:54	Chl.a	0.104	0.076	0.028
October 17, 2001	2:11-14:22		0.146	0.139	0.007
October 17-18, 2001	14:23-1:26		0.124	0.125	-0.001
August 8, 2001	11:51-19:54	NH_4-N	1.37	0.97	0.40
		NO_2+NO_3-N	1.58	0.31	1.27
		DIN	2.95	1.28	1.67
		DON	4.47	5.28	-0.81
		PN	1.84	3.67	-1.83
		TN	9.26	10.23	-0.97
October 17, 2001	2:11-14:22	NH_4-N	4.31	3.98	0.33
		NO_2+NO_3-N	14.75	12.52	2.23
		DIN	19.06	16.50	2.56
		DON	11.35	17.26	-5.91
		PN	1.60	1.25	0.35
		TN	32.01	35.01	-3.00
October 17-18, 2001	14:23-1:26	NH_4-N	4.64	4.76	-0.13
		NO_2+NO_3-N	13.10	11.26	1.84
		DIN	17.74	16.02	1.71
		DON	13.06	13.68	-0.62
		PN	0.98	0.99	-0.02
		TN	31.78	30.69	1.07

*Negative numbers in net exchange show losses from the north pond.

animals while phytoplankton are in the north pond, (2) withered or decomposed seaweeds (*Ulva* spp.), together with resuspended detritus are released from the pond to adjacent waters with the ebb tide. Seawater containing such decomposed seaweeds and detritus are low in chlorophyll *a* concentration but high in SS concentration.

1.67 kg of dissolved inorganic nitrogen (DIN) was consumed in the pond through one tidal cycle, while dissolved organic nitrogen (DON) and particulate nitrogen (PN) were exported from the pond at values of 0.81 kg and 1.83 kg, respectively. As a whole, 0.97 kg of nitrogen was released from the pond on August 8, 2001. On October 17-18, 2001, input exceeded output for DIN (input: 36.80 kg, output: 32.52 kg) and PN (input: 3.44 kg, output: 2.24 kg) but output surpassed input for DON (input: 24.41 kg, output: 30.94 kg). Accordingly, a total of 1.93 kg nitrogen was released from the pond to the outer coastal areas (Table 1). Among the nitrogenous nutrients, values of PN were less than one-seventh of DIN and DON in October. *Ulva* spp. and benthic microalgae grew densely at the north pond of Nanko Bird Sanctuary in August and October 2001. For instance, chlorophyll *a* concentration in the upper layer (0-0.5cm from the surface) of the bottom sediment of the north pond attained 14.3-97.8 mg/g wet sediment with a mean value of 39.0 mg/g wet sediment in May 2002. These results demonstrate that inorganic nitrogen was consumed at the pond by fresh seaweeds and benthic microalgae but, on the other hand, decomposition of aged seaweeds and benthic microalgae was also active and they were released from the pond to the adjacent coastal waters on the ebb tide in the nitrogenous form of DON or PN.

3.2 Hannan Second District

The results of analysis for chlorophyll a and nitrogen budgets by a box model method are shown in Figs. 2 and 3. In September 2000, when only four months had passed after the construction of the artificial tidal flat, the total dissolved nitrogen (DTN) and particulate nitrogen (PN) were exported from the tidal flat to the outside at a value of 3.9 kg/day and 1.5 kg/day, respectively. However, nitrogen was fixed inside the tidal flat at a rate of 3.5 kg/day for DTN and 1.1 kg/day for PN in September 2001. This shows that the artificial tidal flat changed from a source to a sink in terms of the nitrogen budget within 16 months of construction. Chlorophyll *a* was produced inside the tidal flat at 65.6 g/day in September 2000 and 10.8 g/day in September 2001.

Four species of seaweeds, *Ulva pertusa, Ulva fasciata, Ulva* sp. and *Gracilaria vermiculophylla* grew well at the artificial tidal flat of Hanna Second District in November 2001 and their biomass in wet weight were estimated to reach 5422 kg for *Ulva* spp. and 2464 kg for *Gracilaria vermiculophylla*. Okamoto et al. [4] reported that the biomass of macro benthic animals in September 2001 was 3.1 times higher than in September 2000 at the tidal flat of Hannan Second District. Further, the mean DTN concentration showed 7.1mg/L in the pore water of the dredged sediment at the artificial tidal flat in July 2001. This was ca.10 times higher than that of seawater. From the results obtained here, we can give the following assumptions as the reason why the artificial tidal flat functioned as a source for nitrogen in September 2000 and changed as a sink in September 2001.

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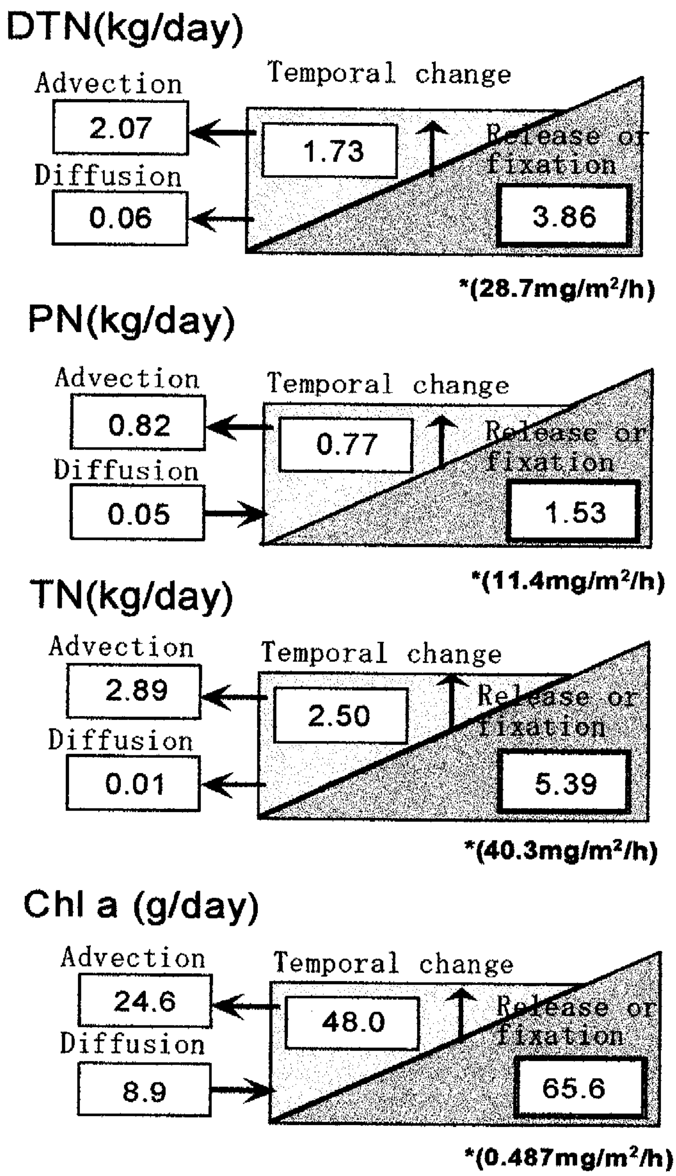

Fig. 2 Budgets of nitrogen and chlorophyll *a* at the artificial tidal flat of Hannan Second District on September 25-26, 2000.
* Numbers in parentheses show the release or fixation of nitrogen per unit time and area.

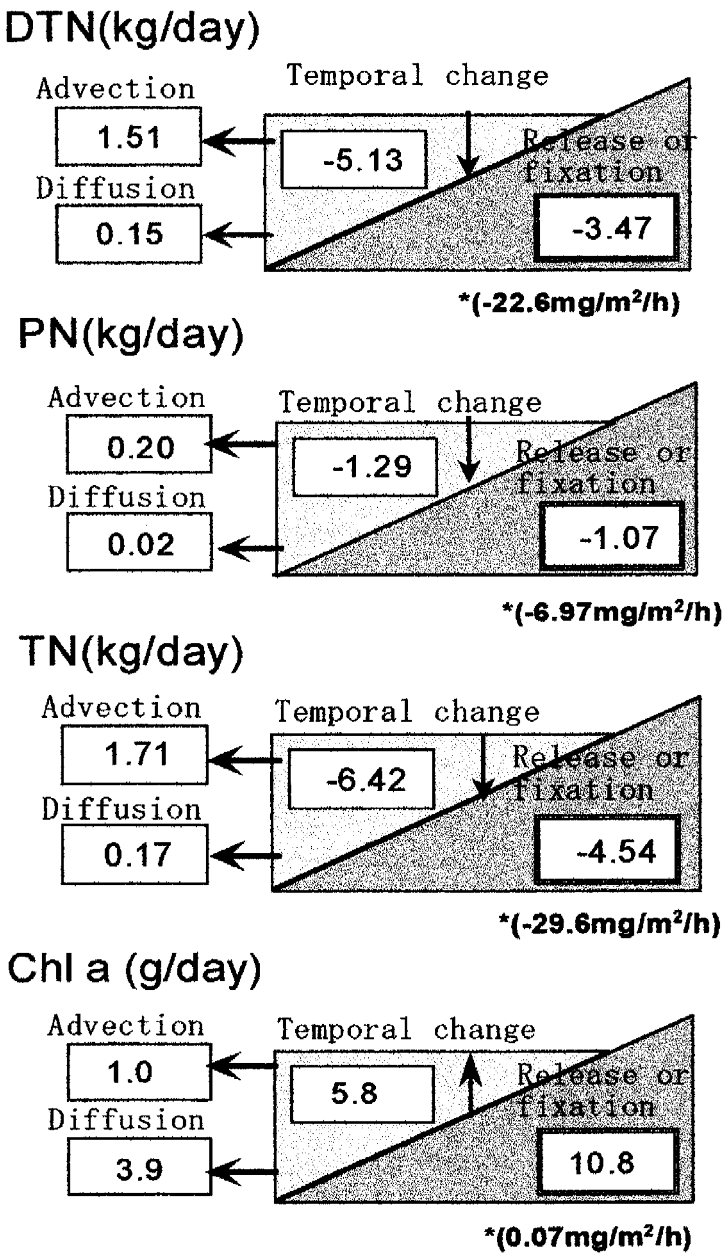

Fig. 3 Budgets of nitrogen and chlorophyll *a* at the artificial tidal flat of Hannan Second District on September 20-21, 2001.
* Numbers in parentheses show the release or fixation of nitrogen per unit time and area.

1) Seaweeds and benthic animals were low in biomass in September 2000 since only 4 months had elapsed since the construction of the artificial tidal flat. Therefore, the uptake of nitrogen by seaweeds and benthic animals was still insufficient. 2) A large quantity of NH_4-N was eluted from the sediment to the seawater in the dredged areas of the artificial tidal flat in September 2000.
3) Benthic animals increased their number and the predominant seaweeds almost covered the surface of the bottom sediment in September 2001. Accordingly the increased numbers of benthic animals reduced the particulate nitrogen content through their filtration activities. In addition, the dominant seaweeds absorbed dissolved nitrogen from the seawater or eluted from the dredged sediments.

Based on the nitrogen contents of *Ulva* spp. (31 mg N/g dry) and *Gracilaria vermiculophylla* (40 mg N/g dry), their maximum growth rate [5,6] and their biomass at the artificial tidal flat of Hannan Second District (*Ulva* spp.: 797 g wet/m^2, *Gracilaria vermiculophylla*: 365g wet/m^2), we estimated the amounts of nitrogen absorbed by the dominant seaweeds per one day. They reached to 1.42 kg N/day for *Ulva* spp. and 1.09 kg N/day for *Gracilaria vermiculophylla*. The total value of the uptake of DIN by the dominant seaweeds accounted for 72% of the total dissolved nitrogen fixed on 20-21 September 2001. This means seaweeds play an important role in the circulation of nitrogenous nutrients at the artificial tidal flat of Hannan Second District, Osaka Bay.

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