Comparative Study of Macrofauna and Sediment of Two Brackish Tidal Flats Located at River Mouths Facing Sendai Bay

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Key Words : Estuarine tidal flat, Macrofauna, Sediment, Sediment-trap material

Abstract

Seasonal investigations of macrofauna, sediment, and deposited particulate matter collected by sediment traps were conducted from September 1989 to July 1990 on two estuarine tidal flats, Gamō tidal flat at the mouth of the Nanakita River and Idoura tidal flat at the mouth of the Natori River, Sendai Bay. The macrofauna detected at the two flats were similar, but with different dominant species. Grain size distribution of the sediment may be one of the important factors determining the dominant species. Most of the macrofaunal biomass were made up of deposit-feeders at both tidal flats. Gamō tidal flat had the higher total biomass of macrofauna in warmer seasons (September and July). The C／N ratios of sediment trap samples and surface sediment of the tidal flats suggested that, the sedimentary organic matter at Gamō tidal flat was of more phytoplanktonic in origin, while that at Idoura tidal flat was of terrestrial origin. It was suggested that the greater sedimentation of POM (particulate organic matter) with a higher nutritional value (a lower C／N ratio) resulted in higher biomass of macrobenthos at Gamō tidal flat. The biomass showed the negative correlations with the amount of POM caught in the sediment traps and positive correlations with the Eh of the sediment in warmer seasons at Gamō tidal flat. This suggested that a lower Eh or more reduced anoxic environment of the sediment, caused by an excess input of more labile organic matter, was a factor limiting the benthic macrofaunal biomass at Gamō tidal flat.

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1. Introducton

In estuarine intertidal flats, the interactions between sediment and the benthic macrofauna have been investigated by many workers (Sanders et al. 1962; Ono 1965; Warwick and Price 1975; Reise 1985; Reise et al. 1994). The grain size distribution of sediment has been shown to be of great importance in determining benthic community structure and production in such areas (Sanders 1958; Gray 1974; Rhoads 1974; Ishikawa 1989). However, there is little evidence that sedimentary grain size alone is the primary determinant of infaunal species distribution (Snelgrove and Butman 1994), since grain size covaries with other parameters such as sedimentary organic matter content, porosity, permeability, Eh, pore-water chemistry and tidal level (Gray 1974; Tsuchiya and Kurihara 1976). As it is usually difficult to separate the effects of these mutually correlated variables, the animal-sediment relationships in estuarine tidal flats are not yet fully understood.

The organic content of bottom sediments is a more likely causal factor than sediment grain size in determining infaunal distributions because such organic matter is a major source of food for deposit-feeders and, indirectly (e.g. through resuspension), suspension-feeders (Snelgrove and Butman 1994). In an estuarine environment, organic matter in the sediment is introduced from a variety of sources and includes terrestrial riverborne and marine allochthonous components, autochthonous biomass derived from planktonic and benthic primary production, additional subsidiary inputs supplied via marginal vegetation, and anthropogenic inputs. The relative importance of these various sources differs between estuaries. Variation in organic input seems to result in complex changes in other chemical, physical, and biological factors of sediments, which in turn have direct and indirect effects on the fauna present (Pearson and Rosenberg 1978; Josefson 1990). Although sedimentation of organic matter from various sources is thought to be a significant factor in determining the sediment properties and food available to benthic animals, the effects of organic input on the animal-sediment relationships in estuarine tidal flats are still poorly understood.

Two estuarine tidal flats, Gamō tidal flat and Idoura tidal flat, are located at river mouths facing Sendai Bay (Fig. 1). Both tidal flats have similar geographical locations, but differ in their degree of eutrophication and water stagnation. Gamō tidal flat is located in a small brackish semi-enclosed lagoon (Gamō Lagoon), which is highly eutrophic and productive because of occasional input of nutrients from adjacent fish ponds (Kikuchi et al. 1992), while Idoura tidal flat has no direct anthropogenic nutrient input. The present study was designed to compare macrofauna, sediment properties, and deposited particulate matter collected by sediment traps between the two estuarine tidal flats to obtain further information on the animal-sediment relationships in estuarine intertidal flats.

2. Materials and Methods

2.1 Study site

Gamō tidal flat and Idoura tidal flat are located on the northern side of the mouths of the Nanakita River and Natori River, respectively (Fig. 1). A narrow canal (Teizan Canal) connects the rivers about 500 m upstream from their mouths. The Nanakita River is about 45 km long with a drainage area of 200 km^2. The tidal range of the Nanakita River estuary, about 80 cm at spring tide, is generally about half that of Sendai Bay, its phase lag of 2-3 hr being due to the shallow and narrow mouth of the Nanakita River (Hanawa and Sugimoto 1979). The Natori River estuary is located 9 km south of the Nanakita River estuary. The

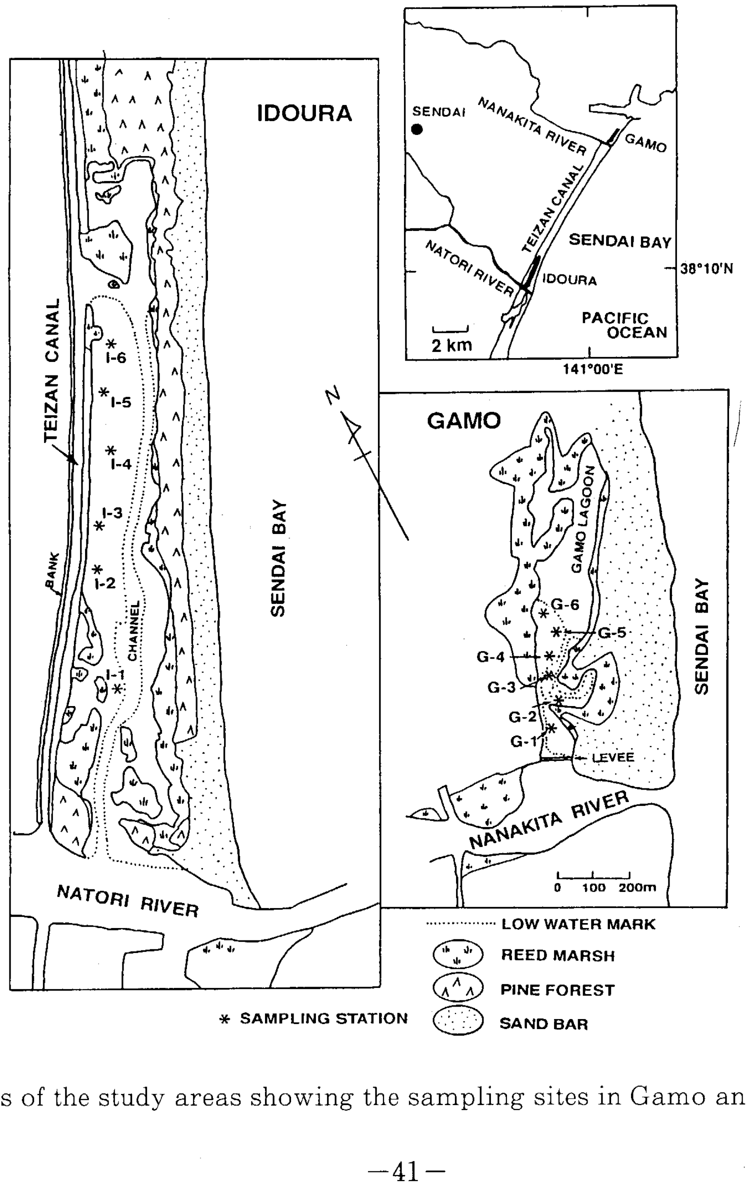

Figure 1. Maps of the study areas showing the sampling sites in Gamo and Idoura tidal flats.

Natori River is about 55 km long with a drainage area of 1,000 km^2. The tidal range in the Natori River estuary is similar to that of Sendai Bay (about 150 cm at spring tide), since the river has a deep, wide mouth.

Gamō tidal flat occupies about half of the area of the sack-shaped brackish lagoon (Gamō Lagoon) located on the northern side and 0.25 km upstream from the mouth of the Nanakita River (Fig. 1). The lagoon is separated from Sendai Bay by a flat shallow sandbar 200 m wide. A stone levee, in which three square concrete tubes (opening, 1.8m x 1.35m) are buried, forms the lagoon gateway through which water is exchanged. The lagoon can be divided into two regions, the intertidal flat (Gamō tidal flat; total area 5 ha) in the vicinity of the lagoon mouth, and the deeper subtidal area in the inner part of the lagoon (Kikuchi et al. 1980). The water depth in the deepest part of the lagoon is about 30 cm at low water with a tidal range of about 50 cm at spring tide.

Idoura tidal flat (total area 10 ha) is located between the stone levee of Teizan Canal and a channel which connects the canal with the Natori River 0.4 km upstream from the river mouth (Fig. 1). The water covering the tidal flat flows upward from the river mouth at flood tide and flows down at ebb tide, and the salinity fluctuates considerably even in a tidal cycle. The tidal range in this area is over 1 m at spring tide.

In this study, 6 stations were selected for intensive investigation at each tidal flat, and arranged longitudinally from the junction of the flat and the river to the inner part of the flat (Fig. 1). The investigation of macrofauna and sediment was carried out in September 1989 and in January, April, and July 1990.

2.2 Sampling

For macrofaunal sampling, a PVC column (20 cm in diameter and 50 cm in depth) was buried vertically at each sampling site in the tidal flats, and a 30-cm sample of deep sediment was collected from each column. The sediment samples were passed through a 1-mm-mesh sieve, and residues on the sieve were preserved in 4% neutralized formalin solution. Sampling was carried out at ebb tide, and three replicates were taken at each site. The macrobenthos collected was sorted, identified and counted in the laboratory. Each species of macrobenthos was dried at 70℃ and weighed, and then its AFDW (ash-free dry weight) was obtained after weight reduction by combustion at 700℃. For bivalves, their shells were removed before weight measurement.

2.3 Physical and chemical analyses of the sediment

The relative height of sampling sites on each tidal flat was determined by measuring the water depth at high water. Redox potential (Eh) was measured using the electrode of an Eh meter (Toa RM-10P) pushed into an undisturbed part of the sediment to a depth of 5 cm on each site.

To analyze the chemical properties of the substratum, surface (upper 5 mm) sediment was sampled at each site. The water content of the sediment was then obtained after weight reduction by drying at 70℃. The total carbon and nitrogen contents of the dried sediment samples were measured using a CN analyzer (Yanagimoto MT500). To determine the silt-clay content of the sediment, 10 g of dried sediment was oxidized with hydrogen peroxide solution to remove the organic matter. After dispersal, the silt-clay content was measured by the sieving method. For the silt-clay content, samples collected in July were measured.

The salinity of the surface water was measured monthly at each tidal flat. A water salinity time-series was also obtained for one tidal cycle on 24 May and 16 September at Gamō tidal flat and on 22 May and 15 September at Idoura tidal flat.

2.4 Deposition rate of suspended particulate matter

Deposition of particulate matter in the tidal flat sediment was estimated from sediment trap collections. Three cylindrical traps (9 cm in diameter and 12 cm in depth) with open tops 5 cm above the sediment were placed for 7 d in September 1989 and in January, April, and July 1990. No poisons or preservatives were used in this experiment. The traps were capped when the tide receded, kept close to ambient water temperature, and returned to the laboratory. The entire contents of the traps were passed through a 1-mm screen and then allowed to settle for 24 hr at 7℃ in a dark room. The clear water overlying the settled material was discarded, and then the settled particles were transferred as a slurry into a glass beaker, dried at 60℃, and weighed. The total carbon and nitrogen contents of the trapped sediment samples were measured with the CN analyzer.

3. Results

3.1 Macrofauna

Tables 1 and 2 summarize the average number of individuals, the average AFDW biomass, and the feeding modes of macrofaunal species which occurred at the sampling sites at Gamō and Idoura tidal flats, respectively. The macrofauna collected at Gamō tidal flat and Idoura tidal flat comprised 15 and 20 species, respectively; 13 of these species were

Table 1. The densities and biomass of species found in Gamō tidal flat.

Species name	Feeding type	G-1		G-2		G-3		G-4		G-5		G-6	
		No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²
Polychaetes													
Neanthes japonica	SD	2378	8.38	4613	11.50	4883	13.99	4063	15.16	2869	10.38	1415	8.52
Notomastus sp.	M	799	5.64	618	5.34	1141	6.92	297	2.43	244	1.55	35	0.15
Heteromastus filiformis	M	287	1.23	35	0.05	13	0.02	8	0.02	3	0.003		
Prionospio japonica	?	43	0.02	72	0.03	11	0.001	16	0.002	64	0.04		
Pseudopolydora kempi japonica	SP, SD	85	0.05	45	0.02	48	0.02	5	0.001	27	0.01	8	0.004
Bivalva													
Macoma contabulata	SD	3	0.07			8	0.08	37	1.37	82	2.98	19	0.60
Nuttalia olivacea	SD	162	10.21	50	3.60	58	1.19	27	0.34	27	0.43		
Ruditapes philippinarum	SP	16	0.008	3	0.04								
Laternula limicola	SP	5	0.08	19	0.97	5	0.01	3	0.002	29	0.45	3	0.05
Arthropoda													
Acmaeopleura parvula	SD			3	0.02			3	0.01	3	0.24		
Callianassa japonica	M	8	0.11			3	0.04						
Upogebia major	M	3	1.40							3	0.24		
Grandidierella japonica	SD	35	0.01	674	0.08	791	0.10	772	0.15	774	0.24	289	0.08
Corophium uenoi	SD									19	0.002	3	0.000
Merita sp.	SD	16	0.002	61	0.003	127	0.02	186	0.03	82	0.02	45	0.008
Total		3872	27.21	6162	21.64	7051	21.38	5741	19.51	4229	16.36	1818	9.41

Abbeviations: SD, surface deposit feeder; SP, suspension feeder; M, mud feeder; ?, unknown

Table 2. The densities and biomass of species found in Idoura tidal flat.

Species name	Feeding type	I-1		I-2		I-3		I-4		I-5		I-6	
		No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²
Polychaetes													
Neanthes japonica	SD	127	0.33	11	0.03	11	0.05	101	0.28	64	0.11	515	0.64
Tyllorhynchus heterochaetes	SD	19	0.003	3	0.001					8	0.004	29	0.009
Notomastus sp.	M	61	0.05	96	0.06	27	0.05	35	0.06	21	0.02	82	0.11
Heteromastus filiformis	M	3158	2.49	2126	2.75	1168	2.27	889	1.59	239	0.43	1011	2.46
Capitella sp.	M									3	0.001		
Prionospio japonica	?	85	0.02	90	0.06	130	0.09	204	0.12	130	0.10	167	0.08
Pseudopolydora kempi japonica	SP, SD	3	0.000	27	0.01	27	0.01	19	0.003	5	0.003	19	0.01
Serpuridae (unidentified sp.)	SP							3	0.001	21	0.03	8	.01
Bivalva													
Macoma contabulata	SD	5	0.005	21	1.84	32	2.65	32	5.74	43	9.45	106	13.75
Nuttalia olivacea	SD	3	0.000										
Corbicula japonica	SP							3	0.45			11	1.47
Laternula limicola	SP	3	0.02			5	0.26	3	0.02			8	0.83
Arthropoda													
Ilyoplax pusillus	SD	19	0.16										
Macrophthalmus japonicus	SD			8	5.02	11	5.00	3	2.78	8	1.84	11	2.30
Acmaeopleura parvula	SD	8	0.02							3	0.004	3	0.007
Callianassa japonica	M	27	1.07	3	0.16					8	1.55		
Upogebia major	M	13	2.28							3	0.12		
Paranthura japonica	?	93	0.27	29	0.05	13	0.01	58	0.07	85	0.10	112	0.13
Grandidierella japonica	SD	56	0.007	27	0.007	27	0.006	19	0.004	16	0.003	24	0.006
Merita sp.	SD	3	0.000					11	0.002			5	0.000
Total		3681	6.73	2439	9.99	1452	10.41	1377	11.12	656	13.78	2110	21.80

Abbeviations: SD, surface deposit feeder; SP, suspension feeder; M, mud feeder; ?, unknown

collected at both tidal flats. Since two species of crabs, *Macrophthalmus japonicus* and

Ilyoplax pusillus, and two species of polychaetes, *Tylorrhynchus heterochaetus* and *Capitella* sp., were collected at other sites on Gamō tidal flat, it was apparent that the species of macrofauna which occurred at the two flats were similar. As for feeding type, deposit feeders (surface deposit feeders and sub-surface deposit feeders) usually comprised more than 90% of the biomass of the benthic fauna in both tidal flats. However, the most abundant species of deposit feeders differed between the two flats. At Gamō tidal flat, the most numerically abundant species were the polychaetes *Neanthes japonica* and *Notomastus* sp., and the amphipod *Grandidierella japonica*, while the polychaete *Heteromastus filiformis* was the most abundant at Idoura tidal flat.

At Gamō tidal flat, the deposit-feeding polychaetes *N. japonica* and *Notomastus* sp. comprised most of the biomass. The bivalves *Nuttalia olivacea* and *Macoma contabulata* also comprised a large part of the biomass at Sta G-1 and Sta G-5, respectively. These 4 species comprised more than 90% of the biomass at each sampling site in Gamō tidal flat. However, at all stations except Sta I-1 at Idoura tidal flat, the crabs *M. japonicus* and the bivalve *M. contabulata* as well as the polychaete *H. filiformis* comprised a large part of the biomass. *M. contabulata* was the most abundant species at Stas I-4, I-5, and I-6 in the portion of Idoura tidal flat distant from the river mouth. The ghost shrimps *Upogebia major* and *Callianassa*

Table 3. Seasonal changes in total macrofaunal biomass (g • m^{-2}) at the sampling sites of the Gamō (Sts. G-1 ~ G-6) and the Idoura (Sts. I-1 ~ I-6) tidal flats.

St.	Sept. mean ± sd	Jan. mean ± sd	Apr. mean ± sd	Jul. mean ± sd
Gamo				
G-1	22.2±5.9	10.5±2.7	14.1±1.4	62.1±48.4
G-2	15.9±4.3	5.7±4.0	24.9±8.4	40.1±10.6
G-3	20.1±2.1	8.0±4.0	16.3±0.6	45.1±4.0
G-4	16.3±5.0	11.5±5.6	14.0±2.6	36.2±5.4
G-5	14.5±6.0	5.3±3.5	9.0±3.4	36.7±9.1
G-6	10.9±5.0	1.4±0.8	5.4±6.8	20.0±8.5
mean	16.6*	7.1	13.9	40.0**
Idoura				
I-1	3.9±1.9	6.9±1.7	7.5±5.3	8.7±9.7
I-2	1.4±0.4	7.5±5.4	18.0±12.1	13.0±19.6
I-3	6.2±8.7	23.2±18.5	4.1±1.1	8.1±8.2
I-4	12.4±4.2	7.2±6.3	15.8±13.0	9.1±6.8
I-5	9.0±7.0	6.1±2.3	27.5±14.4	12.5±6.1
I-6	23.9±7.5	12.3±0.5	15.2±7.1	35.9±5.6
mean	9.5*	10.5	14.7	14.6**

*, significant difference among means at $p<0.1$ (nested ANOVA); **, $p<0.01$

japonica were also abundant at Sta I-1. From a comparison of the average total biomass between Gamō and Idoura tidal flats, the former had significantly higher biomass in September and July (Table 3).

3.2 Physical and chemical properties of sediment

There was little difference in the salinity range (from 7 to 31‰) between Gamō and Idoura tidal flats (Table 4). The salinity changed considerably (by 5-10‰) even in one tidal cycle at both flats. The relative heights of the sampling sites, and the silt-clay and water contents of the sediment are shown in Table 5. The difference in a height among the sampling sites was less at Gamō (up to 20 cm) than at Idoura (up to 51 cm) tidal flat. Sediment grains

Table 4. Range of salinity measured at Gamō and Idoura tidal flats.

	Gamō		Idoura	
	minimum	maximum	minimum	maximum
monthly measurement	6.8	31.2	6.5	30.9
one tidal cycle				
May[1]	9.8	22.1	12.9	30.9
September[2]	23.7	28.6	26.0	30.6

1) Gamō, 22 May 1990; Idoura, 24 May 1990
2) Gamō, 15 September 1990; Idoura, 16 September 1990

Table 5. Physical and chemical properties of the sediments at the sampling sites in Gamō (Stas G-1 ～ G-6) and Idoura (Stas I-1 ～ I-6) tidal flats.

St.	Relative height (cm)	Silt-Clay content (%)	Water content (%)	TC (%) mean ± sd	TN (%) mean ± sd	C/N mean ± sd	Eh (mv) SEP	JAN	APR	JUL
Gamo										
G-1	0	0.8	33.2	0.18±0.105	0.026±0.006	6.6±3.5	170	468	282	213
G-2	18	0.9	31.6	0.24±0.184	0.026±0.012	8.4±3.3	135	385	255	241
G-3	20	1.5	34.6	0.31±0.139	0.038±0.007	8.1±2.4	118	458	255	242
G-4	18	7.5	64.6	1.44±0.652	0.149±0.060	9.4±0.8	99	212	36	127
G-5	17	4.8	53.6	1.38±0.638	0.136±0.065	10.4±0.9	70	242	25	15
G-6	8	12.5	64.7	0.99±0.376	0.117±0.040	8.4±0.4	22	212	10	−50
mean		4.7*	47.1	0.75	0.082	8.5**				
Idoura										
I-1	34	7.0	34.8	0.45±0.157	0.032±0.015	14.7±2.1	392	255	349	152
I-2	4	31.6	57.2	1.64±0.322	0.103±0.029	16.4±2.1	60	281	94	95
I-3	0	41.9	59.0	1.83±0.163	0.119±0.020	15.5±1.1	75	261	92	25
I-4	36	22.6	57.4	1.71±0.399	0.112±0.035	15.5±1.0	42	398	102	46
I-5	43	26.8	51.3	1.08±0.314	0.069±0.019	15.6±0.4	31	416	140	86
I-6	51	16.9	43.6	1.51±1.257	0.086±0.068	17.7±2.8	110	346	257	77
mean		24.5*	50.6	1.37	0.087	15.9**				

*, significant difference among means at $p<0.01$ (t-test); * *, $p<0.0001$ (nested ANOVA)

at Idoura tidal flat were generally finer than those at Gamō. Most of Idoura tidal flat contained a large amount of silt-clay, more than 15%, and the sandy sites were only distributed in a narrow range along the channel around Sta I-1. Most of sediment grains at all sampling sites in Gamō tidal flat were composed mainly of sand, though the finer (silt-clay) fraction tended to increase toward the inner portion. In Figure 2 the total nitrogen content in the surface sediment of sampling sites is plotted against the silt-clay content. A trend for an increase in the silt-clay content with an increase in the nitrogen content at each tidal flat was observed (Gamō , $r=0.768$, $p<0.1$; Idoura, $r=795$, $p<0.1$). The slope of the regression line was higher for Gamō than for Idoura tidal flat ($p<0.1$), suggesting a higher organic content of the silt-clay fraction in the former.

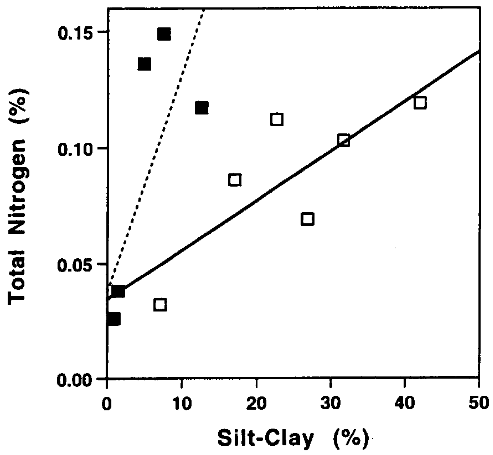

Figure 2. Relationship between silt-clay content and total nitrogen content of sediments at the sampling sites in the tidal flats. ■, Gamō tidal flat; □, Idoura tidal flat

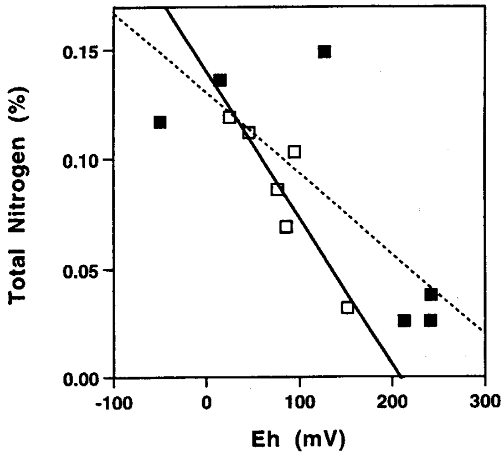

Figure 3. Relationship between Eh and total nitrogen content of the surface sediment measured in July 1990. ■, Gamō tidal flat; □, Idoura tidal flat

The Eh of the sediment tended to show seasonal variation, increased with decreasing temperature, and was found to have the highest value at almost all the stations in January (Table 5). Since measurement of Eh within the sediment is considered to be a useful index of organic matter content (Plante et al. 1989), the Eh of the surface sediment measured in July was plotted against total nitrogen content (Fig. 3), and a negative correlation between the two parameters was observed (Gamō, $r=0.790$, $p<0.1$; Idoura, $r=0.904$, $p<0.05$). There was a significant difference in the C/N ratio of the sediment between the Gamō and Idoura tidal flats (Table 5). The sedimentary C/N ratios exceeded 14 in Idoura tidal flat, while in Gamō tidal flat most of the sediment C/N ratios were lower than 10, suggesting a compositional difference in the sedimentary organic matter pool between the tidal flats.

3.3 Flux of particulate material from overlying water to the sediment

The average flux of particulate material from the water to the sediment tended to be higher in Gamō tidal flat than Idoura flat (Table 6). In addition, the carbon and nitrogen contents of the particulate matter caught in the sediment traps were also higher at Gamō than at Idoura tidal flat. A significant difference in the fluxes of total nitrogen between the two tidal flats ($p<0.05$), suggesting the overall flux of organic matter was higher in Gamō than in Idoura tidal flat. The average C/N ratio of particulate matter deposited in the traps at Gamō tidal flat (C/N 9.2) was significantly lower than that in Idoura tidal flat (C/N 12.9). This suggests that the lower C/N ratios of surface sediments in Gamō tidal flat (Table 5) reflected the values of particulate matter deposited from the water column.

Table 6. Vertical fluxes ($\mathrm{g \cdot m^{-2} \cdot d^{-1}}$) of particulate matter and the organic carbon and nitrogen contents (%) of particulate matter in sediment traps deployed in Gamō and Idoura tidal flats. Abbreviations: Bulk, total particulate material: PC, particulate carbon; PN, particulate nitrogen

Station	Bulk flux mean ± sd	C content mean ± sd	N content mean ± sd	PC flux mean ± sd	PN flux mean ± sd	C/N ratio mean ± sd
Gamo						
G-1	2,039±974	0.54±0.52	0.05±0.03	11.2±12.4	0.78±0.27	10.8±7.0
G-2	554±425	1.05±0.65	0.12±0.07	4.4±4.3	0.49±0.43	8.5±1.1
G-3	1,234±1,146	0.67±0.33	0.08±0.04	7.3±5.3	0.85±0.63	8.8±0.3
G-4	623±439	2.46±0.34	0.27±0.03	15.1±11.2	1.68±1.27	9.2±0.6
G-5	626±361	3.25±0.50	0.35±0.05	20.3±11.2	2.25±1.33	9.2±0.4
G-6	585±362	3.47±0.45	0.40±0.07	20.4±12.0	2.31±1.20	8.7±0.8
mean	944*	1.91	0.21	13.1	1.39**	9.2***
Idoura						
I-1	814±456	0.78±0.46	0.07±0.02	7.6±8.4	0.62±0.40	11.6±6.2
I-2	533±352	2.06±0.20	0.14±0.02	10.6±5.9	0.73±0.47	15.1±1.9
I-3	625±382	1.92±0.17	0.14±0.02	11.8±7.0	0.87±0.50	13.5±0.8
I-4	341±195	1.81±0.29	0.14±0.03	6.0±2.9	0.47±0.26	12.8±0.9
I-5	272±145	1.99±0.67	0.16±0.05	5.7±3.9	0.47±0.33	12.3±0.5
I-6	235±140	2.40±0.56	0.20±0.05	6.1±4.3	0.50±0.35	12.2±0.2
mean	470*	1.83	0.14	7.9	0.61**	12.9***

*, significant difference between Gamō and Idoura tidal flats at $p<0.1$ (nested ANOVA); **, $p<0.05$; ***, $p<0.0001$

3.4 Total macrofauna biomass and sediment properties

In Figure 4, the total biomass of benthic macrofauna in July is plotted against total carbon of the surface sediment and the particulate carbon caught in the sediment traps (Fig. 4). In Gamō tidal flat, there were inverse correlations between biomass and sedimentary total carbon content ($r=0.745$, $p<0.1$), and between biomass and deposited total carbon ($r=0.795$, $p<0.1$). In Figure 5, the total biomass at the stations is also plotted against sediment Eh for

Sept. 1989 and July 1990. The biomass tended to decrease with decreasing Eh in Gamō tidal flat (Sept., $r=0.907$, $p<0.05$; July, $r=0.751$, $p<0.1$).

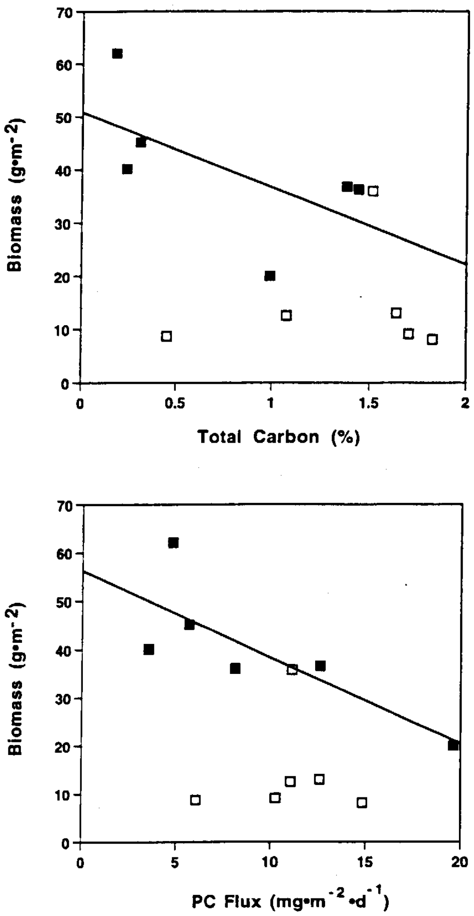

Figure 4. Relationship between total biomass of benthic macrofauna and total carbon content of sediment and between total biomass of benthic macrofauna and particulate carbon (PC) caught in sediment traps at the sampling sites in July 1990. ■, Gamō tidal flat; □, Idoura tidal flat

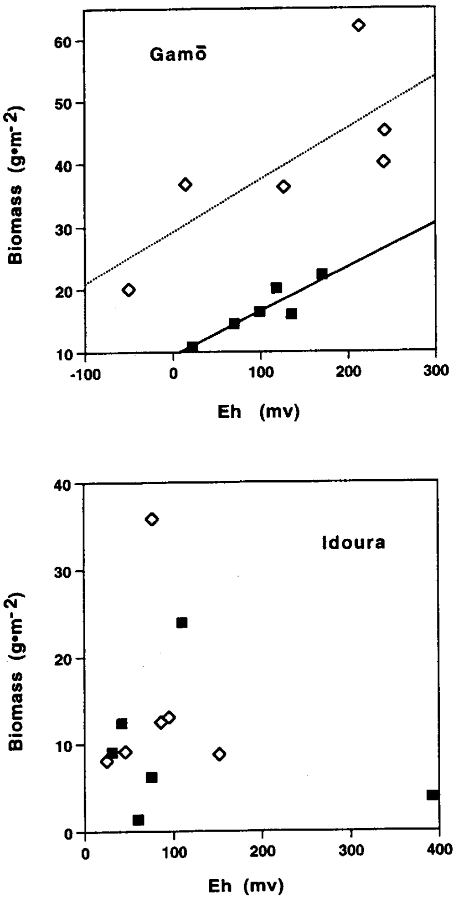

Figure 5. Relationship between total biomass of benthic macrofauna and redox potential (Eh) of the sediment in September 1989 (■) and July 1990 (◇).

4. Discussion

For the species of benthic macrofauna, the most abundant species differed between Gamō and Idoura tidal flats. At Gamō tidal flat, the numerically abundant species were the polychaetes *Neanthes japonica* and *Notomastus* sp., and the amphipod *Grandidierella japonica,* while the polychaete *Heteromastus filiformis* was the most abundant species in Idoura tidal flat. At Gamō tidal flat, the deposit-feeding polychaetes, *N. japonica* and *Notomastus* sp., comprised most of the biomass, while at Idoura, the crab *Macrophthalmus japonicus* and the bivalve *Macoma contabulata* as well as the polychaete *H. filiformis* comprised a large part of the biomass. It is well known that the most influencing factor on the species composition of benthic macrofauna in estuaries and brackish waters is change in the salinity of the water (Beadle 1972; Perkins 1974). However, our results suggested that there was little difference in salinity variation between Gamō and Idoura tidal flats (Table 4).

Tidal levels are considered to play an important role in determining the distribution of macrobenthos in an intertidal flat, since most physicochemical factors change with the duration of exposure and submergence. Some studies have documented the macrofaunal zonation in tidal flats (Ono 1965; Tsuchiya and Kurihara 1976; Tamaki 1984; Koh and Shin 1988). In this study, however, the dominant species were almost the same, irrespective of different tidal levels in each tidal flat.

Grain size distribution showed a marked difference between the two tidal flats. Most part of Idoura tidal flat contained a large amount of silt-clay (more than 15%), except for a small area along the channel around Sta I-1, while the sediment of Gamō tidal flat was composed mainly of sand, and the silt-clay content of the sediment was less than 15%. The crab *M. japonicus* inhabited only the silty mud (Stas. I-2 ~ I-6) of Idoura tidal flat (Tables 2 and 5), and the bivalve *M. contabulata* occurred in finer sediment than *N. olivacea* in both tidal flats (Fig. 6). In an extensive series of studies on the distribution of estuarine ocypoid crabs in Japan, Ono (1965) showed that crab distributions were related to two physical features, the texture of the sediment and the tidal height of the habitat: *M. japonicus* lived in finer silty areas with lower tidal levels, whereas *Ilyoplax pusillus* lived in muddy sand with higher tidal levels. He also reported that ocypoid crabs showed morphological adaptations of their

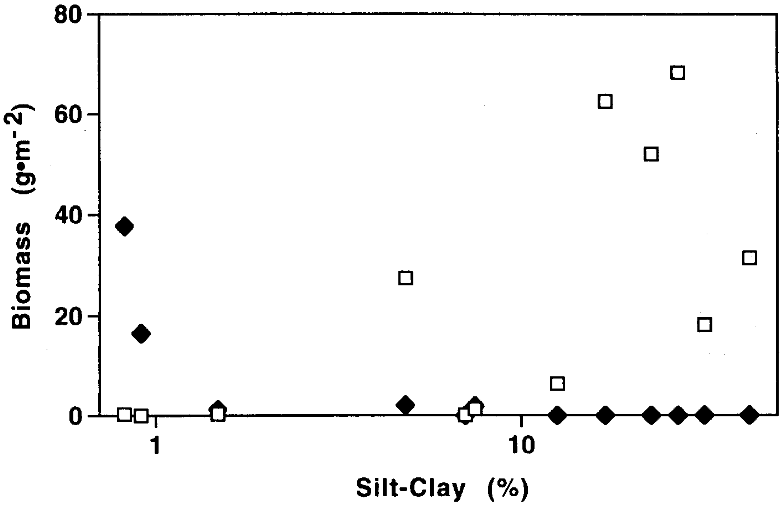

Figure 6. Relationship between biomass of the two bivalves, *Macoma contabulata* (□) and *Nuttalia olivacea* (◆), and the silt-clay content of the sediment. The biomass is plotted against the silt-clay content of the sediment at sampling sites.

mouth parts to the grain sizes of the sediments they fed on (Ono 1965). As for the distribution of bivalves in estuarine tidal flats, Akiyama (1988) suggested that *M. contabulata* was specialized for feeding on finer sediment than *Nuttalia olivacea,* based on their morphological differences. These findings agree with our data on the field distribution of crabs and bivalves in relation to the texture of the sediment. Consequently, it is suggested that the differences in the dominant species of crabs and bivalves between the two tidal flats can be explained by sediment grain size.

The polychaete *N. japonica* was abundant in Gamō tidal flat with sandy sediment. However, Kikuchi (1986) reported that *N. japonica* was highly abundant in muddy sediment (silt-clay 61-73%) at the tidal flat of Nanakita River estuary 1.5 km upstream from the river mouth. In addition, although the sediment at Sta I-1 on Idoura tidal flat showed similar silt-clay contents to the sediments at Stas G-4, G-5 and G-6 on Gamō tidal flat, the dominant species differed markedly between the two flats. At Sta I-1, the polychaete *H. filiformis* was most abundant, while the polychaetes *N. japonica* and *Notomastus* sp. were abundant at Stas G-4, G-5 and G-6. These results indicate that the difference in the dominant polychaete species between Idoura and Gamō tidal flats cannot be explained by the grain size of the sediments.

Many studies have pointed out a direct relationship between the silt-clay element of the sediment and the amount of organic material present (Sanders 1958; Pearson and Rosenberg 1978; DeFlaun and Mayer 1983). Present study also showed a general trend for an increase in the silt-clay content with an increase in the nitrogen content at each tidal flat (Fig. 2). The slope of the regression line was higher for Gamō than for Idoura tidal flat, suggesting a higher organic content of the silt-clay fraction in the former, because exchangeable ammonium accounts for only a small fraction of the sedimentary total nitrogen of the estuarine tidal flat (Sayama and Kurihara, 1983). Since deposit-feeders seem to feed selectively on the silt clay fraction (Tsuchiya and Kurihara 1976; Cadee 1979), the higher organic content of the silt-clay in Gamō tidal flat may have a higher nutritive value for deposit-feeders than that in Idoura tidal flat.

The C/N ratio of particulate matter caught in sediment traps was lower at Gamō (C/N=9.2) than at Idoura (C/N=12.7) tidal flat. In estuaries, organic matter in deposits is derived from several major sources: terrestrial plants, salt marsh plants, and phytoplankton. C/N ratios have been employed as source indicators of sedimentary POM in numerous investigations (Bordovskiy 1965; Peters et al. 1978; Rashid and Reinson 1979; Prahl et al. 1980; Thornton and McManus 1994). The nitrogen content of marine organic matter (phytoplankton) is usually higher (C/N 3∼8; Parsons et al. 1961; Nixon 1981; Grant and Cranford 1991) than that of terrestrial vascular plants ($C/N > 30$) (Alexander 1977; Rice and Tenore 1981). During the degradation of vascular plant detritus containing little nitrogen, the C/N ratio tends to decrease with time and to approach a ratio of approximately 10:1 asymptotically (Alexander 1977), while the C/N ratio of phytoplankton or algal detritus with low C/N ratios (<10) increases with aging time (Rice and Tenore 1981). Consequently, sediment trap samples from Gamō tidal flat have low C/N ratios (<10) indicative of more phytoplankton or benthic micro algae origin, while the higher C/N ratios (>10) of samples from Idoura tidal flat suggest a more terrestrial plant origin. Kikuchi et al. (1992) reported that chlorophyll *a* in water from the inner subtidal area of Gamō lagoon was maintained at a much higher concentration (about 100 $mg \cdot m^{-3}$) than that of intruding sea water or river water, and showed that there was a net export of phytoplankton from the lagoon to the surrounding areas. In addition, stable isotope analysis indicated that the carbon of the polychaete *N. japonica* at Gamō tidal flat was derived from phytoplankton (Kikuchi and Wada 1996). Therefore it is suggested that the autochthonous production of phytoplankton is a significant food source for benthic animals in Gamō tidal flat. In the Gamō lagoon, a fish pond adjacent to the lagoon occasionally discharges pond water with high concentration of phytoplankton, which is deposited and acts as another source of sedimentary organic matter in the lagoon. In contrast to Gamō Lagoon, Idoura tidal flat has no stagnant body of water, indicating that deposited organic matter originates from outside, i.e. is of terrestrial or marine origin. Vascular plants with high C/N ratios from land contain large amounts of refractory substances such as cellulose and lignin which are indigestible by invertebrate animals (Kristensen 1972), while phytoplankton with a low C/N ratio contains high amounts of easily decomposable substances such as protein and carbohydrates. Thus, the C/N ratios of deposited matter can provide an indication of the food quality of organic matter arriving at the bottom (Grebmeier et al. 1988), and the high nitrogen contents or low C/N ratios seem to indicate detritus of high quality as a food for deposit-feeding animals (Tenore 1977; 1981; Grebmeier et al. 1988). Therefore, the higher C/N ratio of deposit or surface sediment at Idoura tidal flat suggests terrestrial deposits, more refractory detrital material, or lower nutritional quality.

The present results showed that the flux of particulate nitrogen from the water column to the sediment was higher at the sampling sites in Gamō tidal flat than at those in Idoura tidal flat (Table 6), suggesting a greater deposition of particulate organic matter (POM) in

Gamō tidal flat. Several studies have shown that the biomass of infauna often increases in response to an increase in sedimentation of organic materials to the bottom (Pearson and Rosenberg 1978; Dauer and Conner 1980; Josefson 1987; 1990). Total benthic biomass per unit area tended to be higher in Gamō than in Idoura tidal flat in summer (Table 3). Therefore, the higher macrofaunal biomass in Gamō tidal flat may be explained by the greater sedimentation of POM as well as the higher nutritional quality of POM deposited.

At Gamō tidal flat, total benthic biomass showed a positive correlation with the Eh of the sediment in warmer seasons (September and July) when the Eh was lower (Fig. 5). The lower Eh or more reduced anoxic environment of the sediment may be a factor limiting the macrofaunal biomass at Gamō tidal flat. At Idoura tidal flat, however, no clear positive correlation between macrofaunal biomass and sediment Eh was observed even in summer. At Gamō tidal flat, the total macrofaunal biomass was negatively correlated with the sedimentary carbon content and the amount of particulate carbon caught in the sediment traps (Fig. 4). In contrast to Idoura tidal flat, a larger input of more labile micro algae-derived organic matter, which occurred in surface sediments at Gamō tidal flat, enhanced activity of microorganisms in the sediment especially in warmer season, and resulted in lower Eh and larger accumulation of reduced substances like sulfides. Our results also showed that the sediment Eh was lower at the inner part of Gamō tidal flat where the carbon and nitrogen contents of the sediment and particulate carbon and nitrogen deposition were higher (Tables 5 and 6). In addition, we were able to smell hydrogen sulfide when the black reduced layer, which was observed under the thin oxidized layer, was disturbed near Sta G-6. It is probable that the stress of low Eh also results partly from the presence of S^{2-}, and that the effects of low Eh alone are not as severe as the combined effects of low Eh and sulfides on the growth of infauna. The macrofauna in Gamō tidal flat may be exposed to more severe sulfide stresses than in Idoura tidal flat, even though the sediment Eh in the two flats was comparable.

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日本語要旨

仙台湾に注ぐ２つの河川の河口に位置する汽水性干潟の底生動物と堆積物の比較研究

仙台湾に注ぐ七北田川河口に位置する蒲生干潟と名取川河口の井戸浦干潟において、大型底生動物と堆積物および干潟に沈殿する粒状物質を1989年９月と1990年１月、４月、７月に採集し、底生動物の組成やバイオマスと堆積物・沈殿物の粒度組成、Eh、炭素量、窒素量、Ｃ／Ｎ比を調べ、干潟間で比較した。その結果、大型底生動物種はほとんどが堆積物食者で、その組成は両干潟で類似していたが、優占種は異なっており、この優占種の違いをもたらす要因の一つとして、両干潟の堆積物の粒度組成の違いがあげられる。干潟堆積物とセジメント・トラップで採集した沈殿物のＣ／Ｎ比から、蒲生干潟の堆積物の有機物は植物プランクトン起源の有機物、井戸浦干潟では陸上の維管束植物起源の有機物の比率がより高く、蒲生干潟の沈殿物の方が堆積物食者の餌としての栄養価が高いと考えられた。蒲生干潟の底生動物のバイオマスは井戸浦干潟よりも大きい。蒲生干潟では沈殿有機物の量が多く、しかも栄養価が高いことが、蒲生干潟の底生動物の大きなバイオマスの理由と考えられる。蒲生干潟では高温の時期（９月、７月）には、堆積物のEhと沈澱炭素量が底生動物のバイオマスとそれぞれ正と負の相関関係を持つ。この事実は、蒲生干潟の有機物の沈澱量が多い場所では、夏期には、活発な有機物の分解に伴ってEhが低下し、無酸素で還元的な環境が発達することが底生動物のバイオマスの増加を抑える要因になることを示唆している。