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Benthic nutrient recycling in shallow coastal waters of the Bohai Sea*

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Abstract Sediment-water fluxes of N and P species in the Bohai Sea were investigated in September-October 1998 and April-May 1999. The benthic fluxes of nutrient species were determined by incubating sediment core samples with bottom seawater bubbled with air or nitrogen. NO_2^-, NH_4^+, dissolved organic nitrogen (DON) and phosphorus (DOP), total dissolved nitrogen (TDN) and phosphorus (TDP), and PO_4^{3-} showed a net exchange flux from seawater to sediment, while NO_3, dissolved inorganic nitrogen (DIN) and SiO_3^{2-} were released from sediment to seawater in the Bohai Sea. Sediment-water nutrient exchange increases DIN and reduces the phosphorus load in the Bohai Sea. The release of silicate from sediment to overlying seawater reduces potential silicate limitation of primary production resulted from decrease of riverine discharge. The exchange flux of nutrients showed no obvious seasonal variation. The present study showed that the concentrations and composition of nutrients in the water column were affected by suspended sediment, and that not all the exchangeable phosphate in sediment could be released via sediment resuspension.

Key words: sediment-water exchange, nutrient elements, adsorption, release, Bohai Sea

1 INTRODUCTION

Nutrient regeneration in sediment plays an important role in the budget and dynamics of nutrients in a water column. Studies had been focused on the role of bottom sediments in regulating nutrients flow to a water column to support aquatic primary production and on the importance of sediments in consuming water column oxygen (Zeitzschel, 1980; Fisher et al., 1982; Garber, 1987; Kemp and Boynton, 1992). It was estimated that up to 50% of organic matter produced in the water column would be decomposed in sediments (Nixon et al., 1983); and that the regenerated nutrients can provide up to 90% of the nitrogen and up to 83 % of the phosphorus required by phytoplankton in three North Carolina estuaries and Mobile Bay (Fisher et al., 1982; Cowan et al., 1996).

The role of sediments as source and sink of nutrients to and from overlying water masses had been extensively studied in European and North American countries. It was reported that fluxes from Chesapeake Bay sediments supplied 10%-40 % of the nutrient loadings (Boynton and Kemp, 1985). The benthic recycling in Port Phillip Bay, accounted for 63 % and 72 % of the annual N and P input, respectively. However, it was shown that 30%-65% of the N entering the ecosystems could be lost via denitrification or sequestered in sediments and was not exported to the coastal ocean (Nixon et al., 1996; Berelson et al., 1998). The benthic fluxes of phosphorus and silica in the NW Black Sea are in the same order of magnitude as that of the annual nutrient input by the Danube River, whereas the ammonia flux from the sediment amounted to about 10% of the Danube input (Friedl, 1998). The benthic silicate flux of about 6.2×10^{11} mol/a in the South Atlantic is about three times the dissolved silicate discharge of the Zaire River, which is the dominant terrestrial source in that region (Zabel et al., 1998). It is necessary, therefore, to understand the diagenetic pathways of bio-limiting nutrients in sediments in shallow coastal ecosystems either for regional environmental management or global biogeochemistry study, or both.

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Bohai Sea is a partly-closed shallow sea with surface area of 77×10^3 km^2 and average depth of 18 m. It connects to the Yellow Sea in the south through the Bohai Sea Strait. Rivers draining into the Bohai Sea include the Huanghe (Yellow River), Haihe, Luanhe, and Liaohe rivers. The average annual freshwater input is approximately 68.5×10^9m^3 of which nearly a half is from Huanghe River. The annual input of average suspended matter is 1.1×10^9 tons of which Huanghe contributed 90% (Martin et al., 1993). The Bohai Sea is affected greatly by continental detritus input by river that is a very important pathway of nutrients to the marine recipient. Several studies had been carried out on the nutrient distributions in the estuaries of the Huanghe, Luanhe, and Liaohe (Zhang et al., 1996; 1999a). Nutrient regeneration from sediments may also contribute significantly to marine primary production in the Bohai Sea. However, the significance of the sediment-water exchange flux of nutrients in the Bohai Sea is still poorly known. This paper presents preliminary results on the benthic fluxes of nutrients in the Bohai Sea and shows the processes affecting the exchange fluxes at sediment-water interface. The nutrients release from and adsorption onto surface sediments were also examined via simulation experiments.

2 MATERIALS AND METHODS

Field observations of this study were undertaken in September-October, 1998 (BH98) and April-May, 1999 (BH99) cruises in the Bohai Sea (Fig.1). Benthic fluxes were measured at four stations (A2, E3, E1 and G2) in the BH98 cruise, and three stations (A2, E3 and A4) in the BH99 cruise. Resuspension and adsorption experiments were conducted with sediments collected at Stations E3 and B1. The experiments were conducted at temperature of 23.7℃-24.7℃in BH98 and 10℃-12℃ in BH99.

2.1 Direct flux measurements

Exchange fluxes of nutrients at the sediment-water interface were determined by incubating the core sediments with bottom seawater. Bottom sediments were collected by a box-corer (60×60 cm). Subcores (7-8 cm inner diameter) with overlying water (ca. 2 L) were placed in a water bath in darkness. The overlying water was continuously bubbled with air or nitrogen. Water samples were taken by plastic syringes from sub-cores at 5 to 12 h intervals over a period of about 50 h. Water samples for incubation were filtered immediately after collection. The change in composition of the overlying water was used to estimate the net solute exchange across the sediment-water interface. The concentrations of dissolved oxygen in the overlying water bubbled with air and nitrogen were 7.51 and 0.91 mg/L, respectively.

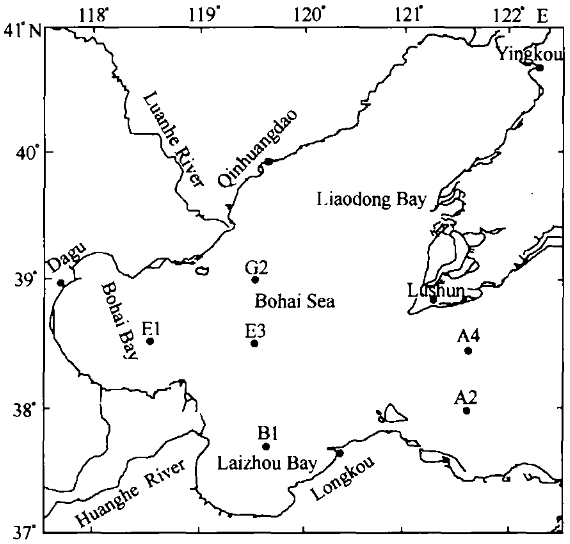

Fig. 1 Sampling stations

2.2 Release and adsorption experiments

Surface sediments (ca. 1 cm) were collected by box-corer at Stations E3 and B1 in the BH99 cruise. The sediments were homogenized, and sub-samples (200.0 g for Station E3 and 50.0 g for Station B1) were mixed in plastic bottles with 200 ml surface seawater poisoned by chloroform. For resuspension experiments, samples were taken at 0.5 to 3 h intervals to study the variation of nutrient release with time. For the experiments on nutrient release from sediment at Station B1, 0, 5, 10, 30, 50, 100 g of fresh sediment were added to each bottle. To study adsorption of phosphorus on sediments, varying amounts (0, 0.2, 0.4, 1.0, 2.0, 4.0 ml from a 2.5mmol/L dissolved phosphate standard) of dissolved phosphate were added to each bottle. The mass of adsorbed phosphate (micromoles per gram of dry sediment) was calculated from the change in phosphate concentration in the water and the mass of sediment added in each experiment. All the sample bottles were floated on surface seawater, and shaken frequently. In the experiment, sub-samples of the homogenized sediment were taken for determination of water content (60℃ 4 days). After the experiment, samples were centrifuged at 3000 rev/min and filtered through 0.45 μm pore-size filters.

Nutrient elements were determined spectrophotometrically following the methods of Grasshoff et al. (1983). The precison for dissolved and total nutrients were 5%-10% at <1-10 μmol/L level and 1%-5% at 10-100 μmol/L for N and P (Zhang et al., 1999b). The concentration of dissolved inorganic nitrogen (DIN) is the sum of NO_2^-, NH_4^+, PO_4^{3-} and NO_2^-. The concentration of dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) are the differences between total dissolved nitrogen (TDN) and DIN, total dissolved phosphorus (TDP) and phosphate, respectively.

3 RESULTS AND DISCUSSION

3.1 The benthic fluxes of N and P in the Bohai Sea

The change rate of nutrient concentrations in the water column indicated the net exchanges between sediment and overlying water during the incubation period. The exchange fluxes were obtained from the change in amount of nutrients divided by the surface area and time of incubation, as described by Lerat et al. (1990) and Liu et al. (1999). According to that calculation, a negative flux would indicate the solute intake by sediment, whereas a positive flux would indicate solute release from sediment. The fluxes of nutrients exchange between the sediment and seawater in the Bohai Sea are shown in Table 1.

In the autumn cruise, the dissolved oxygen concentration of near-bottom waters was 5.60-6.99 mg/L saturation of 80%-99%, at our incubation stations. In the spring cruise, the dissolved oxygen concentration of near-bottom waters increased to 9.63-10.5 mg/L, saturation of 105%-112%. This implied that the exchange fluxes of nutrients in the Bohai Sea were better approached by the incubation under air condition, while the exchange fluxes of nutrients under N_2 condition should be considered as an approach of anaerobic condition.

Table 1 The benthic fluxes of nutrients at the sediment-water interface in the Bohai Sea (mmol/m^2·d)*

Station	Condition	NH_4^+	NO_3	NO_2^-	DIN	DON	TDN	PO_4^{3-}	DOP	TDP
BH98 cruise (September, 1998)										
A2	air	-0.370	0.290	-0.120	-0.190	1.13	0.930	-0.043	0.001	-0.042
	nitrogen	0.520	-3.48	0.410	-2.55	2.89	0.340	0.063	0.087	0.151
E1	air	0.065	0.145	0.009	0.235	-1.31	-1.08	-0.002	-0.068	-0.071
	nitrogen	0.260	-0.655	0.019	-0.380	-2.02	-2.40	0.018	-0.036	-0.019
E3	air	-0.160	1.05	-0.033	0.860	-1.89	-1.03	-0.001	-0.047	-0.047
	nitrogen	0.240	1.08	-0.009	1.31	-0.380	0.930	0.014	0.012	0.026
G2	air	-0.070	-2.33	-0.020	-2.41	-3.46	-5.87	-0.030	-0.037	-0.067
	nitrogen	0.520	-3.55	0.050	-2.98	1.47	-1.51	-0.003	-0.013	-0.016
Mean	air	-0.157	0.761	-0.046	0.575	-2.22	-1.65	-0.014	-0.083	-0.097
Mean	nitrogen	0.506	-0.728	0.104	-0.121	-0.936	-1.06	0.037	0.002	0.039
BH99 cruise (May, 1999)										
A2	air	0.034	0.007	0.009	0.050			0.024		
A4	air	-0.016	-0.004	-0.007	-0.026	-0.025	-0.051	0.001	-0.072	-0.071
	nitrogen	-0.065	-0.034	-0.005	-0.104	-0.142	-0.246	0.020	-0.002	0.019
E3	air	-0.082	-0.048	0.003	-0.129	0.112	-0.015	-0.065	0.050	-0.015
	nitrogen	0.012	-0.255	0.034	-0.210	0.196	-0.014	-0.030	0.045	0.015
Mean	air	-0.057	-0.035	0.003	-0.091	0.078	-0.024	-0.043	0.020	-0.029
	nitrogen	-0.007	-0.200	0.024	-0.184	0.112	-0.072	-0.018	0.033	0.016

* A negative flux indicates the solute intake by the sediment and a positive one for the solute release from the sediment.

3.1.1 The autumn cruise

For incubation with air, the NO_3^- fluxes varied from –2.33 to 1.05 mmol/m^2·d, which were from sediment to overlying water at Stations E1, E3 and A2 (except Station G2). The NH_4^+ and NO_2^- fluxes varied from –0.37 to 0.07 and –0.12 to 0.009 mmol/m^2·d, respectively, indicating the movement from overlying water to bottom sediment. The DIN fluxes varied from –2.41 to 0.86 mmol/m^2·d, which indicated that DIN was released from sediment to water at Stations E1 and E3, but moved from water to sediment at Stations G2 and A2. The DON and TDN fluxes ranged from –3.46 to 1.13 and –5.87 to 0.93 mmol/m^2·d, which showed that DON and TDN moved from water to sediment except at Station A2 (Table 1). The phosphate, DOP and TDP fluxes varied from –0.043 to –0.001, –0.068 to 0.001 and

–0.071 to –0.042 mmol/m^2·d, respectively, which showed that phosphorus moved from water to sediment (Table 1).

In the incubation with N_2, the fluxes of nitrate and DIN ranged from –3.55 to 1.08 and –2.98 to 1.31 mmol/m^2·d, which indicated that NO_3^- and DIN were from overlying water to sediment at Stations G2, E1 and A2 (except Station E3). The fluxes of ammonium, nitrite and phosphate ranged from 0.24 to 0.52, –0.01 to 0.41 and –0.003 to 0.063 mmol/m^2·d, respectively, indicating a transport from sediment to water. The DON fluxes varied from –2.02 to 2.89 mmol/m^2·d, which showed that DON moved from sediment to water at Stations G2 and A2, but from water to sediment at Stations E1 and E3. The fluxes of TDN, DOP and TDP varied from –2.40 to 0.93, –0.036 to 0.087, –0.071 to 0.151 mmol/m^2·d, respectively, which indicated that they moved from sediment to water at Stations A2 and E3, and the opposite direction at Stations E1 and G2 (Table 1).

The sediments in the Bohai Sea are mainly terrestrial detritus, on average, composed of 71% clay, 23% silt and 6% sand (The Geology Research Group, 1985). Taking into account of the sediment type, the geometric mean fluxes of nutrients were calculated and shown in Table 1. The average fluxes of NO_2^-, NH_4^+ PO_4^{3-}, DOP and TDP showed exchange from sediment to overlying water under anoxic condition and the opposite direction under oxic conditions.

3.1.2 The spring cruise

At Station A2 only the data on the nutrient incubation with air is available. The benthic fluxes of nutrients at Station A2 were all from sediment to the overlying seawater. In the incubation bubbled with air at Stations E3 and A4, all the fluxes of N and P species (NO_3^-, NH_4^+, DIN, TDN, TDP and SiO_3^{2-}) transfered from overlying water to sediment, while NO_2^-, DON and DOP transfered from overlying seawater to sediment at Station A4, and from sediment to overlying seawater at Station E3. The benthic fluxes of NH_4^+, NO_3^-, DIN and SiO_3^2 at Stations E3 were 5, 12, 5 and 3 times of that at Station A4, respectivley. This explained partly the fact that the concentrations of NH_4^+, NO_3^-, DIN and SiO_3^2 at near bottom waters at Station E3 were 1, 15, 4 and 5 times of that at Station A4, respectively, and that the contents of total organic carbon in surface sediments at Stations E3 and A4 were 0.44%-0.53% and 0.28%-0.43%, respectively. The exchange fluxes of nutrients at Station A2 were all from sediment to overlying water; which may in part be related to the fact that the nutrient concentrations at near bottom waters at Station A2 were lower than those at Stations A4 and E3.

In the incubation bubbled with N_2, NO_3^-, DIN and TDN fluxes were from overlying water to sediment similar to that bubbled with air, while the fluxes of NO_2^-, NH_4^+, DON, DOP and TDP released from sediment to water at Station E3; but from water to sediment at Station A4 (Table 1). The geometric mean fluxes of NH_4^+, NO_3^-, DIN, TDN, PO_4^{3-}, SiO_3^{2-} flowed from water to sediment, the fluxes of NO_2^-, DON, DOP and TDP released from sediment to water.

If the sediments transferred from oxic into anoxic condition with eutrophication and anoxia, at Station A4, the nitrogen compounds would moved further from overlying water to sediment, while P and Si compounds were freed from sediments. At Station E3, NH_4^+, NO_2^-, DON, DOP and TDP were freed from sediment to water, and the benthic fluxes of NO_3^-, DIN, TDN, PO_4^{3-} and SiO_3^{2-} were from water to sediment. However, only the flux of PO_4^{3-} decreased further.

Under both oxic and anoxic conditions, the nutrient fluxes of NO_2^-, DON and DOP were released from sediment to water, but under anoxic condition the fluxes were greater than those under oxic condition. The benthic fluxes of NH_4^+ and PO_4^{3-} from water to sediment under oxic condition were greater than those under anoxic condition.

3.2 Comparison between spring and autumn nutrient fluxes in the Bohai Sea

Incubation experiments were carried out in both spring and autumn cruises at stations A2 and E3. In the second cruise the incubation at Station A2 was done only under oxic condition, and dissolved inorganic nutrients were analysed.

When incubated with air supply at Station A2, samples showed the fluxes of N and P compounds (except NO_3^-) in the BH98 cruise moved from water to sediment, while dissolved inorganic nutrients indicated a flux from sediment to water in the BH99 cruise. At Station E3, the benthic fluxes of NO_3^- and DIN in the BH98 cruise and NO_2^-, DON and DOP in the BH99 cruise were from sediment to water, fluxes for NH_4^+, NO_2^-, DON, TDN, PO_4^{3-}, DOP, TDP in the BH98 cruise, and NH_4^+, TDN, PO_4^{3-}, TDP and SiO_3^{2-} in the BH99 cruise were from water to sediments.

When incubated with N_2 supply, the benthic fluxes of NH_4^+, NO_3^-, DIN, TDN, PO_4^{3-}, DOP and TDP in the BH98 cruise and NH_4^+, NO_2^-, DON, DOP and TDP in the BH99 cruise were from sediment to overlying seawater at Station E3. It seemd that at Station E3, if the redox condition changed from oxic to anoxic condition, the benthic activities would induce the release of NH_4^+ and PO_4^{3-} from sediment to seawater. To some extent, this is in agreement with the result that ammonium release from sediments increased with increasing temperature and decreasing DO concentrations in Chesapeak Bay (Cowan et al., 1996).

In redox conditions in our case, the benthic fluxes of NO_3^-, DIN and SiO_3^{2-} were from sediment to water, while the benthic fluxes of NH_4^+, NO_2^-, DON, TDN, PO_4^{3-}, DOP and TDP were from water to sediment. The implication was that the exchanges of nutrients between sediment and water induced a change in limiting nutrients (e.g. phosphorus) characters in the Bohai Sea, and retard the depletion of silicon following the decrease of riverine discharge (Yu et al., 1999). Anoxic situation is raised from quick growth in economic development and population around the Bohai Sea, increasing release of NH_4^+, NO_2^-, DON, PO_4^{3-}, DOP and TDP deteriorated water quality, and reduced the release of silicate from sediment that resulted in the decrease of diatom biomass, but helped the formation of dinoflagellates bloom.

In comparison with other coastal/ocean areas the benthic fluxes of nutrients in the Bohai Sea were close to the data from the East China Sea (Aller et al., 1985), Bay of Morlaix (Lerat et al., 1990), Gulf of Trieste (Bertuzzi et al., 1996), Port Phillip Bay (Berelson et al., 1998), Limfjorden (Sloth et al., 1995), Chesapeake Bay and Mobile Bay (Cowan et al., 1996), southern and central California (Berelson et al., 1996), Skagerrak (Hall et al., 1996) and Northwestern Black Sea (Friedl et al., 1998). Most of the areas mentioned above are located in Europe and North America characterized as eutrophic regions with shallow waters.

3.3 The release and adsorption of nutrients

3.3.1 Release of nutrients

Nutrient-enriched sediment can release nutrients into seawater under various thermodynamic conditions. In this study, the amount of nutrients released was calculated from the change in concentration of dissolved nutrients in the experiment. Fig. 2 shows nutrients release against sediment dilution, i.e. the amount of nutrients released by a unit mass of sediment is plotted against the reciprocal of the sediment concentration in water. The amount of nutrients release was estimated via regression of the experimental data. The release of nutrients increased rapidly and reached the maximum with the sediment dilutions up to 0.07 L/g except for the NO_2^-. The maximum releases of NO_3^-, NH_4^+, SiO_3^{2-} and PO_4^{3-} were 0.246, 0.026, 0.387 and 0.012 μmol/g, respectively, from data of Fig.2.

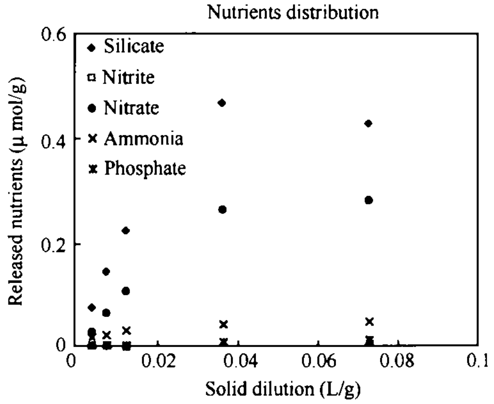

Fig.2 Released nutrients (μmol/g) versus solid dilution (L/g)

The concentrations of suspended particle matter (SPM) near bottom waters at Stations B1 and E3 were 9.6-14.2 and 19.3-24.0 mg/L with averages of 12.2 and 22.2 mg/L, respectively. The reciprocal of the SPM near bottom waters was 0.08 L/g at Station B1 and 0.045 L/g at Station E3. The annual variation of SPM between the BH98 and BH99 cruises were 25% and 11% at Stations B1 and E3, respectively. This implied that the nutrient releases from sediments could be very close to the maximum release. In the experiment the atom ratios of released nutrients was Si:DIN:P = 40:25:1, which indicated that phosphorus amount was relatively low compared to the Redfield ratio (Si:N:P~ 16:16:1) (Redfield et al., 1963).

Fig.3 is the plot of time dependent desorption/release of nutrients from sediments. When surface sediment and seawater were mixed, nutrients, except NO_2^- were released from sediments (Fig.3). At Station E3, the releases of NO_3^-, SiO_3^{2-} and PO_4^{3-} reached maximum in 3 h, being 0.006, 0.083 and 0.001 μmol/g, respectively. The release of NH_4^+ increased and reached the maximum (0.013 μmol/g) in 10-15 hours. The NO_2^- data was highly scattered, partly due to the low concentrations (Fig.3).

At Station B1, the release of NO_3^- and PO_4^{3-} reached the maximum in 2 hours. The concentration of NH_4^+ showed rapid initial increase, followed by a slow fall indicating readsorption. Again NO_2^- at this station was similar to that at Station E3. The overall release of NO_3^-, PO_4^{3-}, NH_4^+ and NO_2^- were 0.016, 0.001, 0.008 and 0.001 μmol/g respectively. The release of SiO_3^{2-} increased gradually and reached maximum of 0.055 μmol/g within 5-8 hours (Fig.3).

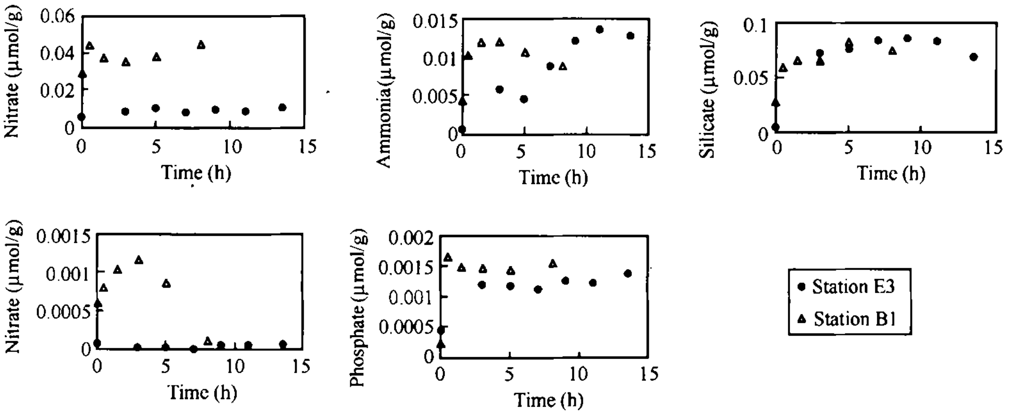

Fig. 3 Time dependence of nutrient releases from sediments in seawater at Stations E3 and B1 in the Bohai Sea

The maximum release of NO_3^-, NH_4^+, SiO_3^{2-} and PO_4^{3-} at Station B1 (Fig.2) were 15, 3.5, 7 and 12 times of those released from the sediment-water mixture at definite solid/water ratio (Fig.3). The atom ratios of Si:DIN:P released from sediment at Stations B1 and E3 was (50-67):(20-38):1. At both stations phosphorus, compared to Si and N, appeared to be less mobile from sediments. These findings indicated that nutrients were released from sediments at Stations E3 and B1 when sediments were resuspended by wave and current (e.g. storm). Owing to the shallow water depth of the Bohai Sea, catastrophic events, such as wind storms, may play an important role in affecting bottom sediment resuspension and sediment mass-balance in this region (Prior et al., 1989). Rapid response of the current circulation and suspended sediment distribution to wind storm was observed.

Since these catastrophic events were temporal and episodic, it was difficult to estimate the sediment transport due to individul wind storms. The calculation of SPM variation was, therefore, based on all grids and anchor stations' investigations at Stations E3 and B1 in the BH98 and BH99 cruises. The concentrations of resuspended SPM were estimated to be 1.97-4.48 mg/L at Station E3 and 2.53-7.82 mg/L at Station B1 by calculation of the variation of SPM concentrations integrated over the water depth. The nutrient loads at Stations E3 and B1 were calculated by integrating nutrient concentrations over the water depth, which showed that released nutrients after resuspension could account for 1% for phosphate, 3%-6% for silicate, 0.2%-0.4% for nitrate and 4-9% for ammonium at Station E3, and 4%-52% for phosphate, 4-83% for silicate, 2%-6% for nitrite, 0.6%-28% for nitrate and 2%-16% for ammonium at Station B1. The difference between Stations E3 and B1 was due to the fact that the resuspension released nutrients at Station E3 were from experiments at constant solid-solution ratio, while those at Station B1 were from the maximum release experiments at Station B1. It was clear that nutrient loads in the water column were affected by resuspension of sediment, especially in shallow water areas.

Resuspension can lead to nutrient release to the water column from sediment particles and porewater. However, resuspension changes the diffusive sediment water fluxes of nutrients. It was reported that in the southwestern Kattegat, Scandinavia, fluxes of nutrients from sediment to water after resuspension were reduced or changed in exchange direction (Christiansen et al., 1997). It was therefore very difficult to determine if the resuspended particles were similar to the surface sediments in chemical composition, grain-size, etc., and had characteristics depending on consolidation and resuspension history (Valeur et al., 1995), and cohesion (Miller et al., 1977). The change of net nutrients exchange fluxes between sediment and water after resuspension in the Bohai Sea needs to be studied further.

3.3.2 Adsorption of phosphate

The results of this preliminary approach to determine the phosphate adsorption are shown in Fig.4. As seen from these data, the adsorption of phosphate by sediments at Stations B1 and E3 can be simulated by a simple linear adsorption isotherm which is a special case of Langmuir and Freundlich isotherms (Krom et al., 1980). Applying it here would yield:

$$C_s=\Delta C_s+C_{si}=K^*C$$

Here C_s is the mass adsorbed per unit mass of total solids, C is the concentration in solution at equilibrium, K^* is the linear adsorption coefficient, ΔC_s is the mass of adsorbed phosphate (per gram of dry sediment) added during the experiment, and C_{si} is the quantity of phosphate originally on the surface of the sediment which is exchangeable with the phosphate added in the experiment. A graph of ΔC_s vs C should be a straight line with slope of K^* (mL/g) and intercept of C_{si} (μmol/g).

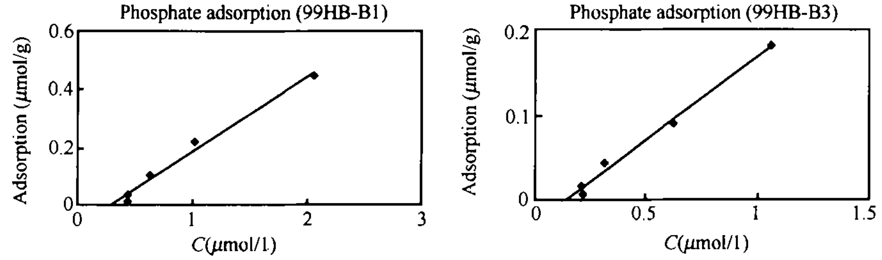

Fig.4 Plot of mass of phosphate adsorbed during experiment in μmol/g dry weight against equilibrium concentration of dissolved phosphate in μmol/L

The linear regression coefficients $r^2=0.99$ for Stations E3 and B1. The linear adsorption coefficients were 189.3 and 248.9 ml/g at Station E3 and B1, respectively, ranked at the lower end in the range for estuarine and oceanic oxic sediments (50-5000mL/g) (Jitts, 1959; Pomeroy et al., 1965; Berner, 1973; Krom et al., 1980).

The concentrations of exchangeable phosphate on the sediments were 0.06 and 0.03 μmol/g at Stations B1 and E3, respectively, which were 40 and 30 times of the released mass of PO_4^{3-} at Stations B1 and E3, respectively, and 5 times of the maximum released mass of PO_4^{3-} at Station B1. This indicated that the values of exchangeable phosphate were much higher than those obtained from release experiments on PO_4^{3-}, and were probably partly due to the fact that not all phosphate combined onto the sediments can be released via sediment resuspension.

4 CONCLUSIONS

This investigation of the benthic fluxes of nutrients in the Bohai Sea showed that exchange fluxes of nutrient elements at sediment-water interface depended on nutrient species, sediment types, etc. The nutrients exchange between sediment and water may lead to a decrease of TDN and phosphate, an increase of nitrate and silicate in the water column. As a result, the release of silicate from sediments may offset the decrease of silicate due to reduced riverine discharge. As the Bohai Sea is surrounded by the areas with rapid rise of population and accelerated economic development, the nutrients exchanges between sediment and water may have important influence on the eutrophic character of coastal waters in this region.

The results from sediment and seawater mixing experiments indicated that the nutrient concentrations in the water column were affected by resuspension of sediment. The atom ratios of nutrient element released from sediments can be quite different from the Redfield ratios, and indicated a depletion of phosphorus relative to N and Si. Part of the exchangeable phosphate in the sediments could not be released via sediment resuspension.

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