The effect of sediment structure on the diversity of benthic marine animals in Japan

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Summary: Ecological data were obtained from a wide area of Japan, including the industrialized port of Nagoya. Using generalized linear models for family presence/absence and generalized linear mixed models for the number of families by class, we found that the key explanatory variables associated with changes in biodiversity were water content, TOC, and the proportion of silt/clay. We consistently found that water content was the best predictor of species (family) richness for a range of taxonomic groups.

Aims

The aim of this study was to find the ecological evidence of effects of sediment quality and structure on the diversity of benthic animals in marine areas.

Background: Marine sediments that have high contaminant loads have already been known to contain toxicants to marine animals (sediment quality), which are present in sediment particles and pore waters. Sediment structure, i.e. the hardness of sediment relates also to the activity of benthic animals (Sassa and Watabe, 2008). Although sediment quality and structures are independent of each other (**Figure 1**), they have correlations. The relationships between sediment quality and sediment structure make it difficult to find evidence of sediment toxicity to benthic animals in the natural environments.

Focus: This study focused on finding the statistical evidence of effects of sediment quality and structure on benthic animals, and on discussing how can we assess the quality of marine sediment in natural environment.

Sediment structures: Water content is an indicator of sediment structure. It is defined as the ratio of water mass (m_W) to particle mass (m_P), which are easy to measure as the following:

$$\text{Water content (\%)} = 100 \times \frac{m_W}{m_P} = 100 \times \frac{\rho_W}{\rho_P} \times e$$

Water content is a function of the weights per unit volume in water (ρ_W) and particles (ρ_P), and sediment porosity (e).

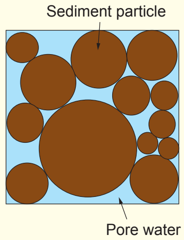

Figure 1. Schematic of sediment structure, consisting of sediment particles and pore water. Sediment quality characteristics of sediment particle and pore waters are independent of sediment structure.

Materials and Methods

Data

Data sets: Data sets include data from all coastal areas of Japan, obtained between July and September, 2002, by the Ministry of Land, Infrastructure, and Transport (MLIT), and from Nagoya Port, obtained in August, 2008, by the regional bureau of MLIT and PARI. The numbers of data in whole Japan area and the Nagoya Port are 66 and 22, respectively (**Figure 2**).

Sampling methods for benthic animals and sediments: Samplings were performed using an Ekman-Birge bottom sampler (0.0675 m^2) and the Smith-McIntyre bottom sampler (0.1452 or 0.4840 m^2) in depths from 0.5 m to 35.7 m, with no replication. The number of samples obtained in a sampling area 0.4840 m^2 was 1. (We do not know the reason why the sample was obtained by different area.)

Sediment data: Sediment temperature, TOC, grain size (% <75 μm defined as silt+clay), water content, and heavy metals.

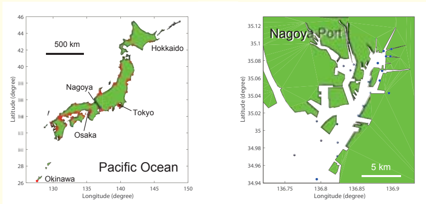

Figure 2. Maps of Japan and the Nagoya Port. Red and blue circles mean the sampling sites of Japan and the Nagoya Port investigations.

Statistical models

Model 1: The number of present families in classes (Polychaeta, Malacostraca, Bivalvia, and Gastropoda) at each site were analysed using the generalised linear mixed model (GLMM), with explanatory variables and a Poisson error distribution with log function (**Figure 3a**). The analyses were performed by R using the glmmML function.

Model 2: The presence or absence of families was analysed using the generalised linear model (GLM), with explanatory variables and a binomial error distribution with logistic function (**Figure 3b**). The analyses were performed by R using the glm function.

Commons in Models 1 and 2: Models for all combinations in explanatory variables, which were Nagoya effects (Nagoya), latitude (Lat), water depth (Depth), sediment temperature (S.temp), sampling area (Sampling), and sediment characteristics were analysed. Sediment characteristics were chosen from TOC, Silt+Clay (Silt and Clay), or WC (Water content). Heavy metals were not included in these models. The data obtained by 0.4840 m^2 in sampling area as considered as random effects in Model 1 and excluded from Model 2 to avoid the bias. Models that had a high variance inflation factor (VIF), greater than 2.0, were excluded from candidate models. VIFs were calculated by using the vif function in the 'car' package.

Explanatory variables: Sampling area was transformed by $\log_e$(sampling area/0.1452 m^2)). TOC and WC were log-transformed from raw data. See relationships between variables (**Figure 4**). Variables except sampling area were standardized for analyses.

Model selection: The models of smallest Akaike Information Criteria (AIC) in candidate models were chosen as the best models.

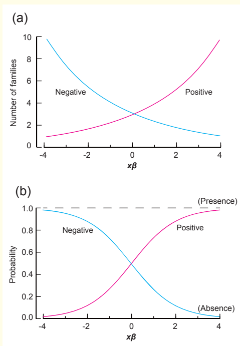

Figure 3. (a) The generalised linear mixed model (GLMM) for the number of present families of class at each site and (b) generalised linear model (GLM) for the presence or absence of families.

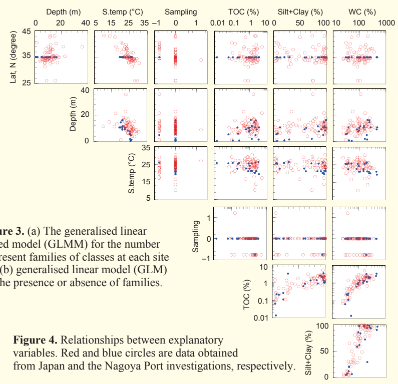

Figure 4. Relationships between explanatory variables. Red and blue circles are data obtained from Japan and the Nagoya Port investigations, respectively.

Results and Discussion

Sediment characteristics: Models for the number of families present that included WC were chosen as the best model in all classes (**Table 1**). In the analyses for presence or absence in families, the chosen 37 models (families) in all (59 families) included the variables of sediment characteristics (**Table 2**). The effects of sediment characteristics in the most of models (31/37) were negative. The number of models that included TOC and Silt+Clay were 3 and 11, respectively. Models that included WC (23 models) were in the majority, although WC had high correlations with TOC and Silt+Clay (**Figure 4**). These results mean that sediment characteristics are important for presence or absence of the most families and species diversity in benthic animals, and that water content would be the representative characteristic of sediment for species diversity. We suggest that the effects of water content (sediment structure) on the benthic animals in marine areas may make it difficult to find the effects of sediment quality due to masking.

Table 1. The best models for the number of present families of classes (Polychaeta, Malacostraca, Bivalvia, and Gastropoda).

Class	Number of families	Intercept	Nagoya	Lat	Depth	S.temp	Sampling	TOC	SiltClay	WC
Polychaeta	38	1.84	-0.59			-0.19				-0.33
Malacostraca	41	0.05								-0.65
Bivalvia	23	0.49		0.15						-0.34
Gastropoda	19	-0.83		0.33						-0.24

Sediment characteristics (TOC, SiltClay, WC)

Latitude and sediment temperature: Positive effects of latitude and negative effects of sediment temperature on the number of families were found in Polychaeta, Bivalvia, and Gastropoda (**Table 1**). The positive effects of latitude and negative effects of sediment temperature on the number of families in the classes mean that the species diversity is higher in the northern or colder area of Japan. However, some families have the opposite (positive) effects of sediment temperature in Polychaeta (**Table 2**).

Depth: Water depth was related to the presence in 10 families positively and 1 family negatively (**Table 2**) but not to the number of families in all classes (**Table 1**).

Sampling area: Sampling area is a parameter of sampling effort, which strongly relates the possibility that a family can be found. The theory of probability shows that sampling area has to have positive effects. However, we can see negative effects in some families (**Table 2**). We have to discuss the causes in a future study.

Table 2. The best models for the presence or absence in families.

Class	Order	Family	Number of present sites	Intercept	Nagoya	Lat	Depth	S.temp	Sampling	TOC	SiltClay	WC
Polychaeta	Eunicida	Dorvilleidae	5	-3.94					-2.75		-0.92	
		Eunicidae	4	-5.21								-2.52
		Lumbrineridae	51	0.53					1.15			
	Phyllodocida	Glyceridae	45	0.29					1.47			-0.77
		Goniadidae	25	-1.08				-0.49				-0.96
		Hesionidae	16	-1.68				-0.46			0.62	
		Nephtyidae	23	-1.12			0.48				-0.65	
		Nereididae	16	-2.08	1.57							
		Phyllodocidae	10	-3.08				-1.09	-2.27			-0.75
		Pilargidae	43	-0.33	1.14			-0.35				
		Polynoidae	10	-2.57	1.22							-0.48
		Sigalionidae	15	-1.17	-18.24			0.78	1.99			
	Sabellida	Oweniidae	6	-5.13		1.09						-2.54
		Sabellidae	17	-2.74	1.85		0.49		-1.93			-1.34
	Spionida	Chaetopteridae	9	-1.98			0.73		24.25			
		Magelonidae	35	-0.40								
		Spionidae	62	0.89	0.91		0.84					-1.00
	Terebellida	Ampharetidae	6	-3.85		0.79	0.97					-1.47
		Cirratulidae	42	-0.23				-0.41	-1.14			-0.39
		Flabelligeridae	5	-4.88				-1.25				-2.31
		Pectinariidae	15	-1.89							-1.01	
		Sternaspidae	15	-1.65				0.51				
		Terebellidae	17	-1.23	-1.30						-0.52	
		Trichobranchidae	13	-1.35	-18.22							
		Capitellidae	38	-0.27								-0.52
		Cossuridae	5	-6.36			1.22				4.17	
		Maldanidae	29	-0.47	-1.46			-0.87				-1.06
		Orbiniidae	6	-2.79	-18.50				24.04			-1.57
		Paraonidae	4	-2.69	-16.87							
Malacostraca	Amphipoda	Ampeliscidae	14	-2.41			0.55					-1.70
		Aoridae	6	-26.89	23.97							-3.95
		Caprellidae	5	-4.13	2.52							
		Corophiidae	6	-3.00								-0.99
		Ischyroceridae	4	-3.30								-0.78
		Melitidae	7	-3.78	2.56		0.67					
		Oedicerotidae	4	-3.75			1.07					-0.98
		Photidae	3	-4.03	-17.58						-1.55	
	Decapoda	Alpheidae	11	-1.68					22.05			
		Macrophthalmidae	4	-9.37				2.21			7.01	
		Penaeidae	4	-4.61			0.90	2.23			-1.10	
		Pinnotheridae	4	-4.13		1.52						
		Varunidae	4	-2.53	-18.49				24.03			0.95
	Stomatopoda	Squillidae	5	-3.97		-2.18						
Bivalvia	Arcoida	Arcidae	4	-21.57	19.96							
	Anomalodesmata	Laternulidae	4	-4.13						-1.43		
	Lucinoida	Lucinidae	4	-4.13	2.18							
		Thyasiridae	4	-4.60		1.85						
	Mytiloida	Mytilidae	13	-1.88						-0.63		
	Solemyoida	Solemyidae	4	-3.14	-18.33				23.91		-1.45	
	Veneroida	Cardiidae	7	-2.49					22.43			-0.83
		Kelliellidae	8	-2.80					-2.12			
		Mactridae	25	-1.39	1.30							-0.65
		Tellinidae	57	0.64								
		Veneridae	17	-1.47								-0.42
Gastropoda	Cephalaspidea	Philinidae	12	-1.71	-1.73	0.64	-0.62					
	Littorinimorpha	Iravadiidae	5	-21.57	20.23							
		Rissoidae	4	-6.73		1.82			-3.74	1.19		
	Neogastropoda	Nassariidae	7	-2.63							0.74	
		Pyramidellidae	7	-3.00	1.39							

Sediment characteristics (TOC, SiltClay, WC)

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