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Physico-chemical and macrobenthic characteristics of a salt marsh created in the aftermath of the Great East Japan Earthquake

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Abstract — In September 2012, we conducted a detailed survey of the physico-chemical and macrobenthic characteristics of a salt marsh created in the aftermath of the 2011 Great East Japan Earthquake in the Moune area of Kesen-numa City in Miyagi Prefecture. This study examined the newly created environments, with a special focus on their ecological development since the disaster. In the 18 months following the disaster, over 53 species of macrobenthos colonized the new aquatic environment. The majority of the dominant species were opportunistic. We detected marsh areas with high and low combinations of animal diversity and biomass. Animal distributions were strongly related to the current velocity of water flowing through a drainage pipe connecting the salt marsh with a river flowing alongside. High current velocities improved conditions for animal life by supplying feed items, such as phytoplankton and resuspended epipelic algae, and reduced the sediment organic content, thereby creating aerobic conditions. Water exchange between the salt marsh and Moune Bay was restricted to this one drainage pipe installed in the retaining banks of the adjacent river. Increased water exchange should improve environmental conditions, species diversity, and biomass.

Keywords: Great East Japan Earthquake, tsunami, disturbance, salt marsh, macrobenthic community, current velocity

Introduction

Earthquakes have direct, indirect, short-term, and long-term effects on the natural environment. Tsunamis are known to cause large-scale and wide-ranging disturbances to the terrain of coastal regions and to biological communities, and can have an extremely large impact on ecosystems (Krishnankutty 2006, Castilla et al. 2010, Jaramillo et al. 2012). However, post-event changes in ecosystems and animal communities are not uniform, and vary with land-level changes, tsunami height, and coastal zone structure, including anthropogenic development.

The Great East Japan Earthquake on March 11, 2011 generated a large tsunami and extensive land subsidence. A 15-m high tsunami struck the Moune district of Kesen-numa City, Miyagi Prefecture (Fig. 1), destroying and washing away 44 of 52 houses in the district (Yokoyama and Hatakeyama 2012). Due to the resulting land subsidence (74 cm), ocean water flooded coastal lands that were used for residential purposes and cultivation, and some areas became salt marshes following the tsunami (Fig. 2).

The tsunami caused considerable changes in the topography of Gamo Lagoon in Sendai Bay, along with the disappearance of seagrass beds, sandy areas, and shoreline dunes, and the degradation of marine sediments (Kanaya et al. 2012). Studies of the impacts of this tsunami on subtidal rocky shore benthic species (Takami et al. 2013), subtidal soft-bottom megabenthos (Seike et al. 2013), and deep-sea meiofaunal assemblages (Kitahashi et al. 2014) have also indicated that the impacts on ecosystems differ among areas, habitats, and communities.

Disaster recovery operations by national and local government authorities are ongoing in all of the devastated eastern regions of Japan, although the procedures for the best use of inundated areas are a topic of some controversy. Recovery operations are advancing on the principle of "restoration to original form," i.e., re-establishment of the way things were before the earthquake (Yokoyama 2013). However, there is a need to consider measures for each coastal region where the topography and environments were largely changed. In such regions, it is important to understand the newly formed environments such as salt marshes, in order to determine the most useful remedial measures.

Salt marshes are productive and biologically diverse ecosystems (Keddy 2000), with unique fauna and flora that are adapted to aquatic or moist environmental conditions (Gibbs 1999). However, salt marshes have been degraded or

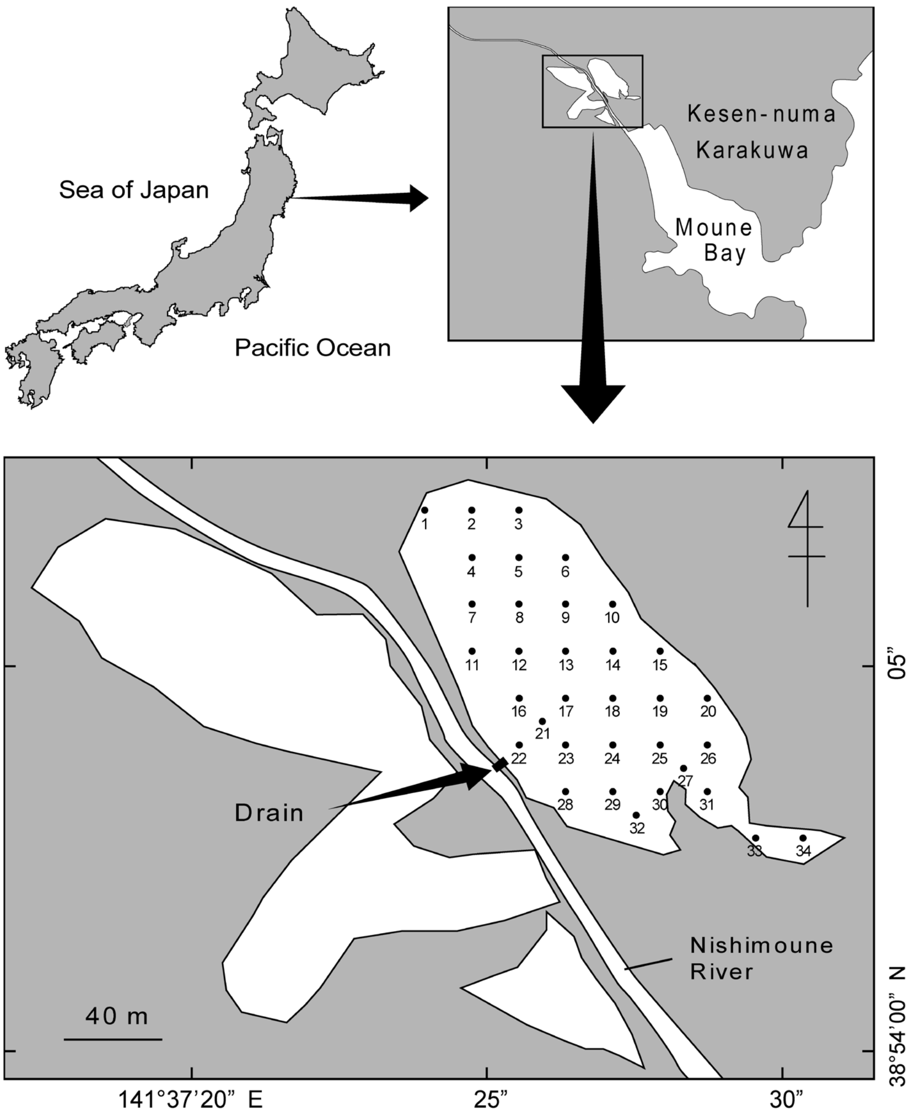

Fig. 1. Location of the study area in Moune Bay. The numbers in the lower figure refer to sampling stations.

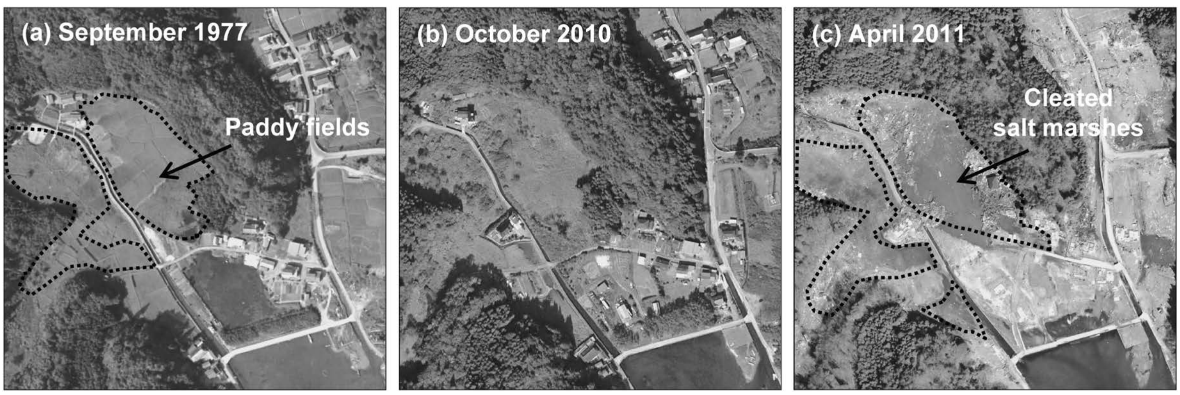

Fig. 2. Aerial photographs of the study area in (a) September 1977, (b) October 2010, and (c) April 2011.

eliminated over large geographical scales through a variety of anthropogenic activities (Dugan 1993). Plans have been made to preserve the new salt marshes in the Moune district as memorials of the earthquake and to provide areas for environmental and ecosystem education for the local community. Our study aimed to improve the understanding of these newly created environments with a special focus on their ecological development since the disaster. The information we assembled will facilitate better use of the marshes as sites for environmental education.

Materials and Methods

Study area

Tidal flats and salt marshes existed in the inner part of Moune Bay at Kesen-numa City (Miyagi Prefecture) up until the 1950s (Tanaka 2012), but they were reclaimed in the 1960s and used as paddy fields and residential lands (Fig. 2a). The paddy fields were abandoned and remained barren from the 1980s onward (Fig. 2b). Land subsidence and the tsunami accompanying the Great East Japan Earthquake converted these areas into salt marshes and tidal flats (Fig. 2c). We established 34 sampling stations at 20-m intervals in the salt marsh, which covers an area of 9,000 m^2 and is located on the eastern side of the Nishi-Moune River (Fig. 1). The other two wetlands, which are located on the western side, have already been reclaimed according to the policies adopted for recovery operations.

Sediment physico-chemical characteristics

We conducted sediment surveys at the 34 stations. The temperature and salinity of the water were measured with a conductivity/temperature profiler (Scoot Meter Model 85; YSI/Nanotech Inc., Kawasaki, Japan) at the same time as sediment sampling. The top 1-cm layer of sediment cores (4.3-cm φ) were collected at each of the stations during September 10–13, 2012. A small portion of each was subsampled for analyses of acid volatile sulfide (AVS) using a H_2S absorbent column (Gastec Co., Yokohama, Japan). The remaining portion of each sample was weighed, dried to a constant weight at 60°C, weighed again to determine the water content, and ground to a fine powder. The sediment samples were soaked in 1.2 N HCl for 2 h to remove carbonates, filtered onto a Whatman nuclepore polycarbonate track-etch membrane filter (pore size = 0.2 μm; Merck Millipore, Billerica, MA, USA), rinsed with distilled water, and dried again. The samples were transferred to tin cups, combusted in an elemental analyzer and injected into a mass spectrometer (ConFlo IV and DELTA V Plus, respectively; Thermo Fisher Scientific, Waltham, MA, USA) to analyze the total organic carbon (TOC) and total nitrogen (TN) contents.

Estimation of current velocity

Current velocity was estimated by measuring the erosion of plaster balls (Doris Japan Co., Komae, Japan). Each plaster ball was fixed with a long bolt (10 cm) to an iron plate (Fig. 3). Plaster balls were immersed in fresh water for 1 h and then weighed to the nearest 10 mg after the surface water had been removed with blotting paper. The balls were set 10 cm above the sediment surfaces at 19 stations from 15:00 on May 25 (high tide) to 07:00 on May 26 (low tide), 2013. Current velocity was measured using an electromagnetic memory current meter (JFE Advantech Co., Nishinomiya, Japan) at six of the 19 stations over the same period. After immersion, the plaster balls were gently removed from each station, rinsed with fresh water, blotted dry, and weighed. The average current velocity at each of the 19 stations was estimated over the 16 h during which the plaster balls were installed in the field using the regression relationship between the average current velocity measured by the current meter and the plaster ball weight losses (Fig. 4). We conducted an additional survey of current velocity at 25 stations during the ebb and flood of the spring tide on October 16 and 17, 2016 respectively, using a propeller current meter (VR-301; Kenek Co., Akishima, Japan). Because we found significant positive correlations ($p < 0.01$) in current velocity distribution among 3 measurements made on May 25–26, 2013 and the ebb and flood tides on October 16 and 17, 2016, we used the May 25–26 data as the current velocity in this study.

Fig. 3. Plaster ball mounted on an iron plate with a long bolt.

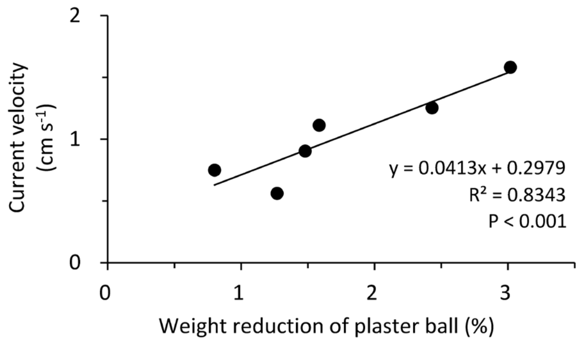

Fig. 4. Relationship between current velocity and plaster ball weight loss.

Macrobenthos

The macrobenthos were collected from 34 stations using an Ekman grab (sampling area: $0.0225\,m^2$) during September 10–13, 2012. Because only one sampling was conducted at each station, the densities of macrobenthos at each station have no mean or standard deviation (SD) values. The sediment was sieved through a 1-mm mesh sieve, and the retained fraction was fixed in 10% neutralized formalin. In the laboratory, the animals were sorted and transferred to 70% ethanol. After sorting, the animals were identified. The number of individuals and their wet weights (without shells or tubes) were determined for each species. When measuring wet weight, animals were blotted with a damp paper towel and their body weight (BW) was quickly weighed to the nearest 0.01 mg following the methods of Yokoyama (1995). We measured the species diversity of the assemblages using the Shannon–Weaver index, H′ (bits), the species richness index, H′max, and the evenness index, J′ (Pielou 1966), for animals weighing < 1 g (wet).

The sampling stations were classified by hierarchical cluster analysis using the group average method based on the Morisita similarity index, C_λ (Morisita 1959). Tukey–Kramer tests were used to examine differences in environmental and community parameters and current velocities among the areas grouped by species similarity. 'KyPlot' software (Kyens Inc., Osaka, Japan) was used for these analyses.

Results

Environmental factors

The marsh is connected to the Nishi-Moune River through a drainage pipe (60-cm diameter). Seawater enters the salt marsh through this pipe during high tide. The north side of this salt marsh is covered with *Phragmites australis* (Stations 1–6, 8–10, 12, and 13) and there are some points of spring water. Seawater is retained on the south side (Stations 13, 14, 16–19, 21–25, 27–30, and 32) even when tides are at their lowest. Salinity ranged from 0.4 to 32.5. The values were > 30 at most of the stations, but low values were found at northern stations due to spring water (Fig. 5).

The AVS contents in the sediments ranged from 0.01 to 6.4 mg/g (dry sediments), with an average of 1.8 ± 1.6 (SD) mg/g. Values were highest in the northern sector of the salt marsh. Total organic carbon (TOC) and total nitrogen (TN) ranged from 1.8 to 149.4 mg/g (average: 60.6 ± 38.2 mg/g) and 0.04 to 6.6 mg/g (average: 3.4 ± 1.65 mg/g), respectively; values for these parameters were relatively low near the drainage pipe.

Average current velocities estimated from 15:00 on May 25 to 07:00 on May 26, 2013 ranged from 0.6 to 1.6 cm/s (average: 0.9 ± 0.3 cm/s) and were highest at station 22, which was located nearest the drainage pipe. The values decreased with distance from the drainage pipe.

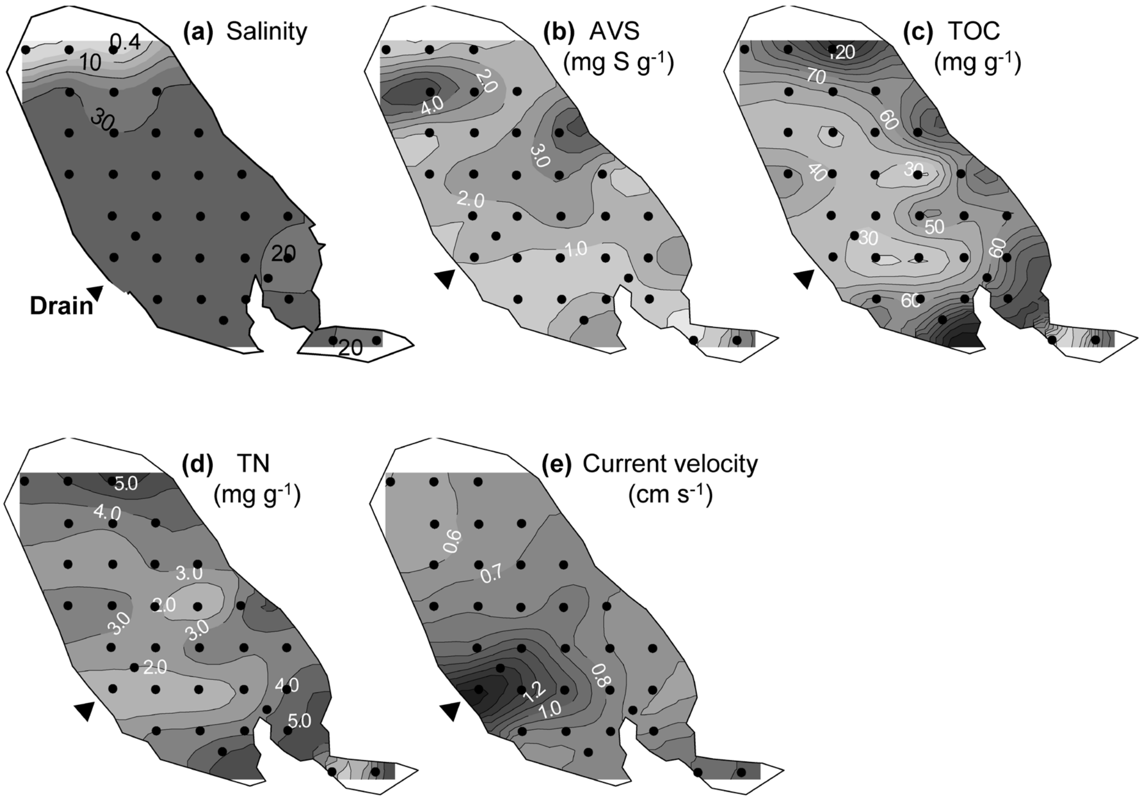

Fig. 5. Spatial distribution of environmental parameter values in the study area: (a) salinity, (b) acid volatile sulfides (AVS), (c) total organic carbon (TOC), (d) total nitrogen (TN), and (e) current velocity.

Macrobenthos

We collected 4,806 macrobenthic individuals belonging to 53 species from the 34 stations (total sampling area: 0.765 m^2) over the study period (Table 1). Densities at each station ranged from 100 to 25,000 individuals/m^2 (Fig. 6). High densities (> 20,000 individuals/m^2) were found in the central sector of the study area and at station 20, which was located in the eastern sector. Densities were low in the northern sector (< 1,000 individuals/m^2). The biomass at each station ranged from 0.4 to 380 g/m^2 (average: 50 ± 69 g/m^2). The highest values were measured around the drainage pipe (> 100 g/m^2; Stations 16, 22, and 24). Biomass values decreased with the distance from the drainage pipe. Additionally, the number of species was highest at stations around the drainage pipe. H′ and H′ max ranged from 0.1 to 3.4 and 1.0 to 4.3, respectively, and values were highest in the sector around the drainage pipe. J' ranged from 0.1 to 1.0, with the highest values in the northern sector.

Environmental and community parameters in the four sample cluster groups

In our cluster analysis, the macrobenthos community in the salt marsh was separated into four cluster groups (A–D) (Fig. 7). Stations 1, 2, 4, 7, 11, 28, 29, and 34 were not included in any of these cluster groups. Among these stations, 1, 2, 4, 7, and 11 were characterized as not always being submerged under sea water, and their animal communities were dominated by terrestrial animals, such as the larvae of Stratiomyidae and Ptilodactydae. Some species from stations 28 and 29 were found in group A, but the numbers of overlapping species were low, and the dominant animals in group A, such as polychaetes and bivalves, were not abundant. At station 34, only two species belonging to Oligocheata and Dolichopodidae were caught. The distributions of the dominant species with the highest densities are shown in Fig. 8.

Cluster group A was located in an area close to the drainage pipe where the current velocity was the highest (average 1.3 ± 0.3 cm/s) of the areas occupied by the cluster groups (Fig. 9a). AVS, TOC, and TN were relatively low in areas occupied by cluster group A (Figs. 9b, c, and d). Macrobenthic density (7,500 ± 2,300 individuals/m^2) and biomass (200 ± 130 g/m^2) in areas occupied by cluster group A were highest among the cluster groups. The biomass in areas occupied by cluster group A accounted for 62% of the total (Fig. 9e). The isopod *Gnorimosphaeroma* sp. (3,500 individuals/m^2), the bivalve *Ruditapes philippinarum*, (900 individuals/m^2), and the gastropod *Haloa japonica* (500 individuals/m^2) were the dominant species in areas occupied by cluster group A. The densities of the bivalves *Macoma incongrua* and *Mya arenaria oonogai* in these areas were relatively high compared with the areas occupied by other cluster groups.

The current velocity in the areas occupied by cluster group B (0.7 ± 0.1 cm/s) was relatively low (Fig. 9a). The

Table 1. List of species collected in the study area (total sampling area: 0.765 m^2). N, number of individuals of each species; W, summed wet weights (mg) of all individuals in each species.

No.	Species	N	W (mg)
	Phylum Cnidaria		
1	unidentified Actiniaria	6	14
	Phylum Nemertinea		
2	unidentified Lineidae	19	130
3	unidentified Tetrastemma	15	78
4	unidentified Hoplonemertea	2	5
	Phylum Annelida		
5	*Eteone* sp.	19	41
6	*Eumida* sp.	1	2
7	unidentified Phyllodocidae	1	11
8	*Opisthosyllis brunnea*	3	16
9	*Ceratonereis erythraeensis*	58	3736
10	*Hediste* spp. 105	1456	
11	*Perinereis wilsoni*	3	246
12	*Perinereis mictodonta*	2	356
13	*Platynereis bicanaliculata*	2	3
14	*Nephtys polybranchia*	5	82
15	*Paraonides nipponica*	1	2
16	*Schistomeringos anoculata*	9	52
17	*Scoletoma longifolia*	1	17
18	*Pseudopolydora paucibranchiata*	8	10
19	*Pseudopolydora kempi*	325	524
20	*Cirriformia tentaculata*	12	1949
21	*Capitella* sp.	127	169
22	*Mediomastus* sp.	109	205
23	unidentified Tubificinae	21	30
24	unidentified Oligochaeta	3	35
	Phylum Mollusca		
25	*Batillaria cumingii*	147	741
26	*Assiminea hiradoensis*	13	39
27	*Retusa matsusima*	6	3
28	*Haloa japonica*	232	1629
29	*Musculista senhousia*	17	2520
30	*Ruditapes philippinarum*	94	10183
31	*Macoma incongrua*	27	3620
32	*Mya arenaria oonogai*	25	2606
	Phylum Arthropoda		
33	*Sinelobus* sp.	36	11
34	*Gnorimosphaeroma* sp.	381	1175
35	*Grandidierella japonica*	58	73
36	*Platorchestia platensis*	1	4
37	*Eogammarus possjeticus*	14	86
38	*Melita shimizui*	74	49
39	*Corophium insidiosum*	1318	536
40	*Ampithoe* sp.	25	38
41	*Upogebia yokoyai*	1	120
42	*Asellus hilgendorfi hilgendorfi*	4	3
43	*Appasus japonicus*	2	712
44	*Orthetrum japonicum japonicum*	1	268
45	unidentified Sialidae	3	145
46	*Erioptera* sp.	2	6
47	*Pseudolimnophila* sp.	9	26
48	*Einfeldia* sp.	1408	2702
49	unidentified Stratiomyidae	38	290
50	unidentified Tabanidae	2	410
51	unidentified Dolichopodidae	6	12
52	unidentified Cyclorrhapha	4	8
53	unidentified Ptilodactylidae	1	188

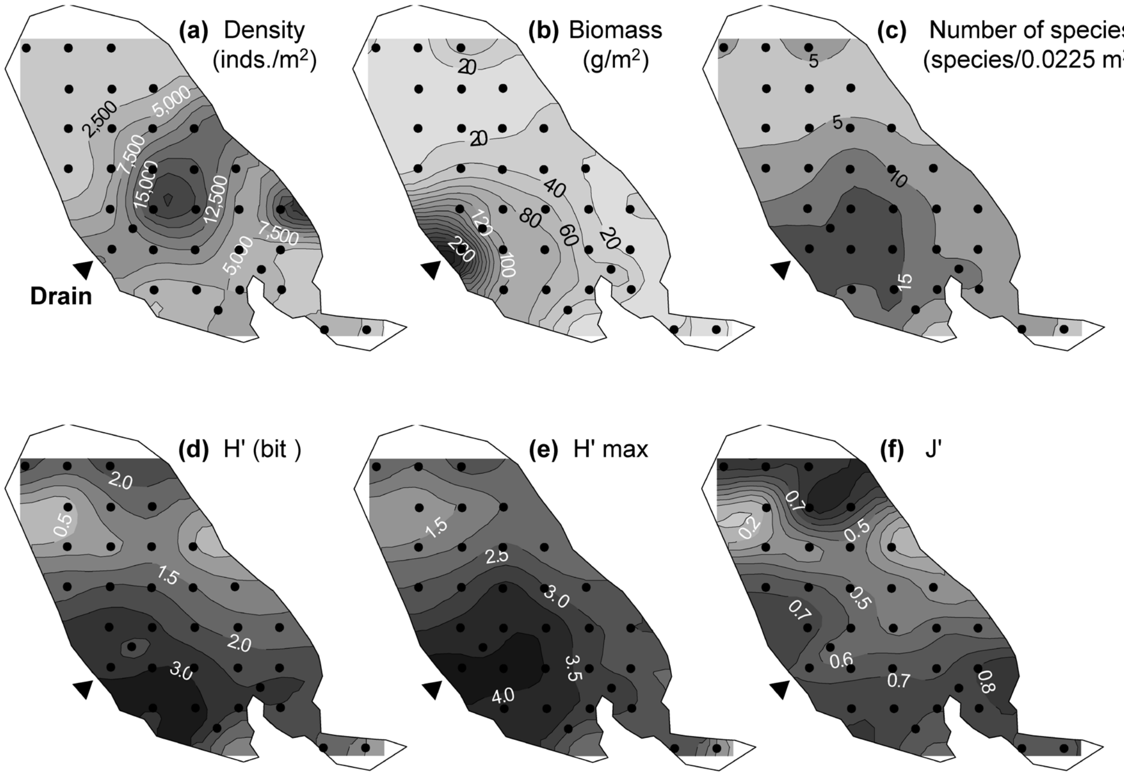

Fig. 6. Spatial distribution of macrobenthic community parameter values in the study area: (a) density, (b) biomass, (c) number of species, (d) H' (bits), (e) H' max, and (f) J'.

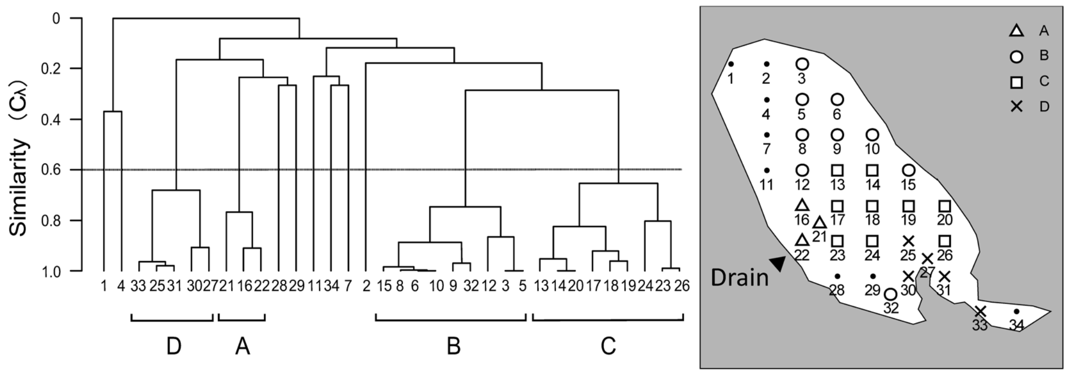

Fig. 7. Cluster analysis of the sampling stations (1–34) in the study area based on macrobenthic species composition; four cluster groups are apparent (A–D). The Morisita's similarity index C_λ values ranged from 0 (lowest) to 1 (highest). The dashed line marks the threshold for cluster recognition.

AVS (2.3 ± 1.6 mg/g), TOC (77.4 ± 40.4 mg/g), and TN (4.2 ± 1.9 mg/g) in these areas were the highest among the cluster group areas (Figs. 9b, c, and d), but the density (4,800 ± 3,700 individuals/m^2) and biomass (21 ± 18 g/m^2) were the lowest (Figs. 9e and f). The dominant species were the insect *Einfeldia* sp. (3,800 larvae/m^2), the polychaete *Pseudopolydora kempi* (300 individuals/m^2), and the polychaete *Capitella* sp. (300 individuals/m^2).

The current velocities in the areas occupied by cluster group C (central region of the salt marsh) ranged from 0.6 to 1.2 cm/s (0.9 ± 0.2 cm/s) (Fig. 9a). The AVS (1.9 ± 1.0 mg/g), TOC (41.3 ± 32.2 mg/g), and TN (2.5 ± 1.7 mg/g) in these areas were moderate (Figs. 9b, c, and d). The density (13,500 ± 8,200 individuals/m^2) was extremely high (Fig. 9f), but biomass (50 ± 35 g/m^2) was relatively low (Figs. 9e and f). *Corophium insidiosum* (6,300 individuals/m^2), *Einfeldia* sp., (3,200 larvae/m^2), and *Haloa japonica* (800 individuals/m^2) were the dominant species. *Corophium insidiosum* accounted for approximately 50% of the macrobenthos density.

The current velocity in the area occupied by cluster group D ranged from 0.5 to 0.8 cm/s (0.7 ± 0.1 cm/s). The AVS (1.0 ± 1.3 mg/g) was the lowest among the areas occupied by the cluster groups (Fig. 9a). The TOC (75.3 ± 50.1 mg/g) and TN (3.7 ± 2.0 mg/g) were relatively low

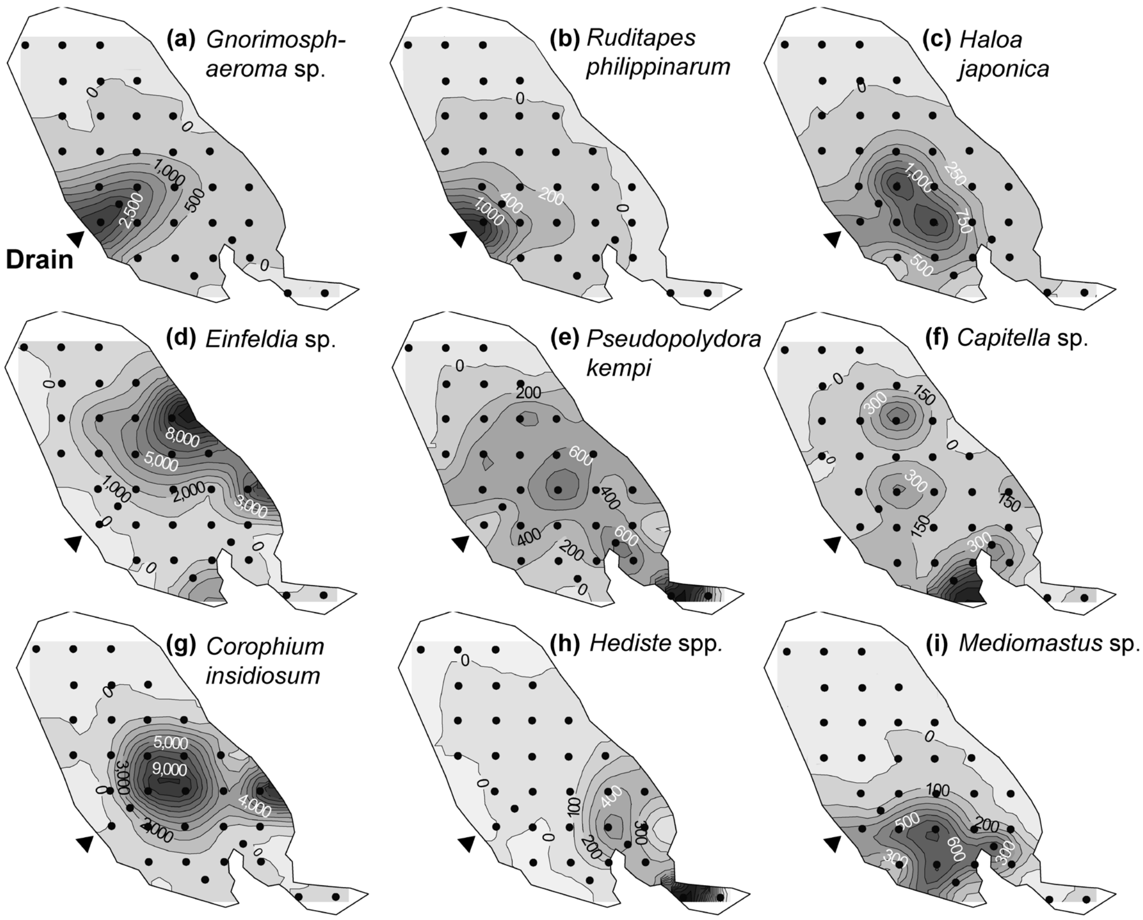

Fig. 8. Density distributions of the nine most abundant species: (a) *Gnorimosphaeroma* sp., (b) *Ruditapes philippinarum*, (c) *Haloa japonica*, (d) *Einfeldia* sp., (e) *Pseudopolydora kempi*, (f) *Capitella* sp., (g) *Corophium insidiosum*, (h) *Hediste* spp., and (i) *Mediomastus* sp.

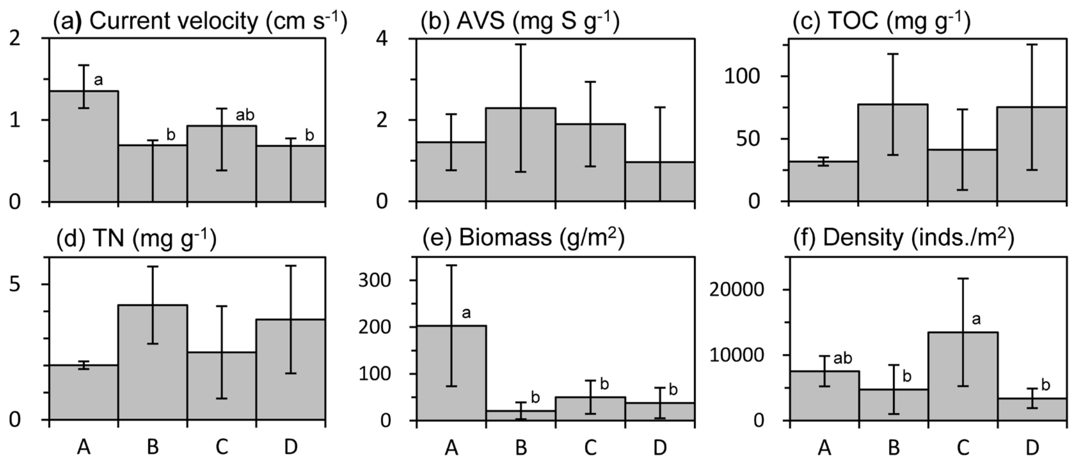

Fig. 9. Environmental and community parameter values in areas occupied by the four clusters identified in Fig. 7 (A–D): (a) current velocity, (b) acid volatile sulfides (AVS), (c) total organic carbon (TOC), (d) total nitrogen (TN), (e) biomass, and (f) density. Values are means ± standard deviation. Different lower case letters above the bars indicate significant pairwise differences ($p < 0.05$; Tukey–Kramer test) between areas occupied by different clusters.

(Figs. 9c and d). *Pseudopolydora kempi* (1,300 individuals/m^2), polychaetes identified as *Hediste* spp. (700 individuals/m^2), and the polychaete *Mediomastus* sp. (400 individuals/m^2) were the dominant species.

Discussion

Within 18 months of the formation of the salt marsh, the macrobenthos community contained more than 53 species.

The polychaetes *Capitella* sp. and *Pseudopolydora kempi*, the amphipod *Grandidierella japonica*, and the isopod *Corophium insidiosum* were the major constituents of this new community. Of these, *Capitella* sp. and *Pseudopolydora kempi* are recognized as opportunistic species that can reproduce throughout the year and have short life cycles (Tsutsumi and Kikuchi 1984, Kanaya et al. 2011). These animals are generally the first taxa to recolonize tidal flats following environmental changes (Grassle and Grassle 1974). *Grandidierella japonica* and *Corophium insidiosum* reportedly reproduce rapidly in response to altered environmental conditions (Aikins and Kikuchi 2002); ovigerous females occur throughout the year, a life-history characteristic that enables rapid responses to favorable ecological conditions. Accordingly, these two species are considered opportunistic and therefore similar to *Capitella* sp. The life history characteristics of opportunistic species, which can undergo rapid population growth under unstable environmental conditions, were likely important factors allowing colonization during the post-tsunami period. The diversity of benthic communities recovers gradually after an ecological disaster, and the abundance of opportunistic species declines over time (Levin et al. 1996, Joydas et al. 2012). We expect the structure of the macrobenthic community in the Moune salt marsh to change gradually in the coming years.

Our cluster analysis identified four macrobenthic groups, with different distributions. The highest species diversity and biomass (Figs. 9e and f) occurred in the area occupied by cluster group A, which was located in the vicinity of the drainage pipe. Horikoshi (1976) classified the macrobenthic biomass of Japanese coastal areas into three levels: poor (< 10 g/m^2), middle (20–50 g/m^2), and high (> 100 g/m^2). The areas occupied by species in cluster group A on the Moune salt marsh clearly fell into the high biomass category (203 ± 129 g/m^2). In these areas, large suspension feeders, such as the clams *Ruditapes philippinarum* and *Mya arenaria oonogai* and the mussels *Musculista senhousia* and *Macoma incongrua*, were the dominant bivalves, accounting for approximately 60% of the total biomass. The current velocity in this area exceeded those in other parts of the marsh (Fig. 9a); the TOC was 32 ± 3 g/m^2, with low quantities in the sediments (Fig. 9c).

Areas occupied by community cluster groups B and D were far from the drainage pipe, where the current velocity, animal diversity, and biomass were low (Figs. 9a, e, and f). In these areas, opportunistic species, such as *Capitella* sp. and *Pseudopolydora kempi*, were dominant. The levels of organic matter in the sediments of these areas were high (Fig. 9c); the AVS content in the sediments was 6.4 mg/g, which was much higher than the standard value of 1.0 mg/g, as is often the case in enriched coastal environments (Japan Fisheries Resources Conservation Association 2000).

In the areas occupied by community cluster group C, which were located in the central part of the salt marsh, the macrobenthos density was high (13,500 ± 8,200 individuals/m^2) (Fig. 6a). Small animals, such as *Corophium insidiosum*, larvae of *Einfeldia* sp., and the spionid polychaete *Pseudopolydora kempi*, were the predominant species; *Corophium insidiosum* accounted for approximately half of the total animal density (Figs. 8d, e, and g). Organic pollution in inner bays and coastal areas generally results in reduced oxygen levels, leading to reductions in large animal species with long life cycles, and increases in small species with short life cycles (Pearson and Rosenberg 1978, Warwick et al. 1987). This combination of traits well describes the Moune salt marsh area occupied by species in community cluster group C.

In the Moune salt marsh, we found many areas with high biomass and high biodiversity and others with low diversity and low biomass, which are typical of coastal regions with increasing organic pollution and unstable, low-quality environments. A crucial factor in the Moune marsh was the water flow through the drainage pipe connected to the Nishi-Moune River. Rapid flow through the pipe brought food to animals on the marsh, such as phytoplankton and resuspended epipelic algae. Fast-flowing water reduces the organic content of the sediments, which in turn promotes the formation of aerobic conditions under which many animals can thrive. The water exchange between the salt marsh and Moune Bay occurs through only one narrow diameter (60 cm) drainage pipe, and rapid water flow occurs only around the mouth of the pipe. Increased water flow over the entire area of the marsh would promote the formation of favorable environmental conditions for aerobic life and increase animal diversity.

Much of the organic content in the Moune salt marsh sediment is derived from leaf litter deposits. Animals in the sea that use organic matter of terrestrial origin are limited because many of them do not have the correct enzymes for cellulose digestion (Kristensen 1972, Yamashita 2014). Accumulation of terrestrial organic matter in the marshes should be examined as a contributing factor to the deterioration of physiological conditions in the sediments. The recovery of benthic animal communities after a major environmental catastrophe can be very protracted (Beukema et al. 1999, Cardoso et al. 2008). Long-term monitoring is essential for a comprehensive understanding of community and environmental development processes.

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