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論　文

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Depositional role of mussels (*Mytilus galloprovincialis*) attached to quaywalls in Amagasaki port, Osaka Bay

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ABSTRACT: The impact of mussels (*Mytilus galloprovincialis*), attached to quaywalls in Amagasaki port, on deposition of materials was studied *in situ* using sediment traps. Observed lowering concentration of dissolved oxygen and phytoplankton near the walls was attributed to metabolic activity of the mussels. Due to deposition of feces and pseudofeces discharged by filter-feeders, sedimentation rate were doubled under the mussels attached on the quaywall comparing to an adjacent reference site. Even more obvious impact was increase in particle organic carbon (POC) and particle nitrogen (PN) fluxes, which are tripled comparing to those at referent site leading to local organic enrichment near the walls. Increased deposition changed downward fluxes of all investigated metals (Zn, Cu, Pb, Cd and Cr). Results of factor analysis indicated influence of mussels on the redistribution of metals and their concentration in deposited matter, first of all, on redistribution and concentration of Zn and Cd through the selection of fine particles. However, contrary to organic matter, whose concentration in surface sediments and trapped material reflect a clear gradient, which decreases from the wall to the referent position, metal concentrations do not reveal similar effect.

KEYWORDS: *Mytilus galloprovincialis, biodeposition, quaywalls, particulate organic matter, trace metals*

1. INTRODUCTION

1.1 Background information

Extensive urbanization and industrial development, that Japan has undergone since the early 1960`s, required more and more land, and one option was to extend the margins of terrestrial habitat into the nearshore ocean. Therefore, large parts of the shallow coastal areas were reclaimed in order to expend industrial and residential zones relaxing the pressure put on towns and cities.

Increased artificiality results in deterioration of coastal waters1),2),3) but that wasn’t the only environmental blow due to reclamation. In many cases the effects of the transformation of the habitat leads to elimination of some species from that environment and the others makes much rarer. Only some species benefit from newly created conditions. In fact, in new conditions, the quays and breakwaters become habitat for sessile suspension feeders confined to hard substrates. Highly invasive Mediterranean mussel, *Mytilus galloprovincialis*, adapted excellently to a new landscape, arise as a consequence of reclamation activities, and now it forms colonies on the seawalls of Osaka Bay.

The growth of these bivalves is due to their great capacity to filter the water column and feed on suspended matter mainly composed of phytoplankton and detritus. Particles they capture, but can’t ingest

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mussels pack and excrete as feces and pseudofeces[4]. They are to large and cohesive to be further transported, especially under conditions with low currents or poor water flushing and exchange often found in the harbor areas[5]. Thus, this process, termed biodeposition, adds new material to the sediment and may be an important pathway for the deposition of heavy metals and other chemical pollutants on the seabed.

1.2 Scope of study

Former studies supported idea that biodeposits from suspension-feeders may contribute significantly to the total suspended load in estuarine and coastal environments[6],[7]. Biggs and Howell[8] even concluded that biologically mediated sedimentation processes have the capability to overwhelm all others in the deposition of fine sediments (particles less than 63 μm) in estuaries. However, most of the studies carried out to date investigated these processes as a assessment of the effects of cultivated mussels [9],[10],[11] or situations in which they are attached on natural substrate [12],[13],[14]. It is assumed that aquaculture is carried out in relatively clean environmental conditions so that the effect of mussels, through biodeposition, is easier to notice, though it is still not quite understood. On the other hand, in natural environment, there are many mechanisms which can "neutralize" or dilute the effects of biodeposition[15].

The aim of our work was to investigate these processes in quite different circumstances. These are the estuarine environments in the vicinity of artificial vertical structures inside of one polluted port in Osaka Bay.

We have chosen the summer period for experiments when the amount of biodeposits increases because the concentration of phytoplankton and the activity of the mussels become high[16]. Also, at that time, there exist extreme environmental conditions such as high temperature, stratification of water column, water hypoxia, etc. Briefly, because of potentially important role of mussels in environmental restoration of reclaimed areas, our aim was to study consequences of filter feeding on this artificial environment under the extreme environmental conditions, mentioned above.

1.3 Study site

The study site was located in Amagasaki port, which lies in the northern, most polluted section of the Osaka Bay (Fig. 1). Port is long about 3 and wide about 1.5 km, surrounded with quaywalls and reclaimed land. Seawater exchange is only possible through 300 m wide ship entrance situated on the southwest side.

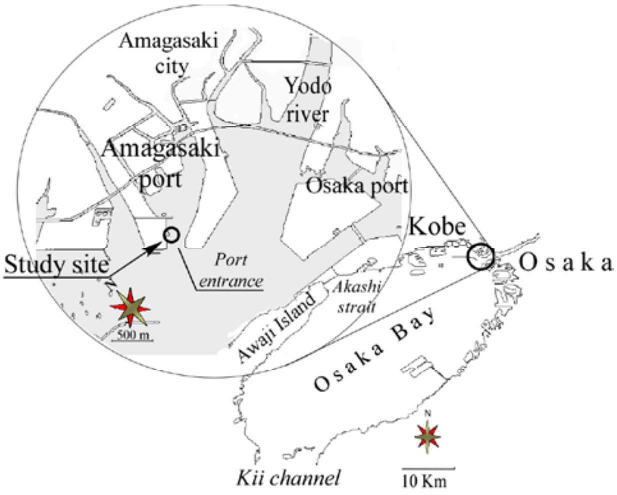

Fig. 1. Location of study site in Amagasaki port. Region of Amagasaki city is enlarged.

Along the port on the reclaimed land, there are many industrial plants, among others recycle center, sewage purification plant, Panasonic plasma factory, etc. Port is dominated by river discharges which mostly originate from Yodo, some smaller rivers and channels. These waters contain considerable amounts of nutrients, suspended solids, organics and chemical pollutants from domestic and industrial sources 17). Thus, a whole region is under strong anthropogenic influence.

Mean tidal range in Amagasaki port is 1.5 m, while the current velocities are below 10 cm·s^{-1}. In rather stagnant and shallow water (average depth is about 8 m) hypoxic events starts to appear in May, and develop most markedly from late July to mid August and then disappear in late September when stratification (density discontinuity) breaks down and vertical mixing between surface and bottom waters begins.

Tolerant to water quality and salinity variations, occurring in critical period (late July to mid August), when predation and competition are low, Mediterranean mussel *Mytilus galloprovincialis* dominates in macrofauna community of Amagasaki port (Fig. 2).

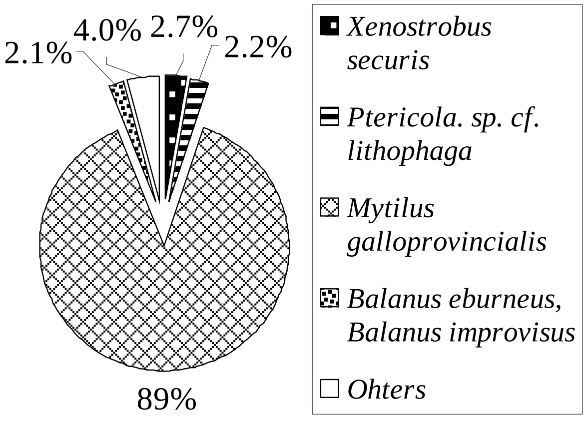

Fig. 2. Macrofauna community structure in Amagasaki port at the end of July 2007. Percentages are calculated on a basis of wet weight (kg · m^{-2})

The sediments of the Amagasaki port are characterized by their fine-grained nature, being rich in mud (>90%). Near the quays, there are also accumulated shells and hard body parts of fallen mussels and other aquatic organisms.

2. EXPERIMENT

2.1 Study design

Investigation of natural sedimentation rates and biodeposition by filter-feeder *Mytilus galloprovincialis* in Amagasaki port was done during two periods: at the end of July 2007, and at the beginning of August 2008 (actual dates were 27th and 28th of July and 9th and 10th of August). For this purpose, 66 cylinders were prepared, which in groups of six, formed 11 sediment traps. Scheme of the construction details of the traps is shown in Fig. 3.

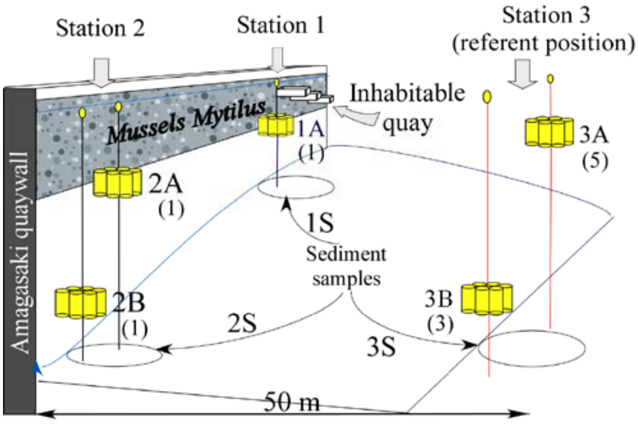

Fig. 3. Construction of the traps and their moorings (schematic). Letters A and B denote the depths of 2.5 and 7 m below the surface, respectively. In brackets are numbers of traps deployed at corresponding position.

Traps were placed on three sampling stations. Two stations (1 and 2) were next to the quaywall with attached colonies of mussels. From these stations, traps are placed at two depths, at 2.5 m below the surface (1A and 2A), just below mussel colonies, and at 7 m below surface (2B), that is 2m from the bottom. Traps from these points collected particles from natural sedimentation together with feces and pseudofeces (biodeposits). In addition, sampling station 1A was used to investigate the impact of inhabitable quaywall placed in Amagasaki port in March 2002. Details about construction and purpose of inhabitable quay wall are given elsewhere[18]. Briefly, the construction, consisting of three shelves at different levels connected to each other, is mounted on quaywall (Fig. 3). Shelves were field with spherical porous concrete and stones to provide larger habitat for sessile organisms and consequently, through their metabolism and high biomass to activate material cycle from suspended solids to sediment. Namely, inhabiting this structure, and feeding on sinking material, suspension feeders can recycle organic matter before it settles on the bottom. In that way, the consumption of free oxygen from the bottom waters due to degradation of organic matter decreases.

Other 8 traps (48 cylinders) were set on referent sampling stations (3A and 3B on Fig. 3) at 50 m distance from the wall at depths corresponding to depths of sediment traps near the quaywall. That group was control, collecting only naturally sedimenting material**.**

Both experiments are started and finished by water quality test. Parameters were measured during mid-flood tidal state at 0.1 m intervals using monitoring systems Alec Electronics AAQ1183-PT for chlorophyll a, temperature, salinity, turbidity, light and Hydrolab DS-5 for dissolved oxygen.

After 24 hours, the cylinders were retrieved from their positions. Immediately after trap recovery sampling containers are stoppered tightly with no headspace. Upper 2 cm layer of sediments were collected from three points at each sampling station by diver directly into sampling containers. Redox potential (Eh) was measured *in situ* using a commercial ORP probe with a Ag-AgCl reference cell.

All samples were transported to the laboratory under refrigeration in the dark.

2.2 Methodology

Pretreatment and analytical procedures were performed in the laboratory. Swimmers were removed from the samples by picking out recognizable zooplankton. Overlying water was carefully siphoned off; afterwards, the samples were centrifuged (20 min; 3500 rpm; ~ 20 ^{o}C). In case of need to obtain sufficient volume for analysis, particulate samples from the same sampling stations and the same depth were composited. The particulate fraction is then frozen, freeze dried, homogenized and dry mass determined as a difference weighing. Sediment samples were treated on the same way. All freeze-dry sediment samples used in our study were passed through 63 μm sieve.

A portion of dried samples was used for organic carbon and organic nitrogen determinations with Thermo Finnigan CN soil analyzer (FLASH EA 1112) after the residue had been treated with HCl solution to remove carbonates. Content of particulate organic matter (POM) in deposited material and sediments is estimated according to Martin and Knauer[19] (as POM = POC x 2.3).

Aliquots of material (~ 0.25 g) designated for metal analysis were decomposed by means of microwave assisted digestion[20] using 5.0 ml of HNO_3, 1.5 ml HF and 2.0 ml H_2O_2. The final acidic solutions were analyzed by the flame and graphite furnace atomic absorption technique (Perkin Elmer AAnalyst 800).

2.3 Quality assurance and quality control

Quality of the data set was assessed by analysis of blanks, duplicates or triplicates and certified reference materials of marine sediment: PACS-2 (from National Research Council Canada) and GBW 07316 (National Analysis Center for Iron and Steel, Beijing, China). The content of each element matched the certified values within 10%.

Blanks, standards and the different solutions used in the analysis were prepared with analytical grade reagents and Milli-Q water.

3. RESULTS AND DISCUSSION

3.1 Water quality parameters

The ranges of environmental parameters recorded at the time of experiments are presented in Fig. 4.

Salinity fluctuated from 16 psu at the surface water to 32 psu near the bottom (a1 and a2 in Fig 4), while the temperature varied between 30 and 21 ^{o}C (b1 and b2 in Fig. 4). Temperature and salinity discontinuities (abrupt change of slope), appeared between 0.5 and 4 m below the surface (see Fig. 4). As a consequence of density gradient, stratification of water column into warmer surface layer and deeper colder layers was observed during both sampling periods.

Concentration of dissolved oxygen (DO) followed a pattern similar to that of temperature and salinity (c1 and c2 in Fig. 4). Density gradient that occurred diminished vertical mixing and therefore the replenishment of bottom water with oxygen, causing hypoxic conditions (when concentration of DO falls below 2 mg·L^{-1}) in the lower layers of water column and bottom water anoxia (c1 and c2).

Concentration of DO in upper layers near the quaywall (stations 1 and 2) was around 30% lower comparing to referent site (station 3). Reason is in *Mytilus galloprovincialis* consumption of oxygen to support its metabolic needs. Mussels frequently attach to each other, so that the colonies can grow in three dimensions, not just two, allowing the number of individuals to pile up in intertidal to subtidal areas.

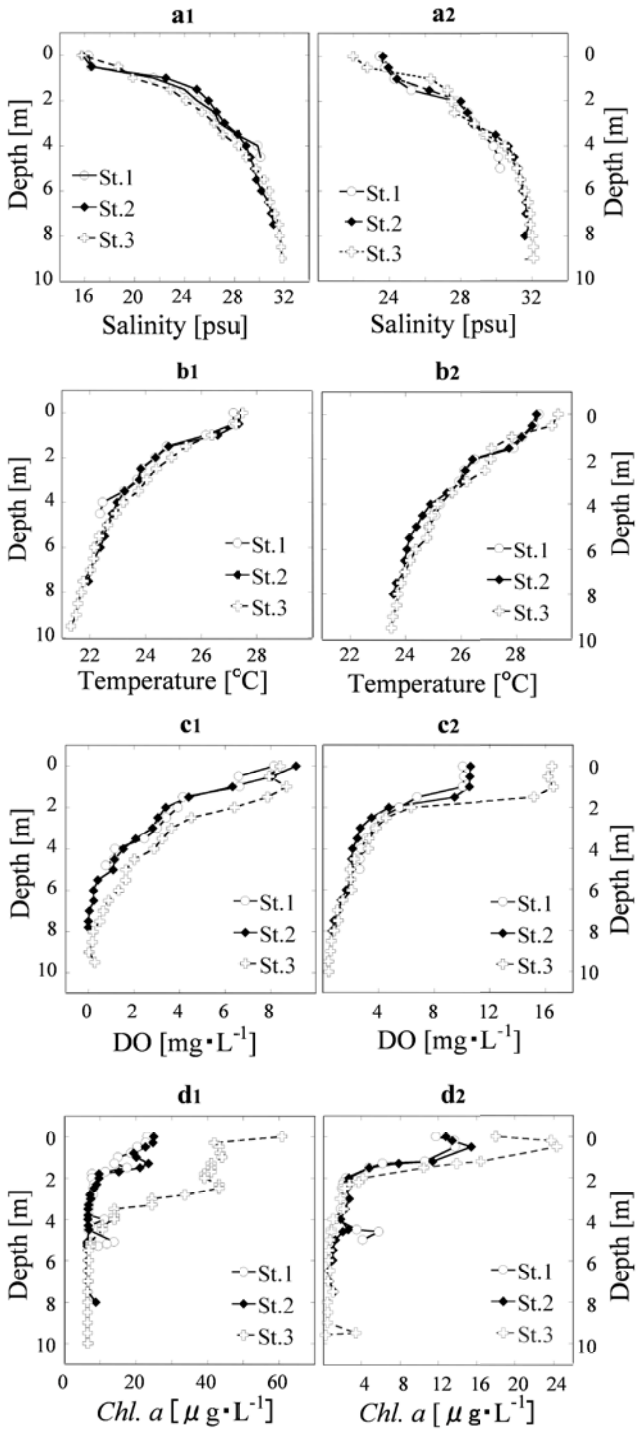

Fig. 4. Water quality parameters at different sampling stations during two analyzed periods: July 2007 (left side) and August 2008 (right side). In order to show more obviously the differences between DO and *Chl.a* concentrations near the wall and at referent station, ranges of concentrations at left and right side in Figs. c1 and c2, and Figs. d1 and d2 are not the same.

Since they are sessile organisms fixed at substrate (quaywall), with significant biomass and high activity in this time of the year, they thereby enhance oxygen depletion of the surrounding water which, because of that, becomes “visible”, that is measurable. Oxygen depletion associated with respiration of bivalve filter-feeders has also been observed in other studies 21), 22).

Chlorophyll a (*Chl. a*) values range from 60 µg·L^{-1} near the surface to 1 µg·L^{-1} in the bottom waters, and differ significantly in surface layer between sampling sites; they are about 50% less near the wall then at referent station 3 (d1 and d2 in Fig. 4). At depth of 3 to 4 m this difference disappears and values become quite similar up to the bottom in both sampling periods.

Of course, this is not because of excessive content of *Chl. a* at the sampling station 3, but most likely as a result of depletion of phytoplankton near the wall due to filter-feeding. Decrease in concentration of phytoplankton (estimated by abundance of *Chl. a*) have been reported also by other authors 23),24), 25).

Observed decrease of DO concentration near the wall, mentioned above, may be affected by lower concentration of *Chl.a.* It is very difficult to separate these two processes (lowering DO due to consumption of oxygen by mussels and lowering phytoplankton concentration) and we have not attempted to do it in our experiment. However, both processes are a consequence of filter-feeding.

We can say that decrease of concentration of DO and phytoplankton (*Chl. a*) represents two features of metabolism of the mussel. The third is the excretion leading to increase in sedimentation, what is described in more detail in the sections that follows.

3.2 Natural sedimentation and biodeposition

The mass fluxes of particulate matter (PM) accumulated in the sediment traps (expressed as dry grams per m^{2} per day) are presented in Fig. 5a.

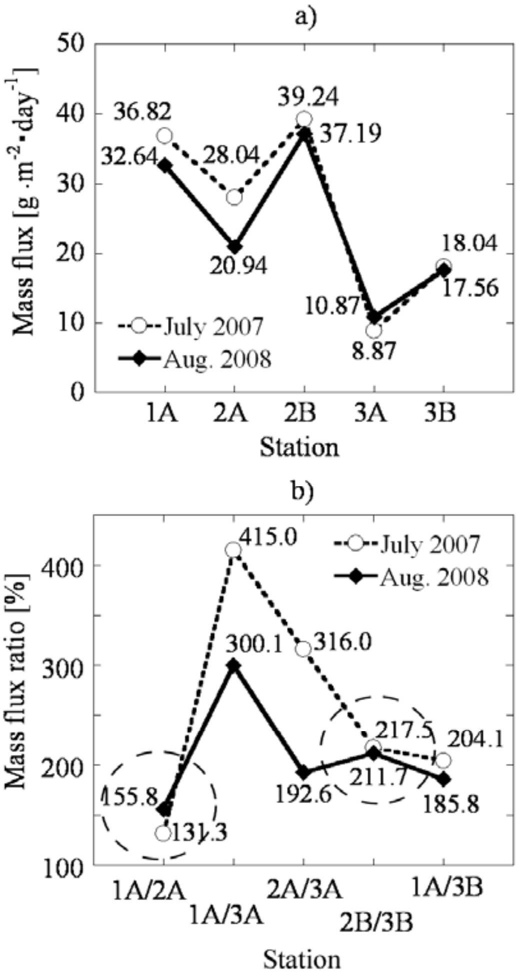

Fig. 5. Mass fluxes at different sampling stations at the time of experiments (a), and ratios of mass fluxes between different sampling stations indicated on abscissa (b).

A consistent pattern of site specific variation was observed in two consecutive years. This indicates similarity of the processes affecting downward flux of particulate matter in Amagasaki port, although the extent and degree of these processes differ considerably among stations.

The quantity of material collected near the quaywall (stations 1 and 2) was significantly higher than that collected in traps from referent position (station 3) for the both analyzed periods (Mann Whitney U-test; $p < 0.001$). Mass flux at station 2B against that at station 3B (2B/3B) was 217.5% in 2007 and 211.7% in 2008, respectively (Fig. 5b, encircled with a broken line). Therefore amounts of particles that settle in traps from position 2B, near the wall, are doubled in relation to referent traps positioned at 3B in 2007 and 2008 respectively. Having in mind that average depth in Amagasaki port is around 8 m, this material is thought to correspond to the gross sedimenting material that will deposit daily on the port floor.

Amount of deposits near inhabitable quaywall (station 1) increases effectively up to 31% in July of 2007 and up to 56 % in August of 2008 comparing to trap 2A set at the same depth near the regular quay (flux ratios corresponding to 1A/2A were 131.3% and 155.8% in 2007 and 2008, respectively, Fig. 5b, encircled with the broken line). This effect is mainly a consequence of increased biomass due to its construction and waves induced sweeping of deposits from the terrace.

In our experiment fecal palettes, recognized by their characteristic cylindrical shape, were not separated from the rest of the deposited matter. Instead, values of biodeposits (feces and pseudofeces together) were determined as difference between weight of total particulate matter collected in the traps near the quaywall (2B) and the control trap values from the same depth (3B). Deposition parameters: number of individuals, biomass, natural sedimentation and the daily biodeposition rates are presented in Table 1.

Let us remind now to results of water quality test and a fact which follows from them: as a consequence of filter-feeding, concentration of phytoplankton (expressed as *Chl. a*, Fig. 4, d1 and d2) is lower near the wall comparing to referent station. This could lead to biased values for biodeposition.

Table 1. Deposition parameters in two analyzed periods

Parameters	[units]	July 2007	August 2008
Mussel density	[ind.$^{*}\cdot$ m^{-2}]	10437	8767
Mussel biomass	[g$^{**}\cdot$ m^{-2}]	358.71	279.79
Natural sedimentation	[g$^{**}\cdot$ m$^{-2}\cdot$ day^{-1}]	18.04	17.56
Biodeposition	[g$^{**}\cdot$ m$^{-2}\cdot$ day^{-1}]	21.20	19.20

*Number of individuals, ** Refer to dry weight

Providing these facts, we can say that both the natural sedimentation and biodeposition are of the same order with tendency of the biodeposition to be even higher than natural sedimentation. As a consequence, the mussels, attached to their supporting structures, double the rate at which suspended matter was being added to the bottom sediment.

3.3 Accumulation rates and organic enrichment

Values of particulate organic carbon (POC), particulate nitrogen (PN) in mg·g^{-1}, POC/PN ratio and percentage of particulate organic matter (POM), in sediment traps and sediments are listed in Table 2.

In both sampling years concentrations of POC and PN were higher in traps and sediments near the wall (1A, 2A, 2B, 1S and 2S) compared to referent site (3A, 3B and 3S). We can say that both POC and PN behave in the same manner. Their significant correlation of $r^2 = 0.93$ indicates that PN is present mainly in organically bound form.

The POC/PN ratios, or shorter C/N, varied between 6 and 7 for collected deposits and between 6 and 10 for the bottom sediment (Table 2). According to Strickland [26] and Parsons *et al.*, [27], C/N ratio values

Table 2. Composition of settling material and sediments collected at different sampling stations during analyzed periods.

Station	POC [mg • g^{-1}]		PN [mg • g^{-1}]		C/N ratio		POM [%]	
	2007	2008	2007	2008	2007	2008	2007	2008
1A	111.1	149.5	16.6	25.8	6.7	5.8	25.6	34.4
2A	118.5	153.3	18.1	26.6	6.6	5.8	27.3	35.3
2B	102.5	115.6	15.5	18.7	6.6	6.2	23.6	26.6
3A	86.6	114.0	12.9	18.7	6.7	6.1	19.9	26.2
3B	59.3	85.9	8.3	13.2	7.2	6.5	13.6	19.7
1S*	129.4	108.6	18.6	17.7	7.0	6.1	29.8	25.0
2S	68.9	64.0	10.1	9.2	6.8	7.0	15.8	14.7
3S	24.6	26.0	2.5	2.8	9.8	9.4	5.7	6.0

*1S, 2S and 3S are sediments below stations 1-3, respectively.

between 4 and 8 are characteristic for productive coastal areas indicating phytoplankton, fecal pellets and other easily degraded material, whereas C/N ratio of 10 or greater characterizes detritus and partly mineralized organic matter. We have not found significant differences among stations in two analyzed periods. Results indicated that investigated locations were influenced by the same composition of depositing matter, but also that the material in the traps, placed near the bottom, was not diluted to any greater extent by resuspended bottom sediments.

Content of particulate organic matter (POM) in deposited material, was in the range between 13.6 % (3B) and 35.3% (2A) suggesting that both naturally sedimented and biodeposited particles contained mostly inorganic constituents, whose amount tend to increase with depth. Dilution with mineral fractions can explain the drop of organic content in lower traps as well as in sediments.

Sediment samples collected at the referent site (3S) showed lower organic matter content comparing to those collected at stations near the wall (1S and 2S , Table 2) especially near inhabitable quaywall, suggesting that organic matter, accumulated under the walls, causes local organic enrichment. Due to low current velocities in Amagasaki port, slow tidal flushing (tidal range was less than 1 m at the time of experiments) and waves directed landwards, organic material couldn't be dispersed. Further, it couldn't be utilized by benthic organisms because most of them escaped or died due to anoxic conditions at the bottom. Because of this, the fate of organic matter depends mainly on microbial degradation, which is tardy in anoxic conditions existing at bottom. In collected sediment samples Eh values ranged from -150 to -250 mV indicating strongly reducing conditions.

Fluxes of POC and PN in both analyzed periods followed deposition rates and were about three times higher near the wall comparing to reference position, as seen from Fig. 6a and 6b. This increase is bigger than that observed for biodeposition (217% and 211%). The important fact is that relative ratio of POC fluxes at stations 1A and 2A (1A/2A in Fig. 6b) agrees well with that for the biodeposition rates (1A/2A in Fig. 5b) and amounts 123.1% and 151.9% in 2007 and 2008, respectively. Both stations were near the wall and at the same depth (see Fig. 3), indicating that mussels considerably increase POC and PN vertical flux, *i.e.* precipitation on the bottom of the port.

Noted increase in relation to biodeposition can be explained by the fact that mussels selectively remove large amount of very fine particles from a natural pool, pack them and send to bottom as feces and pseudofeces [28]. According to Haven and Morales-Alamo[29] size of particles in feces and pseudofeces of oysters ranges from about 0.8 to 13 µm of which at least 80% are less than 2 µm and approximately 95% are less than 3 µm. *Mytilus edulis*, for example, retains particles 1–2 µm with efficiency of 90% [30]. These small particles are most enriched with organic matter because of their large specific surface. On the other hand, without "help" of mussels these particles would not easily settle by themselves. Settling velocities of particles having 1 μm diameter range between 5.5 x 10^{-5} cm·s^{-1} and 7.9 x 10^{-5} cm·s^{-1} (measured at 15 °C). For comparison, settling velocities of 63 μm particles are greater for about four thousand times[31)]. This is the most important difference between biodeposition, which is active process, consequence of filter-feeding and passive natural sedimentation, which mostly depends on a size and density of particles.

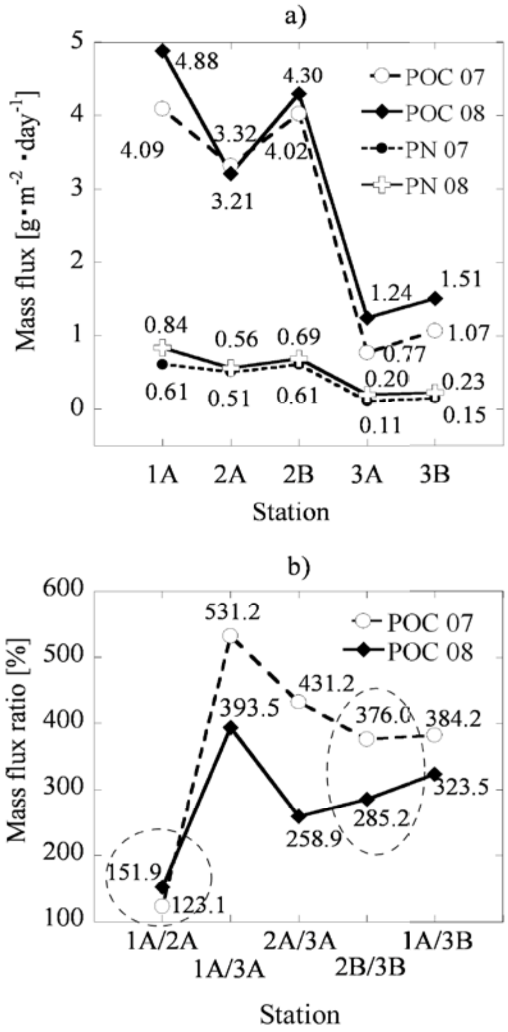

Fig. 6. Mass fluxes at different sample stations in two consecutive years (a) and ratios of POC mass fluxes between different sampling stations indicated on abscissa (b)

Fluxes of POC and PN are in good agreement with a concentration of these components in sediments. Results of Spearman's test (r_s = 0.77, $p < 0.05$ and r_s = 0.58, $p < 0.05$ for 2007 and 2008 respectively) implies that organic enrichment of the sediments is significantly influenced by the degree of sedimentation at the time of our experiments.

3.4 Metals in settling particles and sediments

Concentrations of five metals analyzed in particulate matter and bottom sediments range in intervals characteristic for populated estuarine environments. However, the sediment and suspended matter are greatly enriched by Zn (second and third columns in Table 3) compared to other coastal areas of Japan[32)].

The fluxes of metals varied quite considerably among sampling stations during both studied periods

Table 3. Concentration of metals (μg·g^{-1} dry weight) in settling particulate matter and sediments at different sampling stations at the time of experiments

Station	Zn		Cu		Pb		Cd		Cr	
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
1A	629	757	44.3	68.8	45.8	58.1	1.08	1.15	44.7	44.2
2A	480	553	63.8	75.9	39.6	64.0	0.64	0.95	41.0	47.5
2B	496	496	86.0	81.5	47.5	57.8	1.06	0.93	57.1	54.1
3A	466	420	49.7	46.8	51.9	53.0	0.42	0.81	47.0	39.9
3B	441	412	81.1	77.6	61.3	56.9	1.55	0.82	65.1	54.5
1S*	519	958	68.6	80.6	25.4	63.6	1.19	1.40	47.4	73.6
2S	559	509	101.2	88.9	57.2	66.7	0.68	1.06	80.4	73.6
3S	618	454	94.0	100.2	33.4	91.3	0.39	1.60	86.0	84.8

*1S, 2S and 3S are sediments below stations 1-3, respectively

(Fig. 7), but their pattern points out generally an increase of metal deposition near the wall.

Increase of metal fluxes, expressed by ratios of their values at stations 2B and 3B ranged effectively from 48 % to 155 % depending on metal and sampling year.

Thus increased deposition, as a consequence of filter feeding, changed downward fluxes of all investigated metals.

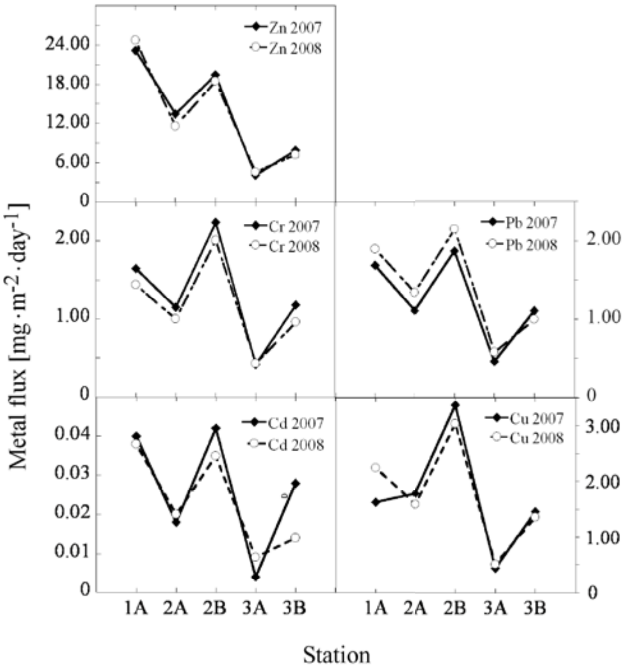

Fig. 7. Metal fluxes at different sampling stations during analyzed periods.

However, contrary to POC and PN, whose concentrations in surface sediments and trapped material reflect a clear gradient, which decreases from the wall to the referent position, metal concentrations do not reveal similar effect (Table 3). It seems that concentration of metals in sediment and deposit does not depend from location, *i.e.* distance from the wall, and consequently, from biodeposition.

In order to clarify the effect of mussels on the content and distribution of metals and organic matter in deposited material, factor analysis was used.

3.5 Factor analysis (FA)

The scope of the FA is to group chemical species and processes according to the similarities of variations and to assign physical and chemical significance to these groups.

Deposited matter (Dep.) expressed as mass flux, concentrations of five metals and POC, measured in material collected at sampling stations near the quaywall and at referent position were subjected separately to FA with Varimax rotation. The analysis was performed using the SPSS statistics package.

According to scree test [33], four factors (F1–F4) were selected for the set of data concerning samples taken near the wall and three factors (F1-F3) for set of data concerning samples collected at referent position. They account for 91.57 % and 92.31 % of the total percentage of explained variance, respectively (Table 4).

In analyzed data set for samples taken near the wall, the first factor accounts for 34.87 % of the total variance and includes Dep., Zn and Cd with high loadings (> 0.70), and POC with moderate loading (0.54).

POC is significantly correlated with all metals except with Cr (Table 5a). It is included with similar

Table 4. Rotated component matrix of data obtained for two different sampling locations.

	Stations near the wall				Referent station		
	F1	F2	F3	F4	F1	F2	F3
Dep.	0.85	-0.06	0.30	-0.15	0.93	0.24	0.13
Zn	0.80	-0.16	0.06	0.29	0.01	0.13	0.98
Cu	0.11	0.20	0.96	0.09	0.78	0.55	0.06
Pb	-0.06	0.92	0.26	0.22	0.94	0.10	-0.22
Cd	0.87	0.46	-0.02	0.08	0.68	0.45	0.33
Cr	0.08	0.17	0.07	0.95	0.58	0.75	0.19
POC	0.54	0.55	0.60	-0.03	-0.16	-0.97	-0.10
Variance %	34.87	20.83	20.55	15.31	45.34	29.95	17.02
Cumulative Variance %	34.87	55.70	76.25	91.57	45.34	75.23	92.31

Extraction method: principal component analysis.

Table 5. Coefficients of correlation between accumulated deposits (Dep.), POC concentrations and trace metal concentrations in sediment trap samples

(a) Stations near the wall n = 18

	Zn	Cu	Pb	Cd	Cr	POC
Dep	0.734^{**}	0.105	-0.115	0.717^{**}	0.098	0.438
Zn		0.306	0.226	0.771^{**}	0.431	0.528^{*}
Cu			0.494^{*}	0.156	0.196	0.757^{**}
Pb				0.355	0.280	0.629^{**}
Cd					0.344	0.643^{**}
Cr						0.266

(b) Referent station n = 12

	Zn	Cu	Pb	Cd	Cr	POC
Dep	-0.133	0.921^{**}	0.844^{**}	0.854^{**}	0.778^{**}	-0.438
Zn		-0.063	-0.200	0.161	0.280	-0.417
Cu			0.821^{**}	0.701^{*}	0.888^{**}	-0.566
Pb				0.692^{*}	0.596^{*}	-0.214
Cd					0.725^{**}	-0.543
Cr						-0.818^{**}

* $p < 0.05$, ** $p < 0.01$

loading also in second factor (F2) together with Pb, and in third factor (F3) together with Cu.

First three factors explain 76.25 % of variance, indicating that POC may be the most important driver which determines the content of metals in deposited matter near the wall.

Cr is included alone, uncorrelated with other parameters, in forth factor (F4).

For samples from the referent station, first factor (F1) explains 45.34 % of the variance. It includes Dep. and all analyzed metals, except Zn, with high (Pb, Cu, Cd) and moderate (Cr) loadings. This fact and their significant mutual correlation (Table 5b) indicate that their concentration is affected by the same factor.

Cr, Cu and Cd are included also in the second factor, which explains 29.95 % of the variance (Table 4). With this factor POC is negatively correlated with high loadings (-0.97) which may suggest that association of mineral particles with phytoplankton and other organic matter lowers concentration levels of deposited metals. Same effect has been observed also in other studies[34),35),36)]

Explanation for such behavior may be as follow. Since the natural sedimentation is limited on free fall of particles, in sediment trap at referent position will find firstly the most heavy particles mainly of inorganic origin and flocculated colloidal aggregates. Because density of these particles is rather higher than that of water, they rapidly precipitate carrying with themselves sorbed metals and, to a less extent, due to smaller specific surface, organic matter. Metal-organic interactions, characteristic for particles accumulated near the wall, here are less expressed. It appears that the metals are diluted by organic fraction. However, near the wall, as mentioned in previous section, due to filter-feeding, mussels select firstly the smallest particles having largest specific surface, pack them and send to bottom as feces and pseudofeces. These particles carry the most organic substance that affects on metal concentrations in deposited material. The good example is Zn. The fact that it is included alone and uncorrelated in the last factor, contrary to previous case (near the wall), indicates that it is primarily associated with particles mostly reprocessed through filter feeding. Because these particles may be weakly motile and because they have density similar to that of water[37)], Zn remains to float at water surface or precipitates much slower.

Above explanation, however, doesn’t mean that increasing of metal content in small particles arises only via organic matter, but simply indicates different partition processes for trace metals and the carrier phase. In other words, POC is not the most important driver which determines the content of metals in particles but in those fine particles processed by mussels. Importance of mussels is in selection of very fine particles and in this way the influence on metal content.

In the process of natural sedimentation, metals are sorbed on particles which settle towards a bottom mechanically, more or less rapidly depending on their weight.

Positive effect of mass flux on metal concentrations in sediment was noted only for Zn in 2009 ($r_s = 0.56$, $p < 0.05$). Reason is the much lower metal concentrations and higher sensitivity to a number of complex processes than that of organic matter

4. CONCLUSION

Decrease of concentrations of DO and phytoplankton near the quaywalls represents two of three consequences of filter feeding observed in our study. The third is the increase in sedimentation. At mussel densities representative of Amagasaki port, excretion of feces and pseudofeces roughly doubled the rate of sediment deposition on the bottom. The production of fecal material is reflected even more on the POC and PN sedimentation rates. Consequently, this leads to local organic enrichment in a low energy environment of Amagasaki port.

Increased deposition changed fluxes of all investigated metals. However, the difference in sedimentation rates of metals between investigated sites was not as pronounced as in the case of POC and PN (organic matter).

Results of FA indicate that mussels, through selection of small particles, affects the redistribution of metals and their concentration in deposited matter, first of all the redistribution and concentration of Zn and Cd. Results also support prevalent effect in the case of organic matter.

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Literature Cited

1) Matsumoto, E.: Pollution history of coastal marine recorded in its sediments, Geological News, No. 293, pp. 27–33, 1979 (in Japanese).

2) Gohda, S., and Yamazaki, H.: Heavy metal pollution in Osaka Bay sediment, Kinki University General Education Department Bulletin, No. 19, pp. 29–36, 1982.

3) Joh, H.: Oxygen-deficient water in Osaka Bay, Bulletin of Coastal Oceanography., Vol. 26, pp. 87–98, 1989 (in Japanese).

4) Jørgensen, C.B.: Bivalve filter feeding revisited, Marine Ecology Progress Series, Vol. 142, pp. 287 – 302, 1996.

5) Griffiths, C.L., and Griffiths, R.J.: Bivalvia. In: Pandian TJ, Vernberg FJ (eds.) Animal energetics, Academic Press, New York, pp. 1–88, 1987.

6) Haven, D.S. and Morales-Alamo, R.: Occurrence and transport of fecal pellets in suspension in a tidal estuary, Sedimentary Geology, Vol. 2, pp. 125–140, 1968.

7) Smaal, A.C., Verhagen, J.H.G., Coosen, J., Haas, H.A.: Interaction between seston quantity and quality and benthic suspension feeders in the Osterschelde estuary, The Netherlands Ophelia, Vol.

26, pp. 385–399, 1986.

8) Biggs, R.B. and Howell, B.A.: The estuary as a sediment trap: alternate approaches to estimating its filtering efficiency, In: V.S. Kennedy, Editor, The Estuary as a Filter, Academic Press, Orlando pp. 10 –129, 1984.

9) Hatcher, A., Grant, J., and Schofield, B.: The effects of suspended mussel culture (*Mytilus spp*.) on sedimentation, benthic respiration, and sediment nutrient dynamics in a coastal bay, Marine Ecology Progress Series, Vol. 115, pp. 219–235, 1994.

10) Grant, J., Hatcher, A., Scott, D.B., Pocklington, P., Schafer, C.T., and Winters, G.V.: A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities, Estuaries, Vol. 18, No. IA, pp. 124 –144, March 1995.

11) Otero, X.L., Vidal, P., Calvo de Anta R., and Macías F.: Trace elements in biodeposits and sediments from mussel culture in the Ría de Arousa (Galicia, NW Spain), Environmental Pollution, Vol. 136, pp. 119 – 134, 2005.

12) Kautsky, N., and Evans S.: Role of biodeposition by *Mytitus edulis* in the circulation of matter and nutrients in a Baltic coastal ecosystem, Marine Ecology Progress Series, Vol. 38, pp. 20 – 212, 1987.

13) Jaramillo, E., Bertrán C., and Bravo A.: Mussel biodeposition in an estuary in southern Chile, Marine Ecology Progress Series, Vol. 82, pp. 85 – 94, 1992.

14) Smaal A., Stralen M.V., Schuiling E.: The interaction between shellfish culture and ecosystem processes, Canadian Journal of Fisheries and Aquatic Sciences, Vol. 58, pp. 991 – 1002, 2001.

15) Kurihara, Y.: Ecology for environmental conservation of coastal area and harbors, Civil Engineering, Vol. 83, pp. 26 – 28, 1998.

16) Tsuchiya, M.: Biodeposit production by the mussel *Mytilus edulis* on rocky shores, J. exp. mar. Biol. Ecol., Vol. 47, pp. 203 – 222, 1980.

17) Nakanishi, H.: Comparison between Tokyo Bay and the Steo Inland Sea. In Ogura, N (ed), Tokyo Bay – Environmental Changes. Koseisha Koseikaku, Tokyo, pp. 157 – 162, 1993.

18) Miyoshi, J., Kozuki, Y., Kurata, K., Kitano, M., Murakami, H., Mizuguchi, H.: Development of an Inhabitable Quaywall for Improvement of Material Cycle, Proceedings of The Thirteenth International Offshore and Polar Engineering Conference Honolulu, Hawaii, USA, pp. 338 – 344, 2003.

19) Martin, J.H., and Knauer, G.A.: The elemental composition of plankton. Geochimica et Cosmochimica Acta , Vol. 37, pp. 1639 – 1653, 1973.

20) Wu, S., Zhao, Y., Feng, X., and Wittmeier, A.: J. Anal. At. Spectrom., Vol. 11, pp. 287 – 296, 1996.

21) Jorgensen, B.B.: Seasonal oxygen depletion in the bottom waters of a Danish fjord and its effect on the benthic community, Oikos, Vol. 34, pp. 68 – 76, 1980.

22) Effler, S.W., and Siegfried, C.: Zebra mussel *(Dreissena polymorpha)* populations in the Seneca River, New York: impact on oxygen resources. Environmental Science & Technology, Vol. 28, pp. 2216 – 2221, 1994.

23) Asmus, R.M., and Asmus, H.: Mussel beds: limiting or promoting phytoplankton? J. Exp. Mar. Biol. Ecol., Vol. 148, pp. 215 – 232, 1991.

24) Gerritsen, J., Holland, A.F., and Irvine, D.E.: Suspension-feeding bivalves and the fate of primary production: an estuarine model applied to

Chesapeake Bay, Estuaries, Vol. 17, pp. 403 – 416, 1994.

25) Kamermans, P.: Similarity in food source and timing of feeding in deposit and suspension-feeding bivalves, Marine Ecology Progress Series, Vol. 104, pp. 63 – 75, 1994.

26) Strickland, J.D.H.: Measuring the production of marine phytoplankton. Fish. Res. Bd Can. Bull., No. 122, pp. 1– 172, 1960.

27) Parsons, T.R., Takahashi, M., and Hargrave, B.: Biological oceanographic processes, Oxford, Pergamon Press, p. 332, 1977.

28) Navarro, E., Iglesias, J.I.P., Perez-Camacho, A., and Labarta, U.: The effect of diets of phytoplankton and suspended bottom material on feeding and absorption of raft mussels (*Mytilus galloprovincialis*), J. Exp. Mar. Biol. Ecol., Vol. 198, pp. 175–189, 1996

29) Haven, S.D., and Morales-Alamo R.: Aspects of biodeposition by oysters and other invertebrate filter feeders, American Society of Limnology and Oceanography, Vol. 11, Issue 4, pp. 487 – 498, 1966.

30) Mohlenberg, F., and Riisgard, H. U.: Filtration rate, using a new indirect technique, in thirteen species of suspension-feeding bivalves, Marine Biology, Vol. 54, pp. 143-148, 1979.

31) Cheng, N.S.: Simplified Settling Velocity Formula for Sediment Particle, Journal of Hydraulic Engineering, Vol. 123, No. 2, pp. 149 –152, 1997.

32) Hoshika, A., and Shiozawa T.: Heavy Metals and Accumulation rates of Sediments in Osaka Bay, the Seto Inland Sea, Japan, Journal of the Oceanographical Society of Japan, Vol. 41, pp. 39 – 52, 1986.

33) Cattell, R.B.: The scree test for the number of factors. Multivariate Behavioral Research, No.1, pp. 245 – 276, 1966.

34) Windom, H.L., Smith Jr. R.G., and Rawlinson, C.: Particulate trace metal composition and flux across the southeastern U.S. continental shelf, Marine Chemistry, Vol. 27, pp. 283 – 297, 1989.

35) Balls, P.W.: Distribution and composition of suspended particulate material in the Clyde estuary and associated sea lochs, Estuarine, Coastal and Shelf Science, Vol. 30, pp. 475 – 487, 1990.

36) Zwolsman, J.G., and Gijsbertus, T.M.: Geochemistry of major elements and trace metals in suspended matter of the Scheldt estuary, southwest Netherlands, Marine Chemistry, Vol. 66, Issues 1 – 2, pp. 91 – 111, 1999.

37) Turner, A., and Millward, G.E.: Suspended particles: Their role in estuarine biogeochemical cycles Estuarine, Coastal and Shelf Science, Vol. 55, No. 6, pp. 857 – 883, 2002.

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Depositional role of mussels (*Mytilus galloprovincialis*) attached to quaywalls in Amagasaki port, Osaka Bay

尼崎港内の懸濁物質の沈降特性に及ぼすムラサキイガイの影響

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要旨：尼崎港内の直立護岸周辺で，有機物や重金属の環境動態に及ぼすムラサキイガイの影響を明らかにすることを目的に研究を行った．護岸壁面にはムラサキイガイが多量に付着し，その活発な摂餌活動によって，直立護岸前では植物プランクトン量は少なく，溶存酸素は低くなっていた．また，ムラサキイガイの糞や偽糞の排出によって，沈降物量は直立護岸から50mの港湾中央部と比べて2倍大きく，これを懸濁態有機炭素および窒素に換算すると港湾中央部と比べて3倍の値を示した．また，重金属の中でも特にZnの沈降過程にはムラサキイガイの摂餌作用が大きな影響を及ぼし，CdとPbはより粒径の細かい懸濁物の挙動に影響を受けていることが示唆された．

キーワード：ムラサキイガイ，生物学的堆積作用，直立護岸，懸濁態有機物，重金属