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The Monitoring of Biogeochemical Interactions Between Sediment and Water: a Mesocosm Study

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A series of mesocosm experiments has been conducted to investigate the effects of sediment on the qualities of superficial water over the tidal flats. The experiments involved two different kinds of sediments (Silt and Fine Sand) to mimic the natural habitats. Other environmental conditions in the mesocosm were kept as natural as possible. The mesocosm coincided with the annual patterns of the natural water qualities and was identical with the composition of benthic organisms of three reference sites of natural tidal flats. DIP has been leached out from sediment from June to October, but not for ammonium and DIN. The mesocosm was successfully able to simulate the environmental situations of natural tidal flat and will be a useful tool to assess the environmental impacts by human activities.

Key words: Mesocosm, Tidal Flat

INTRODUCTION

Biogeochemical interactions between water and sediments in coastal marine ecosystems became widely recognized within the past two decades (Nixon, 1981; Taylor *et al.*, 1995; Taylor *et al.*, 1999). In nature, the interactions between water and sediments are important features affecting the lives of organisms and may often control the qualities superficial water on the tidal flat.

The western coast of Korean peninsula is characterized with the high tidal range and the well-developed tidal flat along her coastline. In Korean history, tidal flats have been the easy targets of reclamation to provide the land for agricultural purposes. Recently a huge reclamation project, the so-called, "The Saemankeum Reclamation Project" is on the way. The project has triggered several environmental questions, such as "What are the environmental consequences of the reclamation?" "What happen, if the tidal flats are disappeared?" or "What are the roles of sediments on the water quality above?".

For these, we have three approaching ways: 1. Intensive *in situ* monitoring programs, 2. Numerical modeling, and 3. Simulation experiments. There have been comprehensive field measurements for the water qualities in the tidal flats (Kim and Yang, 2000; Yang and Kim 2002; Yang *et al.* 2003) and the long-term observations in the estuarine environment (Lee and Yang, 1997). Yet their monitoring activities in the tidal flats had revealed several difficulties, such as great environmental diversity, high range of variations, and mounted costs of field observations to overcome the spatial and temporal variations in the coastal environment.

A numerical modeling on the water qualities in Saemankeum area has been tried with high uncertainties on their input data (Kim *et al.*, 2002). Such uncertainties are attributed to the incompleteness of scientific information on the biogeochemical interactions between different components of a coastal ecosystem. That is hard to achieve in reality. Therefore an artificial tidal flat (mesocosm) would be an alternative choice to investigate environmental impacts due to the development project.

Since an early proto type (Abbott, 1966), mesocosms have been tried to investigate the diverse fields on marine sciences, such as plankton (Antia, 1963; Conover and Paranjape, 1977), benthic community (Blake and Jeffries, 1971; Wilde and Kuipers, 1977), and the interactions between plankton and benthos (Pilson *et al.*, 1979). Nowadays such applications have been expanded to the fields of nutrient dynamics (de Vries *et al.*, 1998; Hinga, 1989; Short, 1986; Van

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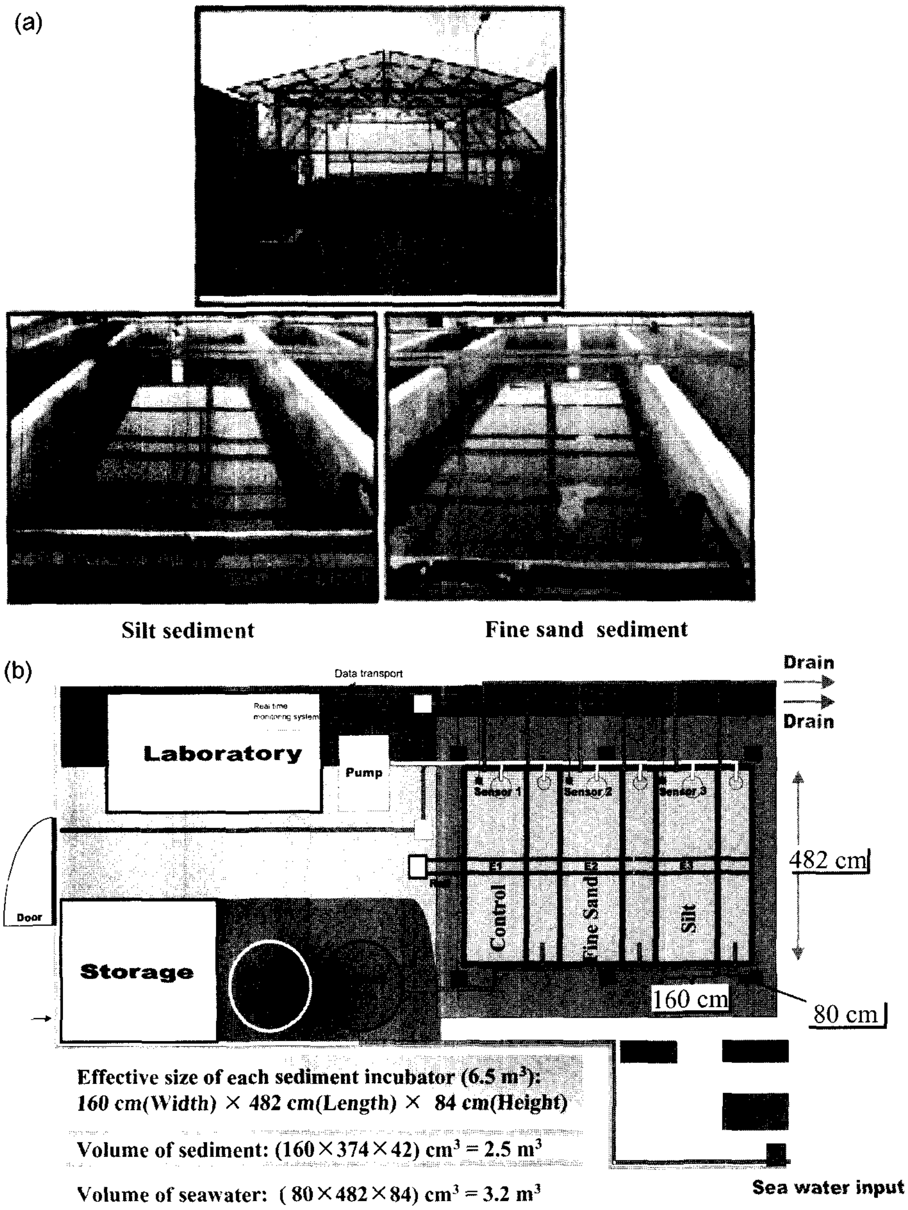
Raaphorst *et al.*, 1992) and even to the assessment of sediment contamination (Fletcher *et al.*, 2001). Notwithstanding most of the mesocosm has been applied to the three purposes: 1. to gain an understanding of biogeochemical interactions in a complex system between water and sediment and provide data for testing various hypotheses in ecosystem theory, 2. to study the effects on the systems by the perturbations such as, the inflow of freshwater, the elongated exposure period to the air, and so on, and 3. to study the biogeochemical behavior of various substances of interest, usually heavy metals and other pollutants.

Herein, we are going to focus on the biogeochemical interactions between water and sediment. First of all we have to confirm the normal function of our mesocosm facility. Therefore the actual goals of this paper are 1. How good the mesocosm replicates each environment of silt and fine sand tidal flats in terms of nutrients and benthic organisms. 2. Which environmental parameters are well simulated and which are not in the mesocosm? And why?

MATERIALS AND METHODS

Description of Mesocosm

An artificial tidal flat (mesocosm) was established in May 2001 at the mouth of Keumg River Estuary (Fig. 1a). The detailed dimensions of the mesocosm



Effective size of each sediment incubator ($6.5\ m^3$):
160 cm(Width) × 482 cm(Length) × 84 cm(Height)

Volume of sediment: $(160 \times 374 \times 42)\ cm^3 = 2.5\ m^3$

Volume of seawater: $(80 \times 482 \times 84)\ cm^3 = 3.2\ m^3$

Fig. 1. (a) Photographs of the mesocosm, (b) The schematic view of the mesocosm.

are illustrated in Fig. 1b. The mesocosm consists of three parts: Silt Sediment, Fine Sand Sediment and Control. Each part has 18 sectors of sediment. The Silt (1~4ϕ : 9.3%; >5ϕ : 90.7%) was obtained from the Keumgang tidal flat near the mesocosm, and the Fine Sand (1~4ϕ : 43.9%; > 5ϕ : 56.1%) from the tidal flat near the Kunsan Airbase. Both sediments were put into the mesocosm immediately after the excavation to keep the living organisms as intact as possible.

In the normal batch operations, water from Keumgang Estuary was pumped from a depth of about 2 m below the surface to the storage tankers and kept until use. When necessary, the water was allowed to flow by gravity through a series of flow control devices into each part at a rate sufficient to replace the water in the mesocosm. This was done to allow a continuous introduction of pelagic species and larvae of benthic organisms to the mesocosm.

We tried to keep each mesocosm as similar as possible to natural environment. A semi-diurnal tidal motion was generated by inflow and drain of water synchronized with the tidal rhythm of Keumgang Estuary. To minimize any noisy effects of primary production by epiflora, the walls of the mesocosm were cleaned regularly. Natural sunlight was illuminated through the transparent sunroof, but direct input of precipitation has been blocked to avoid any interference by rainwater. As we have no prior experience in designing the mesocosm, we tried to maintain the mesocosm at reasonably normal conditions. During the first year of operation, we made no attempt to change the environmental conditions until May 2002.

Operation of Mesocosm

Ten incubation experiments have been conducted through a routine procedure from 11 May 2002 to 29 April 2003. Each procedure took over 6 tidal cycles (3 days) from the inflow of new water to the end of an experiment. Any artificial manipulations of environmental parameters have not been made except during the long-lasted heavy rainstorm. Flushing time of water has set to be about 3 days (6 tidal cycles) to match the flushing time of the Keumgang Estuary (Yang *et al.*, 1999), which was proved enough contact time for the interactions from the several prior experiences. The sediment in the mesocosm was covered with 30 cm depth of water during the flood tides.

For each experiment, the concentrations were monitored at the introduction of new water, during the experiment, and at the final stage. The final concentrations were corrected by subtracting the data of Control from those of Silt and Fine Sand Mesocosms. The fluxes of nutrients from the sediments were estimated from the corrected nutrients per unit time and area of the experiment. Therefore we assumed the estimated nutrient fluxes are free from any effects caused by the superficial water column on the sediment.

Water Sampling and Monitoring in Mesocosm and in Nature

Five hundred ml of surface water have been obtained from 20 cm below the water surface every 6 hours (every tidal cycle) from the mesocosms during the experiments. Simultaneously, same volume of

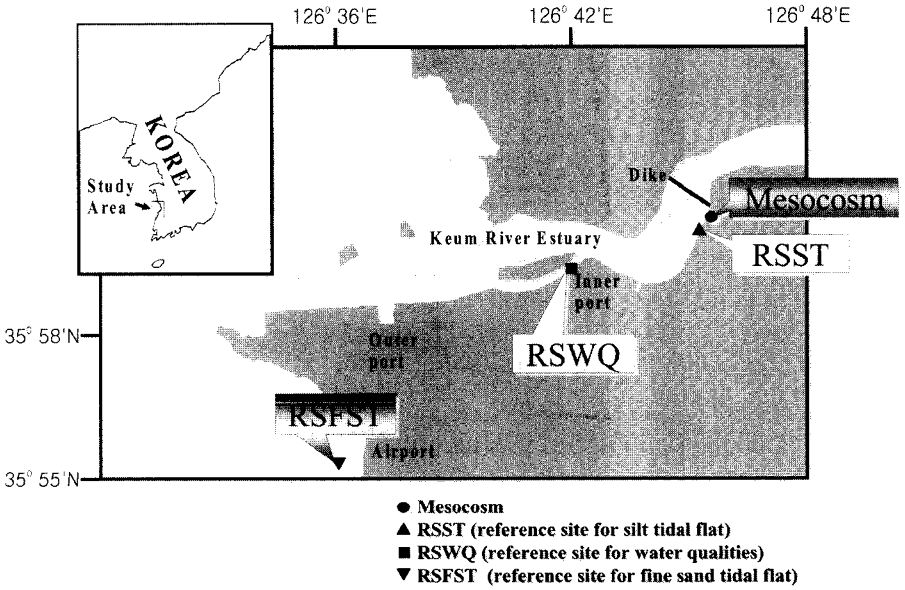


Fig. 2. Locations of mesocosm and reference sites for water qualities (RSWQ) and tidal flats (RSST, RSFST).

surface water has been manually collected weekly at a pier located 4 km south of the mesocosm, "the Reference Site for Water Qualities" (RSWQ, Fig. 2) at the high tide since June 1995 (Fig. 1). The water samples were transported to the laboratory and kept below -20°C until the analysis. The samples were not kept more than a month before chemical analysis.

Basic environmental parameters (water temperature, salinity, chlorophyll-*a*, and suspended solids) have been monitored simultaneously with water sampling. To monitor any alteration of the biological parameters during the studied period, one part from 18 sectors was removed and all the benthic macro benthos within the sediment were separated and identified. The animal composition of benthos was monitored and compared with the natural habitats every month. Two reference sediments were collected from Reference Site for Silt Tidal Flat (RSST) and Fine Sand Tidal Flat (RSFST) for silt and fine sand habitats, respectively.

Chemical Analysis

Suspended solids in 500 ml of water samples were filtered through GF/C and dried for 1.5 hour at 103°C in a dry oven. Phosphate in 10 ml of water samples were reacted with the mixed reagents of ammonium molybdate solution, sulfuric acid, ascorbic acid, and potassium antimonyltartrate solution and finally determined at 885 nm with a spectrophotometer (Parsons *et al.*, 1984). Ammonium in 10 ml of water samples were fixed with phenol and reacted with sodium nitroprusside solution, alkaline reagent, sodium hypochlorite solution, and oxidizing solution and finally quantified at 640 nm with a spectrophotometer (Solorzano, 1969). Nitrite in 10 ml of water samples were mixed with sulfanilamide solution, naphthylenediaminedihydrochloride solution and analyzed at 543nm with a spectrophotometer. Nitrate in 10 ml of water were measured using AutoAnalyzer (SYSTEA FLOWSYS). Chlorophyll-*a* was determined by acetone extraction method (Parsons *et al.*, 1984) by a spectrophotometer (SHIMADZU UV-160A). Salinity and water temperature were measured using a salinometer (YSI 290A).

Flux Estimation of Nutrients From Sediment

Fluxes of nutrients were estimated from the difference of nutrient concentrations in water after contacting with sediment in the mesocosm. The calculations were completed through four steps. The first step; the corrected final concentrations were obtained by subtracting the initial concentrations from the final ones for Silt and Fine Sand mesocosm. The second step; those of Control were subtracted from the corrected final concentrations for each mesocosm. The third step: after the second step, the concentrations were normalized to unit time. For the final step; the following equations were applied for the calculation (Warnken *et al.*, 2003).

$F_m = (\Delta C/\Delta t) \times V/A$
F_m: benthic flux (mmol m^{-2} day^{-1})
$\Delta C/\Delta t$: concentration changes with time (mmol^{-1} d^{-1})
V: volume of overlying water column (3,239 *l*)
A: surface area of sediment (5.984 m^2)

RESULTS AND DISCUSSIONS

Site mor Water Qualities between the Mesocosm and the Reference Site for Water Qualities (RSWQ)

Comparisons were made for the annual variations of environmental factors between the mesocosm and the RSWQ (Fig. 3,4). Control denotes a mesocosm set filled with only water without sediment, whereas Silt and Fine Sand indicate two other sets with silt and fine sand, respectively. A nearly perfect match was found for the annual variations for water temperature (Fig. 3a), and somewhat difference in the variation of salinity between the mesocosm and RSWQ (Fig. 3b). During the summer season of the studied period, there has been unusually long period of heavy rainstorm. To keep the mesocosm under healthy condition, we had to maintain the salinity in the mesocosm under the condition of not below 10 psu. That caused such difference in the salinity.

Despite some gaps, we found a consistent pattern for DIP, ammonium and DIN between RSWQ and mesocosm (Fig. 4). Almost identical patterns were found for DIP (Fig. 4a) and DIN (Fig. 4b), but rather greater deviations were revealed for ammonium (Fig. 4c). There were significantly higher concentrations in Control (both initial and final concentrations) than in the natural seawater (RSWQ). This is partly due to the artifact by pumping seawater from the Keum River estuary. During the pumping process of water, resuspended fine sediment in water probably have contributed such higher initial concentrations of ammonium.

In Control, the initial concentrations (rectangular) were greater than the final values (circle) for DIP,

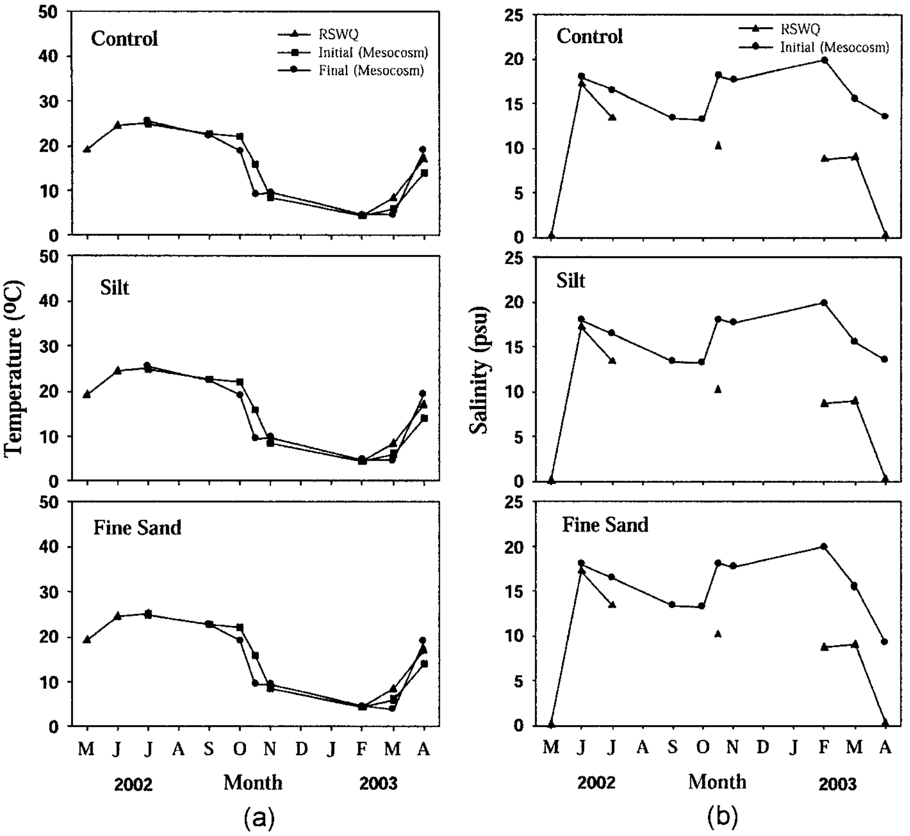


Fig. 3. (a) The monthly variations of temperature from May 2002 to April 2003, (b) The monthly variations of salinity from May 2002 to April 2003 (Initial: The concentrations of new seawater into mesocosm; Final: The concentrations at the end of an experiment in mesocosm; RSWQ: The concentrations at the reference station of water qualities).

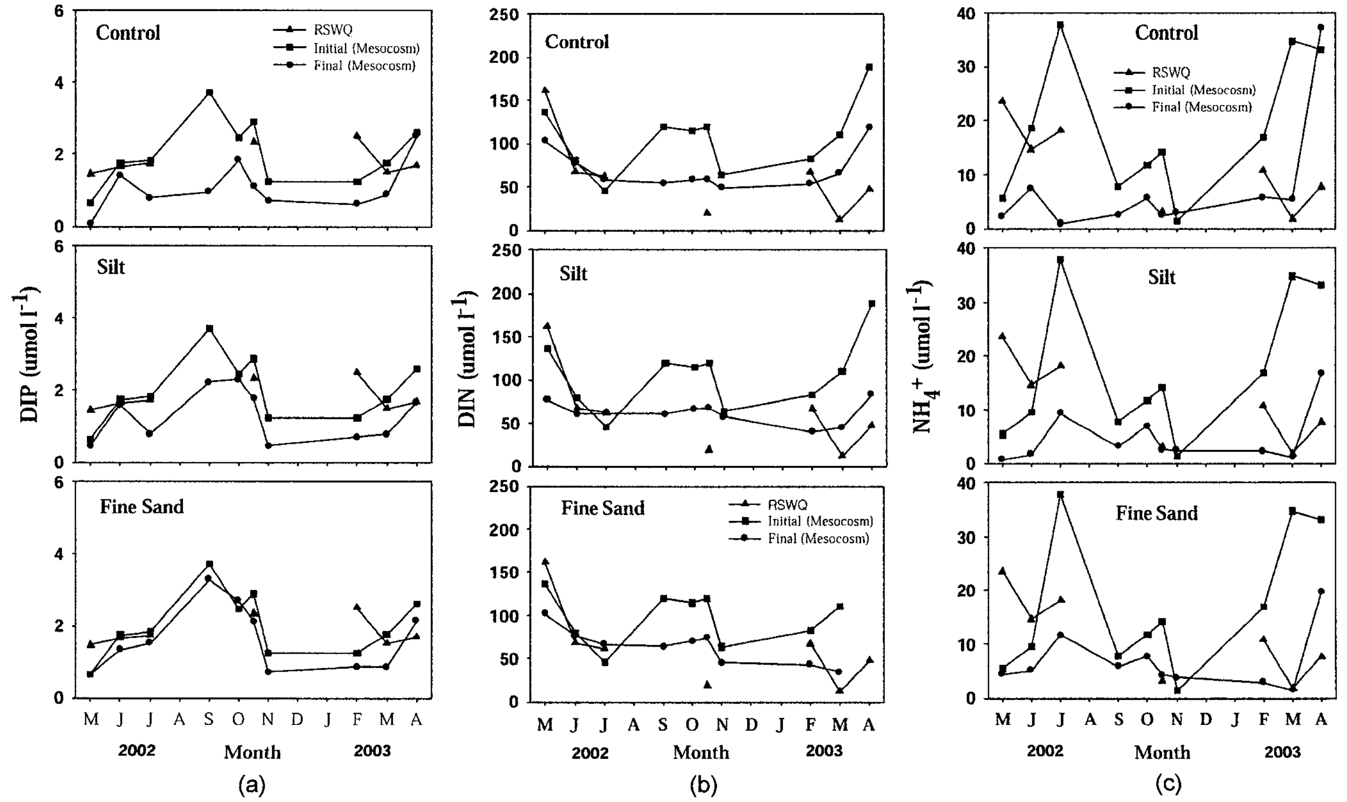
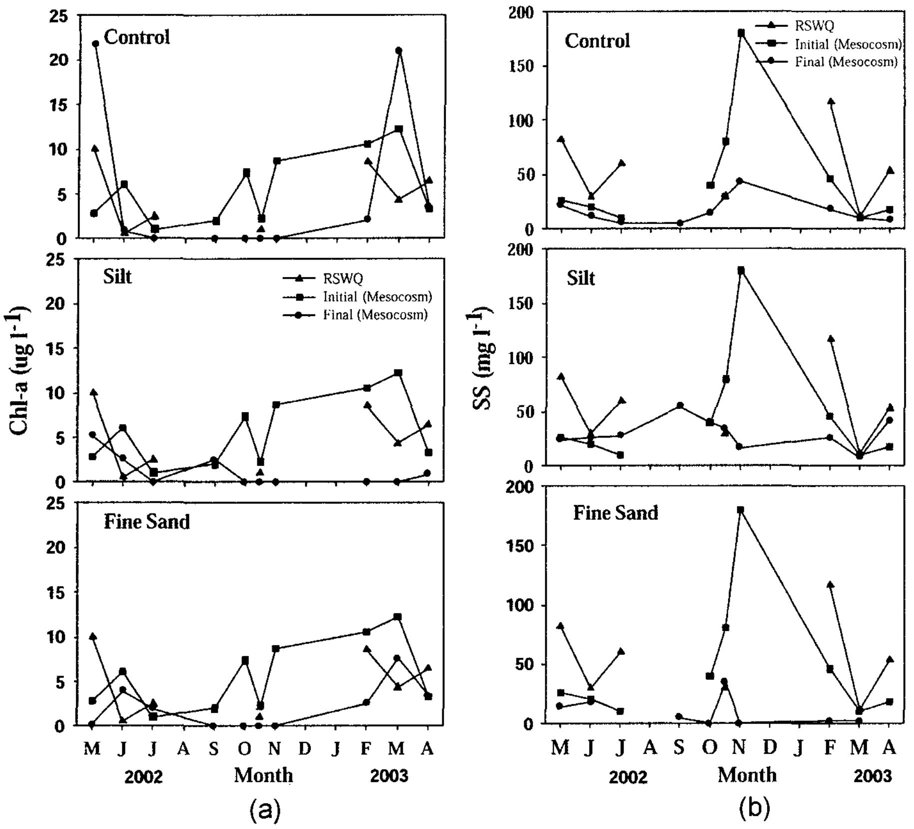


Fig. 4. (a) The monthly variations of DIP from May 2002 to April 2003, (b) The monthly variations of DIN from May 2002 to April 2003, (c) The monthly variations of NH_4^+ from May 2002 to April 2003.



(a) (b)

Fig. 5. (a) The monthly variations of SS from May 2002, (b) The monthly variations of Chl-*a* from May 2002 to April 2003.

DIN (mostly nitrate), and ammonium (Fig. 4). That suggests the removal processes of nutrients from the water column in the mesocosm. Such processes probably consist of consumption of nutrients by phytoplankton. The greatest differences were found in the variations of ammonium: significant removals of ammonium were noticed in all the mesocosm of June 2002 and March 2003 (Fig. 4c). A totally opposite pattern, higher final concentrations than the initial ones, was appeared in May 2002 and Mar. 2003 for chlorophyll-*a* (Fig. 5a). Such correspondence of chlorophyll-*a* peaks and ammonium removals in spring suggests the preference of ammonium by the actively growing of phytoplankton in the water column. For the dynamics of phytoplankton in Keum River Estuary, algal bloom was frequently proceeded by the introduction of high ammonium contents in the water column (Lee and Yang, 1997). Two major peaks of chlorophyll-*a* in Control were attenuated in Silt and Fine Sand. This was probably due to the strong feeding activities by benthic organisms in the mesocosms.

There was a different pattern in the variation of suspended solids (Fig. 5b): higher RSWQ concentrations than the mesocosm except for the winter. This means higher suspended solids concentrations in natural seawater than in the mesocosm during the period of high biological activity.

Even with some artifacts describe previously, still we had fairly good agreement of patterns in water qualities between the mesocosm and the reference station.

Comparisons of Benthic Organisms between the Mesocosm and the Reference Sites of Silt Tidal Flat (RSST) and Fine Sand Tidal Flat (RSFST)

Comparisons were made for the annual variations of benthic organisms between the mesocosm and the RSST and the RSFST (Table 1). We found almost identical dominant species and species compositions during the studied period. Even though we did not have entire lists of all the living organisms in the sediment, we still were able to suggest that there is no drastic change in the composition of living organisms during the experiments even after more than two years of operation. It has been successful for the maintenance and the operation of a healthy ecosystem in the mesocosm. We assume that the mesocosm can successfully represent the environmental situations of natural tidal flats. Based on this, the mesocosm facility could be a helpful tool to simulate the natural habitats at least for macro-benthic organisms. In the future, we hope to use the mesocosm to assess

Table 1. (a) Comparisons of benthic organisms between mesocosms and Reference Site for Fine Sand Tidal Flat (RSFST) ind./m^2

Species	May. 2002		Jun. 2002		Jul. 2002		Aug. 2002		Sep. 2002		Nov. 2002	
	ref.	meso.	ref.	meso.	ref.	meso.	ref.	meso.	ref.	meso.	ref.	meso.
Mollusca												
Bivalvia	1268 (93.3%)	571 (79.7%)	1039 (93.4%)	1302 (72.9%)	695 (88.9%)	757 (73.2%)	921 (96.2%)	700 (89.3%)	935 (89.9%)	724 (76.3%)	632 (87.4%)	1243 (79.9%)
Crustacea												
Decapoda	7 (0.5%)	2 (0.3%)	2 (0.2%)	12 (0.7%)	7 (0.9%)	3 (0.3%)	3 (0.3%)	3 (0.4%)	5 (0.5%)	12 (1.3%)		7 (0.4%)
Amphipoda				2 (0.1%)					5 (0.5%)			2 (0.1%)
Polychaetes												
Neanthes japonica												
Nephtys polybranchia												
Capitella capitata												
Pseudopotamilla occelata												
Perineresis aibuhitensis	29 (2.1%)	37 (5.2%)	27 (2.4%)	43 (2.4%)	26 (3.3%)	60 (5.8%)	26 (2.7%)	60 (7.7%)	32 (3.1%)	65 (6.8%)	24 (3.3%)	168 (10.8%)
Mysta ornata	5 (0.4%)	12 (1.7%)	7 (0.6%)	15 (0.8%)	5 (0.7%)	14 (1.3%)	5 (0.5%)	3 (0.4%)	3 (0.3%)	12 (1.3%)	7 (1.0%)	14 (0.9%)
Mediomastus sp.	51 (3.8%)	94 (13.1%)	37 (3.4%)	410 (23.0%)	49 (6.3%)	201 (19.4%)	2 (0.2%)	17 (2.2%)	60 (5.8%)	136 (14.3%)	60 (8.3%)	122 (7.8%)
Glycera chirori				2 (0.1%)								

Table 1. (b) Comparisons of benthic organisms between mesocosms and Reference Site for Silt Tidal Flat (RSST) ind./m^2

Mollusca												
Bivalvia	12 (4.9%)	5 (8.6%)	12 (2.0%)	2 (1.7%)	3 (1.0%)				3 (1.8%)	2 (0.7%)		5 (1.2%)
Crustacea												
Decapoda	3 (1.2%)	5 (8.6%)	26 (4.4%)	3 (2.6%)	9 (3.0%)	3 (2.9%)		2 (1.5%)	3 (1.8%)	12 (3.9%)	9 (3.3%)	9 (2.2%)
Amphipoda	2 (0.8%)		270 (45.4%)	12 (10.3%)		27 (26.0%)	2 (1.1%)	54 (41.2%)	3 (1.8%)	221 (72.2%)	112 (41.6%)	272 (65.1%)
Polychaetes												
Neanthes japonica	219 (90.1%)	27 (46.6%)	277 (46.4%)	63 (53.8%)	279 (92.7%)	58 (55.8%)	187 (98.9%)	61 (46.6%)	153 (91.6%)	54 (17.6%)	92 (34.2%)	78 (18.7%)
Nephtys polybranchia	5 (2.1%)	5 (8.6%)	2 (0.3%)	10 (8.5%)		2 (1.9%)			3 (1.8%)	3 (1.0%)	56 (20.8%)	14 (3.3%)
Capitella capitata	2 (0.8%)	9 (15.5%)		2 (1.7%)		3 (2.9%)						
Pseudopotamilla occelata		7 (12.1%)	9 (1.5%)	15 (12.8%)		7 (6.7%)		5 (3.8%)		10 (3.3%)		9 (2.2%)
Perineresis aibuhitensis												
Mysta ornata				2 (1.7%)				2 (1.5%)				7 (1.7%)
Mediomastus sp.				9 (7.7%)	10 (3.3%)	3 (2.9%)		7 (5.3%)		3 (1.0%)		26 (6.2%)
Glycera chirori												

the environmental impacts on the tidal flat by human disturbances.

Fluxes of DIP and DIN

The fluxes of DIP and DIN (mostly nitrate) were estimated from the corrected concentrations of the Silt and Fine Sand mesocosms (Fig. 6; Table 2,3, and 4). There have been mostly out-fluxes of DIP from the sediment through the year. No difference in pattern was found between the Silt and Fine Sand mesocosms, which suggests a similar rate of interactions between sediment and superficial water even with some textural differences between two meso-

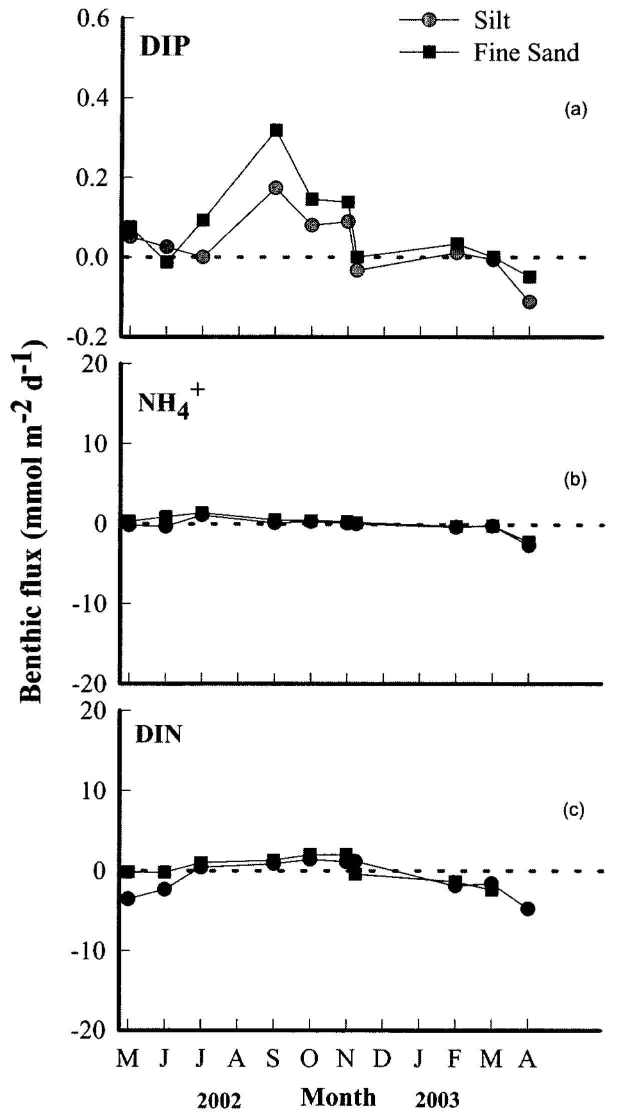


Fig. 6. The benthic flux of DIP, NH_4^+, DIN in mesocosm.

cosms sections. A promoted out-fluxes have been found for DIP from June to October (Fig. 6a), nearly no peak for ammonium (Fig. 6b), and mostly negative fluxes for DIN (mostly nitrate) (Fig. 6c).

The estimated fluxes of DIP in Fig. 6 could be the result of the following equation:

$$DIP_{\text{estimated flux}} = DIP_{\text{total flux}} - DIP_{\text{benthic comsumption}}$$

There must be total out-fluxes of DIP continuously from the sediment. Yet we were able to estimate the residual portion of the DIP, the net flux of DIP only. The loss term of the DIP was probably due to the photosynthetic consumption at the sediment surface presumably by benthic diatom. Therefore the total fluxes would be greater than the estimated fluxes of DIP. The annual flux was estimated 27.9 umole m^{-2} day^{-1} and 74.3 umole $m^{-2}day^{-1}$ for the Silt and the Fine Sand mesocosm, respectively (Table 2). Previous investigations by *in situ* observations reported a wide range from 18.2 to 1,450 umole $m^{-2}day^{-1}$. From two years of intensive field observations at the Narragansett Bay, Nowicki and Nixon (1985) reported 27.4 and 19.2 umole $m^{-2}day^{-1}$ for mud and sand sediment, respectively. The estimated DIP fluxes in this work are comparable to these previous reports.

For DIN, a similar argument would be possible as follows:

$$DIN_{\text{estimated flux}} = DIN_{\text{total flux}} - DIN_{\text{benthic consumption}} - DIN_{\text{denitrification}} + DIN_{\text{nitrification of organic matter}}$$

There must be out-fluxes of DIN continuously from the sediment, yet we are able to estimate the residual fluxes of DIN only because of the two loss terms: the removal processes by benthic consumption and denitrification. Assuming that the rate of nitrification of organic matter to nitrate was constant in such a short period like 3 days of experiment, the two removal processes probably greatly attenuated the out-fluxes of DIN.

Denitrification rate is sensitive to temperature with lowest values in winter and highest in summer (Seitzinger *et al.*, 1984). Frequently denitrification represented a major sink for fixed N in the sediment: annually the N_2 production is equal to about 50% of the fixed inorganic N loading to the estuary from rivers and about 30% of the organic nitrogen mineralized in the sediments (Seitzinger *et al.*, 1984). Such removal mechanism through denitrification at the surface of the sediment probably explained the consistent low fluxes of DIN appeared during the experiments. As a result, annual flux of DIN was estimated -0.90 mmole $m^{-2}day^{-1}$ and 0.20 mmole $m^{-2}day^{-1}$, respectively (Table 3).

Previous investigations by *in situ* observations reported a range from 0.41 to 1.76 mmole $m^{-2}day^{-1}$. From two years of intensive field observations at the Narragansett Bay, Nowicki and Nixon (1985) reported 0.01 and -0.38 mmole $m^{-2}day^{-1}$ for mud and sand sediment, respectively. The estimated DIN fluxes in this work are compatible to these previous reports. For ammonium, previous works ranged from 0.23 to 14.4 mmole $m^{-2}day^{-1}$ and Nowicki and Nixon (1985) reported 0.55 and 0.19 mmole $m^{-2}day^{-1}$. In this work, we estimated annual influxes of -0.28 and 0.07 mmole $m^{-2}day^{-1}$. This smaller out-fluxes and ammonium will

Table 2. The comparison of benthic DIP fluxes between mesocosm and *in situ* observations

unit: umol m^{-2} day^{-1}

This study			Previous studies		
Periods	Fluxes		Periods	Fluxes	Authors
	Silt	Fine Sand			
May 11 2002	51.1	75.9	May	20.0	Takayanagi and Yamada (1999)
Jun 28 2002	25.6	-12.8			
Jul 03 2002	0.00	92.5	Jul	1,450	Forja *et al.* (1994)
			Jul	19.08 ~ 342.0	Conley *et al.* (1997)
Sept 25 2002	173	319	Sept	31.1	Takayanagi and Yamada (1999)
Oct 03 2002	79.9	146			
Oct 24 2002	89.7	139			
Nov 19 2002	-33.4	0.00			
Feb 17 2003	11.3	33.9			
Mar 01 2003	-6.41	0.00	Mar	18.2	Takayanagi and Yamada (1999)
Apr 29 2003	-112	-49.5			
Annual average	27.9	74.3	Annual average	27.4 (mud) 19.2 (sand)	Nowicki and Nixon (1985)

Table 3. The comparison of the benthic DIN fluxes between mesocosm and *in situ* observations

unit: mmol m^{-2} day^{-1}

This study			Previous studies		
Periods	Fluxes		Periods	Fluxes	Authors
	Silt	Fine Sand			
May 11 2002	-3.52	-0.18	May 1999	1.06	Laursen and Seitzinger (2002)
Jun 28 2002	-2.34	-0.20	Jun 1998	0.7	Laursen and Seitzinger (2002)
Jul 03 2002	0.42	1.00	Jul 1993	0.41 ~ 1.19	Conley *et al.* (1997)
			Jul 1997	1.21	Laursen and Seitzinger (2002)
Sept 25 2002	0.87	1.33	Sept 1998	1.76	Laursen and Seitzinger (2002)
Oct 03 2002	1.42	2.01			
Oct 24 2002	1.14	2.03			
Nov 19 2002	1.19	-0.42	Nov 1998	0.87	Laursen and Seitzinger (2002)
Feb 17 2003	-1.90	-1.37			
Mar 01 2003	-1.58	-2.38			
Apr 29 2003	-4.73				
Annual average	-0.90	0.20	Annual average	0.01 (mud) -0.38 (sand)	Nowicki and Nixon (1985)

be discussed more in problems.

Problems

In designing a mesocosm system, we always have to consider whether the response of the system will be seriously affected by enclosed physical environments or by excluded higher trophic levels in mesocosm. Some of the key parameters for a perfect mesocosm are size (scaling), sediment/water ratio, light intensity or turbidity in water, residence time of water (exchange rate of water), and the presence of predators in a mesocosm.

Size (Scaling): The most important rule of thumb regarding to the size of mesocosm is "the bigger, the better". But unfortunately we are not able to expand the size of mesocosm limitlessly. Sometimes, the bigger size merely resulted in more expenses to build and to monitor the system. Even a small microcosm did not reveal any difference with a much bigger sized mesocosm during the investigation of biogeochemical behaviors of chemical substances (Pil-

Table 4. The comparison of benthic ammonium fluxes between mesocosm and *in situ* observations

unit: mmol m^{-2} day^{-1}

This study			Previous studies		
Periods	Fluxes		Periods	Fluxes	Authors
	Silt	Fine Sand			
May 11 2002	-0.22	0.28	May 1992	7.2	Mazouni *et al.* (1996)
Jun 28 2002	-0.40	0.84	Jun 1989	0.38	Bolalek and Graca (1996)
Jul 03 2002	1.07	1.37	Jul 1991	14.4	Mazouni *et al.* (1996)
			Jul 1993	0.23 ~ 0.83	Conley *et al.* (1997)
Sept 25 2002	0.08	0.45	Sep 1992	14.4	Mazouni *et al.* (1996)
Oct 03 2002	0.24	0.36			
Oct 24 2002	0.02	0.24			
Nov 19 2002	-0.06	0.12	Nov 1992	0.72	Mazouni *et al.* (1996)
Feb 17 2003	-0.45	-0.37			
Mar 01 2003	-0.33	-0.30			
Apr 29 2003	-2.71	-2.32			
Annual average	-0.28	0.07	Annual average	0.55 (mud) 0.19 (sand)	Nowicki and Nixon (1985)

son and Nixon, 1980). Lower size limits may be set by the practical consideration that repeated sampling should not deplete the stock of specimen too much, and upper limits may be set by the cost of achieving statistically adequate replication. Our mesocosm is big enough for repeated subsampling and small enough for handy maintenance.

Sediment/Water Ratio: Sediments are known to play an important role in recycling nutrients in coastal water. Yet, the sensitivity of mesocosm to this parameter was not yet fully explored. If a mesocosm has thick sediment relative to shallow superficial water, the effects of sediment on the water qualities may be exaggerated. Still much of the important chemical process are known to take place in the upper several few centimeters and even within the few millimeters in a fine-grained organic-rich sediment. Despite the water table of seawater falls down to lower tidal level during ebb tides, still the surface particles in sediment are in water-saturated state. Capillary effect keeps their water content constant even after its surface has been emerged in the air for several hours (Kuwae *et al.*, 2003). Therefore sediment /water ratio will be less critical unless their surface sediment are exposed to be totally dehydrated in the air.

Light Intensity/Turbidity in Water: Light is an essential parameter for photosynthesis both in pelagic and benthic algae. Such algal activities will significantly affect the dynamics of nutrients and biogeochemical consequences. In this work, the mesocosm has been set up outdoors to receive natural sunlight. Intensity and irradiation of sunlight usually has seasonal patterns in nature. To mimic the seasonal patterns, there are several possible options: screening meshes, turbidity in the water column, or water depth control. Another option may be the controlling of the emerged time of the mesocosm to sunlight. In this work, we applied approximately 30 centimeters of water depth during the flood and synchronized with the *in situ* tidal rhythm.

Turbidity in seawater has strong influence on marine organisms by shading sunlight for primary producers, by inhibiting filtering activity of herbivores, and by poor visibility to predators. No attempt has been applied to mimic the natural turbidity condition in this work. Therefore, relatively low concentrations of suspended solids were revealed during the experiments due to the less dynamic condition in the mesocosm facility (Fig. 5b). Therefore the sediment surface of the mesocosm has experienced higher irradiance due to the less shading effect by decreased suspended solids in the water column. It probably has accelerated the benthic primary production and the nutrient consumption rate. Even with higher demand of nutrient by benthic algae at the sediment surface of the mesocosm, DIP has been reported rarely limited in this area (Yang and Kim, 2002). However the ammonium leached from sediment might be consumed instantly at the surface by benthic microflora due to their preference to other nitrogen sources. Therefore the low concentration of suspended solids in the water column of the mesocosm might partly explain the low out-flux of ammonium during the summer in this work.

Residence Time of Water (Exchange Rate of Water): Most mesocosms of three sections have been operated as batch cultures, as in this work. Some others allowed continuous exchange of seawater as a chemostat (Perez *et al.*, 1977). They compared the behavior of the 150-liter mesocosms operated with water-turn-over times ranging from 7 to 100 days. The effect on the systems was almost nonexistent. There were increased numbers of grazers by the longer turnover times, but the standing stocks of algae and nutrients were unchanged.

The Existence of Predators: It is generally accepted that a community structure is powerfully influenced by the activities of top predators. Such effects are strikingly demonstrated in rocky inter-tidal communities like kelp beds (Mann, 1977). Moreover various trophic levels of planktonic communities are known tightly coupled. However various experiments on the effect of predation on the structure of soft-bottom communities in Narragansett Bay have also failed to demonstrate a marked effect (Pilson and Nixon, 1980). Such results supported a lack of direct adverse effect on the in-fauna of soft-bottom communities. In this work, we have inoculated the natural benthic communities into the mesocosm intact and kept it under healthy condition for two years. Therefore we exclude any side effects due to the lack of predators.

Summary of Problems: In this work, the mesocosm we installed was proved to be the optimum size for handy maintenance and sub-sampling. Sediment/water ratio has not been a critical defect unless exposed totally dehydrated in the air. Increased residence time of water in a mesocosm could induce elevated number of predators, yet the standing stocks of algae and nutrients were found unchanged. Moreover we introduced the intact sediment community into the mesocosm. The only defect in this mesocosm was low turbidity in the water column, which probably resulted in the underestimation of ammonium flux from the sediment.

Future Directions

We cannot over-emphasize that no mesocosm ever be an exact replica of nature. Because the enclosed system is isolated from a real world and its behaviors will be to some extent modified anyhow. Furthermore the natural system is sufficiently variable that it is difficult to select the exact region to be matched, and that region will change rapidly depending on the outside world. In this work, we found that low concentration of suspended solids in the water column could be a problem to perfectly mimic the natural tidal flat. For this, a turbidity-generating device like a propeller will be applied to the mesocosm facility in the future. Despite this problem, the experience from two years of operation convinces us that mesocosm is a very useful tool. Moreover, the chemical behavior of mesocosm may be less vulnerable to any defect in the mesocosm than their biological behavior. Properly designed mesocosm will have wide applications for the diverse fields of biogeochemical studies on the environmental impact assessment such as freshwater introduction, increased nutrient load, and elevated suspended solids and so on.

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