



## Impacts of environmental and anthropogenic stresses on macrozoobenthic communities in Jinhae Bay, Korea



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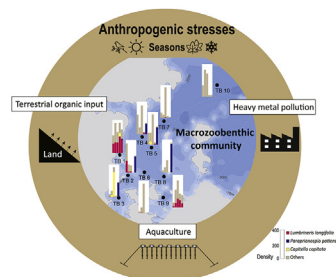
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### HIGHLIGHTS

- Spatiotemporal dynamics of macrofaunal assemblages in Jinhae Bay were addressed.
- Peak abundances in spring and distinctive species shifts in summer were characteristic.
- Oyster farming was one potential anthropogenic stress affecting macrofaunal communities.
- Analysis of five ecological quality indices indicated moderate pollution in given area.

### GRAPHICAL ABSTRACT



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### ABSTRACT

In this study, spatiotemporal dynamics of macrofaunal assemblages and their associations with environmental conditions were examined in Jinhae Bay (10 sites), where the obvious sources of pollution including industries, oyster farms (hanging cultures), and municipal discharges has surrounded. The survey had performed over five consecutive seasons in 2013–2014. Target sedimentary variables included grain size, organic content, C/N ratio, carbon and nitrogen stable isotope ratios, and some heavy metals. Five ecological quality indices (EcoQ) were calculated from the benthic community data to evaluate ecological qualities in site-specific manner. Jinhae Bay is a shallow (depths range, 11–24 m) and typical semi-enclosed bay. The benthic environments represented mud dominated bottoms (>70%) with fairly substantial organic content levels (>2%) over all five seasons. Seasonal patterns were observed with peak abundances in the spring and distinctive macrozoobenthos species shifts in the summer. The spring bloom could be explained by drastic increases of some polychaetes, mainly *Capitella* sp., at certain site, particularly near the shore. The oyster farms situated in the innermost locations seem to provide organic-rich bottoms being dominated by opportunistic species and/or organic pollution indicator species, such

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as *Lumbrineris longifolia*, *Capitella* sp., and *Paraprionospio patiens*. In general, the EcoQ indicators indicated that Jinhae Bay was moderately polluted, with exceptionally poor EcoQ in a few locations during the specific season(s). Overall, adverse effects on benthic community was broadly attributable to contaminations of heavy metals and nearby aquatic farm activities in Jinhae Bay, which requires a prompt action toward ecosystem-based management practice in the given area.

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## 1. Introduction

Marine sediment would comprise one of the largest and oldest habitats in the world showing relatively great biodiversity and production under the dynamic physicochemical changes though (Gray, 2002). Meantime, terrestrial contaminants tended to accumulate in estuarine and coastal sediments, say a spot for final sink, reaching their concentrations being capable of harmful effects to organisms. The negative effects on growth and/or reproduction of macrozoobenthos in contaminated sediments have long been evidenced in Korean coastal waters, particularly in semi-closed industrial bays (Khim and Hong, 2014). Moreover, the alteration of natural species composition including species extinction could be found in the heavily contaminated coastal sites, and thus following long-term population changes would become a significant ecosystem threat in the given environment. As macrozoobenthos are one representative sedentary organism in coastal area, the monitoring of macrozoobenthos community would be a reliable indicator which would address the benthic ecological quality associated with coastal sediment pollution (Gray et al., 1992).

Many studies have investigated spatiotemporal changes of macrozoobenthic communities in relation to the natural and/or anthropogenic disturbances (Crawford et al., 2003; Metzger et al., 2007). Aquaculture is an important industry worldwide in socio-economic aspects but also considered as one of the representative anthropogenic activities due to water-column eutrophication followed by planktonic blooms in coastal areas. Further a hypoxic condition in bottom water and further inside of sediment would have a bad influence on benthic ecological quality (Pearson and Rosenberg, 1978). Also, the continuing input of terrestrial organic matter from various land-use activities could affect the long-term changes of macrozoobenthic communities. A convergence of evidence from numerous previous studies pointed out the transportation of land-based organic matter into coastal systems as one of the common pathways to bring coastal environmental deterioration (Weston, 1990; Essink, 2003; Gamito, 2008). Of note, these adverse effects tend to be most severe in the areas with poor water exchange, say semi-enclosed industrial bay system (Read and Fernandes, 2003).

Next, the heavy metal pollution would be one significant category relating to the anthropogenic stresses resulting in adverse toxic effects on benthic organisms. For example, sedimentary zinc has been known to cause early survival of benthic invertebrates (Watzin and Roscigno, 1997) and interstitial cadmium has shown to give negative effects on recolonization of macrozoobenthos (Hansen et al., 1996). More recently, the long-term accumulation of sedimentary heavy metals in semi-closed industrialized bays revealed the alteration of macrozoobenthic community structure (Josefson et al., 2008; Ryu et al., 2011). Of note, the long-term ecological effects by the persistent organic pollutants, which could commonly co-occur with heavy metals, have also been evidenced in highly contaminated coastal sediment, in Korea (Ryu et al., 2016), but mechanism or direct effect for long-term association remains in question.

Efforts to improve and protect ecological quality of coastal areas from such man-made impacts have long been practiced worldwide. The assessment of ecological quality (EcoQ) status was one of key components in terms of management tools. The European Water Framework Directive (WFD) has led to a development of these tools for analysis of macrozoobenthos community. Single or limited indices tend to over- or underestimate the benthic ecological conditions in the given area. The present study adopted the European WFD's EcoQ approach which classifies ecological status into five scales (high, good, moderate, poor, and bad) to assess the benthic ecological condition in the study area.

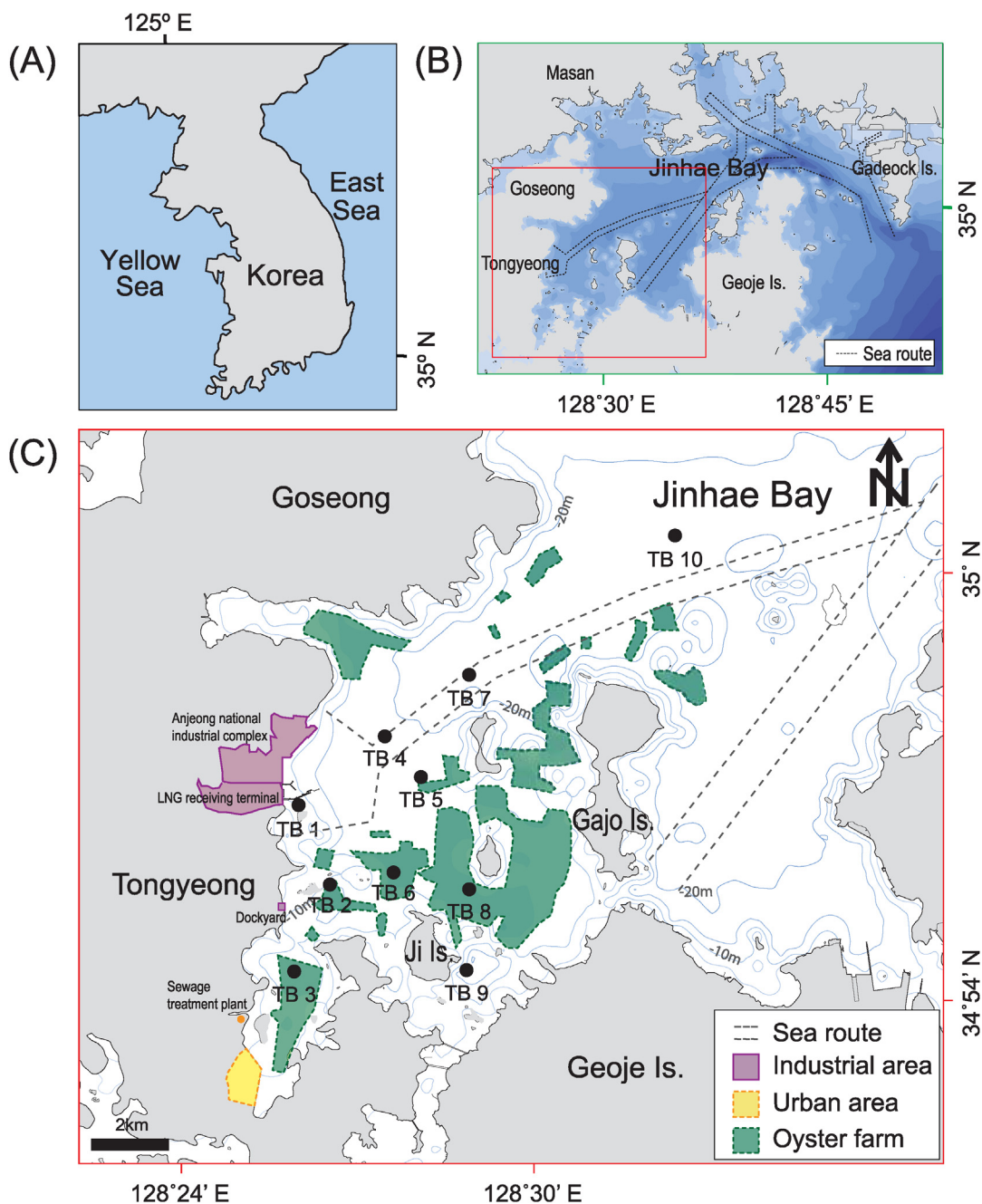
As well known, contaminants tend to accumulate in estuarine and coastal sediments and further bioaccumulate, thus potential adverse effects associated with sediments becomes a serious problem, particularly in semi-enclosed bay system, including our study area of Jinhae Bay. Jinhae Bay is exposed to obvious point-sources of coastal pollution including industries, oyster farming (hanging culture), and municipal sewage discharges. Since 1980s, the nearby coastal area has been heavily impacted by drastic increases in industrialization and human populations which seemed to deteriorate macrozoobenthos community (Hong, 1987; Lim et al., 1992; Seo et al., 2014). In particular, Jinhae Bay is known as one of the large aquaculture production areas for the oyster culture, where coastal eutrophication has long been a significant environmental issue (Lim et al., 1992, 2006). The macrozoobenthos community might reflect the historical feature of geographical conditions in which both single and/or multiple parameters could collectively influence certain ecological alteration.

In the present study, we aimed to address the macrozoobenthos relationship between several important sediment variables and macrozoobenthic communities (viz., species composition and abundances) in semi-enclosed industrialized bay system of Jinhae area. In particular, spatio-seasonal association of macrozoobenthos assemblages to potential anthropogenic sources around Jinhae Bay area was highlighted. The assessment of benthic ecological quality over five seasons was also presented in order to identify the major anthropogenic source(s) in the given environmental conditions. Finally, we discussed a long-term community change of macrozoobenthos in association with representative human activities around the Jinhae Bay region since late 1980s (Fig. S1 of the Supplementary Materials (S)).

## 2. Materials and methods

### 2.1. Study area

The study area is situated in the south-western part of Jinhae Bay, Korea (Fig. 1), which is a shallow semi-enclosed bay. A channel was located in southern part of study area, between Tongyeong and Geoje island and oyster farming is prevailing over seasons in large scale with >500 ha of aquaculture area. Jinhae Bay is surrounded by three major cities, Changwon, Tongyeong, and Geoje, of which populations reach >1 M, >250 K, and >400 K, respectively. A sewage treatment plant, which was located in the innermost of



**Fig. 1.** Map of sampling sites (TB1–TB10) located in southwestern Jinhae Bay, Korea. The map also presents information of surrounding activities, such as industrial area, urban area, oyster farm, and sea route.

study area, nearby Tongyeong City, discharged maximum 200 tons per day of treated effluent into the bay. The city of Tongyeong has a recently developed industrial complex with Liquefied Natural Gas (LNG) receiving terminals of which construction began in late 1990s and more recently Anjeong national industrial complex was developed in 2010 by reclaiming public water (Fig. 1). Of note, the Jinhae Bay area has long been associated with sediment deterioration (Khim and Hong, 2014), but not systematic monitoring program has been practiced.

## 2.2. Sampling

Macrofaunal assemblages and sedimentary variables were

examined in Jinhae Bay (10 sampling sites; TB1–TB10) from November 2013 to October 2014 (Fig. 1 and Table S1). Sediment samples were collected twice using a van Veen grab, covering a surface area of 0.1 m<sup>2</sup>. Surface sediments (<3 cm) were subsampled from a grab sample and subjected to analyses of the following target variables; sediment grain size, organic carbon content, C/N ratio (total organic carbon to nitrogen ratio), stable isotope ratios, and heavy metal concentrations. Of note, pooled samples were used for species identification and individual counting which would minimize the site-specific variation or possible technical error in grab sampling. Environmental variables of bottom seawater (depth of 11–24 m) including pH, salinity, dissolved oxygen (DO), and temperature were monitored using a YSI multi-parameter

device (YSI 556 MPS, YSI Environmental, Yellow Springs, OH).

### 2.3. Laboratory analyses

The fauna samples were sorted and identified to the species level before being counted. Sediment grain size was analyzed by the dry sieve and pipette method (Konert and Vandenberghe, 1997). In addition to assessing general sedimentary properties, we measured the concentrations of several heavy metals including nickel, chromium, zinc, lead, lithium, cadmium, copper, arsenic, and mercury. Heavy metals in the sediment were analyzed using ICP-MS & ICP-OES (PerkinElmer, Waltham, MA) following the method described elsewhere (Kitano and Fujiyoshi, 1980).

Carbon and nitrogen contents and stable carbon and nitrogen isotope ratios were measured by Elemental Analyzer-Isotope Ratio Mass Spectrometry (IRMS, Elementar, Hanau, Germany). Following sample treatment with 1 M HCl to remove inorganic carbon, total organic carbon (TOC), and carbon stable isotope ratio ( $\delta^{13}\text{C}$ ) were measured (Rumolo et al., 2011). The international isotope standards, IAEA-CH-3 and IAEA-CH-6, were used to calibrate  $\delta^{13}\text{C}$ .

### 2.4. Data analyses

Cluster analyses aiming at describing representative macrozoobenthos groups in Jinhae Bay over time and space were carried out with PRIMER 6 statistical software (PRIMER-E Ltd., Plymouth, UK). The original data matrix was reduced by eliminating species that contributed <1% of the total abundance. Bray-Curtis similarity coefficients were calculated and the data were subjected to group average sorting. Abundances were fourth root-transformed so as to balance across the occurring taxa in the measure of similarity (Clarke and Warwick, 2001). Four criteria delineated by Salzwedel et al. (1985) for identification of local characteristic species were used (Holligan et al., 1984): (1) the ratio of species abundance in each group over the total abundance in the corresponding group (dominance); (2) the ratio in the number of locations at which the species occurs in each group over the entire number of locations for the corresponding group (constancy); (3) the ratio of species abundance in each group over the total abundance of corresponding species in the entire area (degree of association regarding individuals); and (4) the ratio of the number of locations at which the species was found in each group over the total number of locations at which the corresponding species occurs in the entire area (degree of association regarding locations).

Five overall community ecological indicators were monitored, including four internationally established indices; the AZTI Marine Biotic Index (AMBI), Multivariate -AMBI, Infaunal Quality Index (IQI) and the Shannon-Wiener diversity index ( $H'$ ; natural log) as well as the Benthic Pollution Index (BPI), which was developed in Korea (KORDI, 1995). The information including algorithms, remarks, and references of these indices presented in Table S2. Finally, five classification groups of ecological quality indices (EcoQ), say bad, poor, moderate, good, and high, were obtained and compared cross the seasons (KORDI, 1995; Rosenberg et al., 2004; Labruno et al., 2006; Quintino et al., 2006; Blanchet et al., 2008).

## 3. Results and discussion

### 3.1. Environmental condition

The general water quality data (i.e., temperature, salinity, pH, and DO) obtained for the study area are reported in Tables S3 and S4. Throughout most of the year, except for summer, pH, salinity, and DO remained being fairly constant. Of note, fairly low concentration of bottom DO (close to  $\sim 2 \text{ mg O}_2 \text{ L}^{-1}$ , of hypoxia

diagnosis level) was observed in the northern part of the study area (TB4, 5, 7, and 10) (Table S5). These locations were situated relatively far from nearby cities and oyster farms (Fig. 1C). Thus, the lack of DO in the bottom waters could not be explained by geographical conditions, but rather likely reflect a thermocline effect. Overall, data on the study area showed typical characteristics of semi-enclosed bay, but site-specific activities distinctly affected study area with seasonal changes.

Over the five sampled seasons, sediment grain size did not vary in relation to season, indicating lesser sedimentation and/or deposition in the given area. Sediment samples contained a mean grain size of 8.4 phi (range, 2.1–10.2 phi), representing predominated soft bottom condition (>80% silt and clay). Sites TB1 and TB9 contained relatively coarse sediments, with mean grain sizes of 3.9 phi and 3.8 phi, respectively. Of note, TB1 seemed to be affected by public water reclamation for expansion of adjacent industrial complex (Fig. 1). Overall, the study area was an organically rich environment with dynamic bottom condition.

Multivariate statistical technique, namely PCA, was used to evaluate correlations among heavy metals and other environmental variables. The result of a Kaiser-Meyer-Olkin (0.71) and Bartlett's test ( $p < 0.001$ ) suggested that PCA was suitable for analysis of the data set. An eigenvalue of the first component was found to be 7.08. Of the total variance, ca. 39% was controlled by first component, showing greater loading for Cr, Ni, Zn, Pb, Li, Cu and grain size. The result reflected strong correlation between heavy metals and sediment grain size. Sediment grain size also showed positive correlation with Cd and As (0.684 and 0.215, respectively), while Hg showed negative correlation ( $-0.370$ ). Although cadmium showed positive correlation with sediment grain size, it had greater loading in second component with organic content and TN. It is supposed that concentration of cadmium was affected by the anthropogenic activities.

In general, heavy metal concentrations were elevated in the fall and winter then tended to decrease by about half during the following three seasons. More than half of locations exceeded the effect range low (ERL) guidelines recommended by NOAA (Long et al., 1995) for Ni and Cu, indicating that these metals were stressors in the given environment. None of the metals exceeded the ERL guidelines for all seasons in any of the study locations, indicating that heavy metal pollution in the study area was low to moderate.

The C/N ratios obtained for most of sediment samples collected in the study were in the range of 6–8, referring to a marine origin (Stein, 1991). However, site TB9 had an unusually great C/N ratio (>18), implying that there was an input of organic matter with terrigenous origin (Holligan et al., 1984), possibly transported from the nearby Ji-Island or Geoje Island (Fig. 1).

Except TB1 and TB9,  $\delta^{13}\text{C}$  value ranged between  $-21.0\text{‰}$  and  $-20.3\text{‰}$ . These values indicated that organic matter in surface sediments was of similar origin. However, the organic matter properties at TB1 and TB9 showed distinctively smaller values in particular seasons. A value of  $\delta^{13}\text{C}$  at TB1 was drastically elevated in summer, which was smallest ( $-24.0\text{‰}$ ) and then increased gradually being heavier in the following seasons. Of note, the second smallest value was  $-23.5\text{‰}$  at TB9 in summer. These results generally suggested influence of terrestrial organic matter in the sites adjacent to the municipal cities. Reclamation nearby TB1 might be responsible for the input of terrestrial organic matter to the sea, temporarily, which was a good agreement with previous report of increasing of terrestrial organic matter due to land reclamation (Jia and Peng, 2003). Meanwhile, seasonal fluctuation was observed for  $\delta^{15}\text{N}$  at TB1.

Altogether, the stable isotope ratios result indicated that specific locations seem to be closely associated with land-driven sources of

organic matters in a seasonal manner. Also, it should be noted that relatively great variations in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  were observed across the sampling locations in summer and winter period, respectively. These variations would be evidence of changes in environmental conditions in the given area primarily from land-activities.

### 3.2. Spatial distribution of macrozoobenthos

Over the period of five seasons, a total of 166 macrozoobenthos species, primarily polychaetes, were found with a mean density of 765 ind.  $\text{m}^{-2}$  (Tables S3 and S6). *Lumbrineris longifolia* was the single most abundant species, representing 33.4% of all counted individuals. The next most dominant polychaetes included *Paraprionospio patiens* (6.8%), *Capitella* sp. (6.5%), and *Sigambra tentaculata* (4.1%) (Fig. 2). A total of 104 and 98 taxa were found at TB9 and TB1, respectively, over five seasons; among the 10 sampling sites, TB9 showed the greatest seasonal variation (Fig. 2). Of note, *L. longifolia*, known as opportunistic species or potential organic enrichment indicator, was consistently the most abundant species at TB1 and TB9 (Yu et al., 2013). Some drastic seasonal increases in particular species were observed (particularly in spring and fall); these increases were associated with the presence of limited taxa or species, reflecting rapid and episodic population changes in the environment.

Further, cluster analysis of the locations with pooled data from five seasons demonstrated a clear macrozoobenthic assemblage into three representative groups, seemingly associated with the

geography of the sampling locations (Figs. S2 and S3). The TB1 and TB9 locations were grouped together into Group A, the group characterized by a great abundance and a high species diversity, particularly in TB9. The second representative group, Group B, encompassed the locations close to oyster farming areas (TB2, TB3, TB6, and TB8); their abundances were generally smaller than those in Group A. Finally, Group C was comprised of the northern locations (TB4, TB5, TB7, and TB10), where the lowest quantities of macrozoobenthos were observed throughout the year. Only five species occurred more than 5% each to total abundance of Group C, *Theora fragilis*, *Parapriono spioatiens*, Stomatopoda sp., and *Oratosquilla oratoria*. *T. fragilis* and *P. patiens* were organic enrichment indicator, and Stomatopoda and *O. oratoria* were mobile species. The cluster analysis results indicated that the assemblage groups, regardless of seasonal changes, reflected the spatial distribution of macrozoobenthos fairly well in terms of geographic and oceanographic settings. MDS plotting of dominant species (e.g., *L. longifolia*, *P. patiens*, *Capitella* sp., and *S. tentaculata*) also fit to well the geographical settings of the sampling locations (Fig. S2).

### 3.3. Seasonal variation of macrozoobenthos

Although the macrozoobenthos exhibited a distinct spatial distribution over the year, a couple of locations showed clear seasonal changes in species composition and/or relative abundance (Table S3). To better understand the seasonal dynamics of the macrozoobenthos community, all 50 datasets (10 locations  $\times$  5

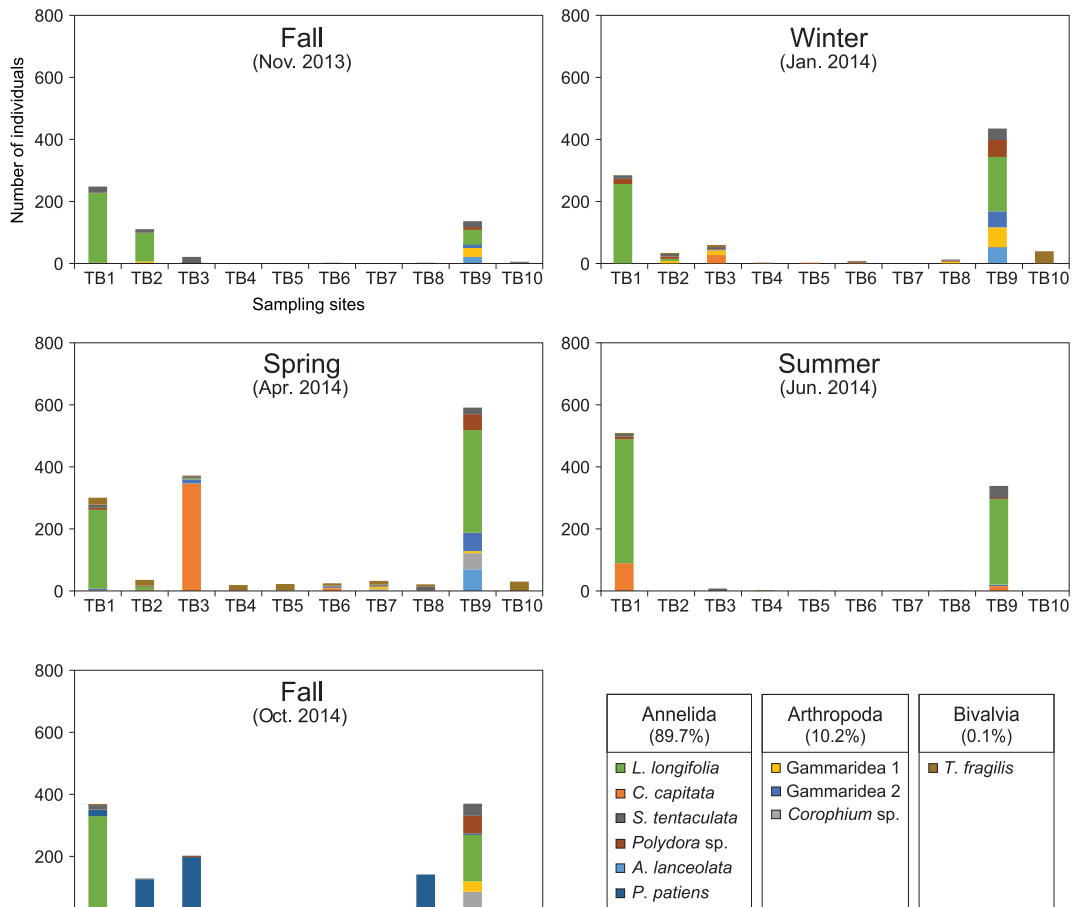


Fig. 2. Seasonal macrozoobenthos distributions (density, ind.  $\text{m}^{-2}$ ) in Jinhae Bay from Nov. 2013 to Oct. 2014; mostly dominated by polychaetes (*A. lanceolata* indicates *Armandia lanceolata*).

seasons) were subjected to further cluster analysis (Fig. S2). The cluster analysis revealed four major groups (Groups I-IV), three minor groups (Groups V-VII), and others (ungrouped organisms), reflecting characteristic temporal and spatial distribution patterns. The four major groups (Groups I-IV in Fig. S2) seemed to be similar to the spectrum of the three earlier-found groups (Groups I-III in Fig. S3). The comparability between these two cluster analyses indicates that, in general, the temporal variation may be less pronounced than the spatial variation. Notwithstanding, the newly observed sophisticated groups seem to indicate that there are certain group-related characteristics for which seasonal variations are of significance.

To better understand the newly observed groups, we scrutinized the environmental variables of seawater and bottom sediments that were associated with macrozoobenthos assemblages (Table 1 and Fig. 3). Group I encompassed 12 datasets, of 50 total (10 locations  $\times$  5 seasons), including all 10 seasonal datasets from TB1 and TB9 (2 locations  $\times$  5 seasons), plus spring data for TB3 and fall data for TB2 (Fig. S2). Group I was highly similar to “other” groups in terms of sediment characteristics such as gravel and sand dominated bottoms; relatively low amount of organic matter; and lighter  $\delta^{13}\text{C}$  values. The large number of species and great faunal density in Group I datasets (Table 1) suggests habitat conditions that are favorable to benthic organisms. The Group I datasets had 13 characteristic species, with *L. longifolia* being the premiere dominant species, making Group I the cluster of the most dynamic assemblages of macrozoobenthos in the study area.

The Group IV seemed to be consequent to a certain event, such as population changes after summer extinctions in the corresponding locations, namely TB2, TB4, TB5, and TB8 (Fig. 2). *P. patiens* (Polychaete: Spionidae) was given as characterizing species of Group IV (Table 1). Most of Spionidae in Korea have increased in July, however, *P. patiens* seemed to delay settlement by reducing postsettlement mortality (Ahn, 2005; Powers et al., 2013).

Altogether, the Group II dataset seemed to be influenced by a combination of multiple environmental variables, while the Group IV dataset may have been associated with a specific time-locked event.

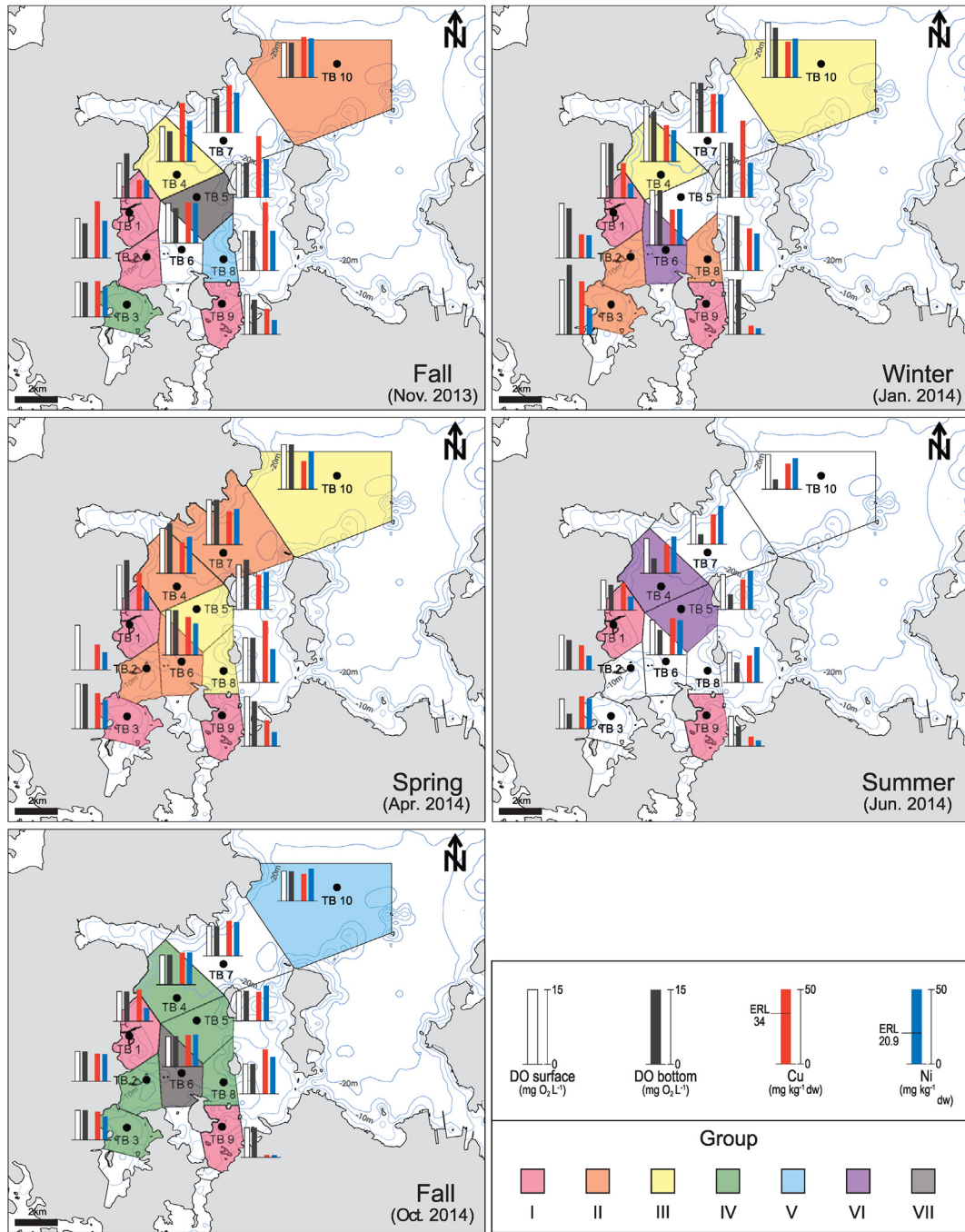
Meanwhile, the Group III was fairly consistent with the former Group III, with the assemblage involving northern locations far from coastal zones. Of note, the sites in Group III regrouped into other minor groups after the summer season, probably due to a lesser association of the macrozoobenthos assemblage with the seasonal changes. Note that half of the summer datasets (5/10) did not cluster into a group, perhaps due to a seasonal effect and/or a heterogeneity across the sampling locations. In other words, they might have been grouped if they had more similar geographical characteristics because they indeed shared similar temporal environmental conditions. Overall, the seasonal variations of macrozoobenthos assemblages observed in this study fairly well reflected an episodic event, namely a summer distinction.

#### 3.4. Association of species composition with environmental condition

Deukryang Bay is semi enclosed bay with relatively lesser anthropogenic stresses. Deukryang Bay is similar to study area in terms of depth, salinity, grain size and range of TOC and TN. Of note, the concentrations of DO in Deukryang Bay were reported to be 4.62–7.27 mg L<sup>-1</sup>, which was similar to those found in Jinhae Bay except for summer. Overall, it seemed that Deukryang Bay represents better benthic ecological condition in terms of species richness and abundance compared to those in Jinhae Bay. In addition it seemed that Deukryang Bay represent much better condition in terms of species richness and abundance than study area. Sediment facies may be a key factor affecting species composition and biomass in coastal areas (Ryu et al., 2011). In fact, because such environmental conditions may change over time and space, it is

**Table 1**  
Characteristics of seawater and sediment samples and key indices for macrozoobenthos communities in the major clustered groups (refer to the spatiotemporal distributions of assemblage groups in Fig. S2).

	Group I	Group II	Group III	Group IV
<b>Seawater</b>				
Temperature (°C)	19.7	13.4	11.5	9.9
Salinity (psu)	31.8	32.9	32.6	32.8
pH	8.0	8.2	8.1	8.0
DO (mg L <sup>-1</sup> )	6.2	8.1	9.2	9.1
<b>Sediment properties</b>				
Grain size ( $\phi$ )	9.8	5.0	8.5	10.0
OC (%)	2.1	1.9	2.2	2.2
TN (%)	0.3	0.2	0.3	0.3
$\delta^{13}\text{C}$ (‰)	-20.7	-21.4	-20.9	-20.7
$\delta^{15}\text{N}$ (‰)	7.3	7.4	7.0	7.1
<b>Key heavy metals</b>				
Cu (mg kg <sup>-1</sup> dw)	17.3	18.7	24.3	28.4
Ni (mg kg <sup>-1</sup> dw)	16.8	11.5	19.9	24.4
<b>Macrozoobenthos</b>				
Number of species	154	59	34	14
Mean density (ind. m <sup>-2</sup> )	2670	244	174	456
Characterizing taxa	<i>Decapoda</i> sp., <i>Dorvillea</i> sp., <i>Eteone</i> sp., <i>Glycera chirori</i> , <i>Heteromastus filiformis</i> , <i>Lumbrineris longifolia</i> , <i>Arcuatula senhousia</i> Nemertinea unid., <i>Ophiodromus</i> sp., Paraonidae unid., Platyhelminthes unid., <i>Praxillella affinis</i> , <i>Prionospio membranacea</i>			<i>Paraprionospio patiens</i>



**Fig. 3.** Spatial and seasonal distributions of macrozoofaunal clustered groups (I to VII, see Fig. S3), concentrations of DO in the water column, and concentrations of Cu and Ni in surface sediments in Jinhae Bay from Nov. 2013 to Oct. 2014.

important to trace such variables after characterizing a baseline pattern in the field.

In the present study, *L. longifolia* was extremely dominant at TB1 (49%) and TB9 (35%). These locations showed less contamination with heavy metals and organic matter than the other ones throughout the sampling periods, and observations indicated better bottom conditions being favorable to macrozoobenthos. Of note, these locations also had distinctive sedimentary properties with sand dominated bottoms and smaller  $\delta^{13}\text{C}$  values with expansive seasonal variation. Such dynamic changes in sedimentary properties might have facilitated the drastic increases in opportunistic taxa observed in these locations (Yu et al., 2013). In anyhow,

sediment contamination by specific heavy metals such as Cu and Ni, of which concentrations far exceeded the sediment quality guidelines of ERL (Long et al., 1995), influenced spatiotemporal changes in species composition (Fig. 3). Metal contamination should have a negative effect on structure and function across taxa, whereas organic enrichment can stimulate the growth and reproduction of some opportunistic species (Rygg, 1986; Wilson and Jeffrey, 1994).

Seawater quality would also be a critical factor influencing population changes in the benthic environment (Chapman and Wang, 2001; Rabalais et al., 2002). Our results revealed a summer distinction of macrozoobenthos in several locations that was

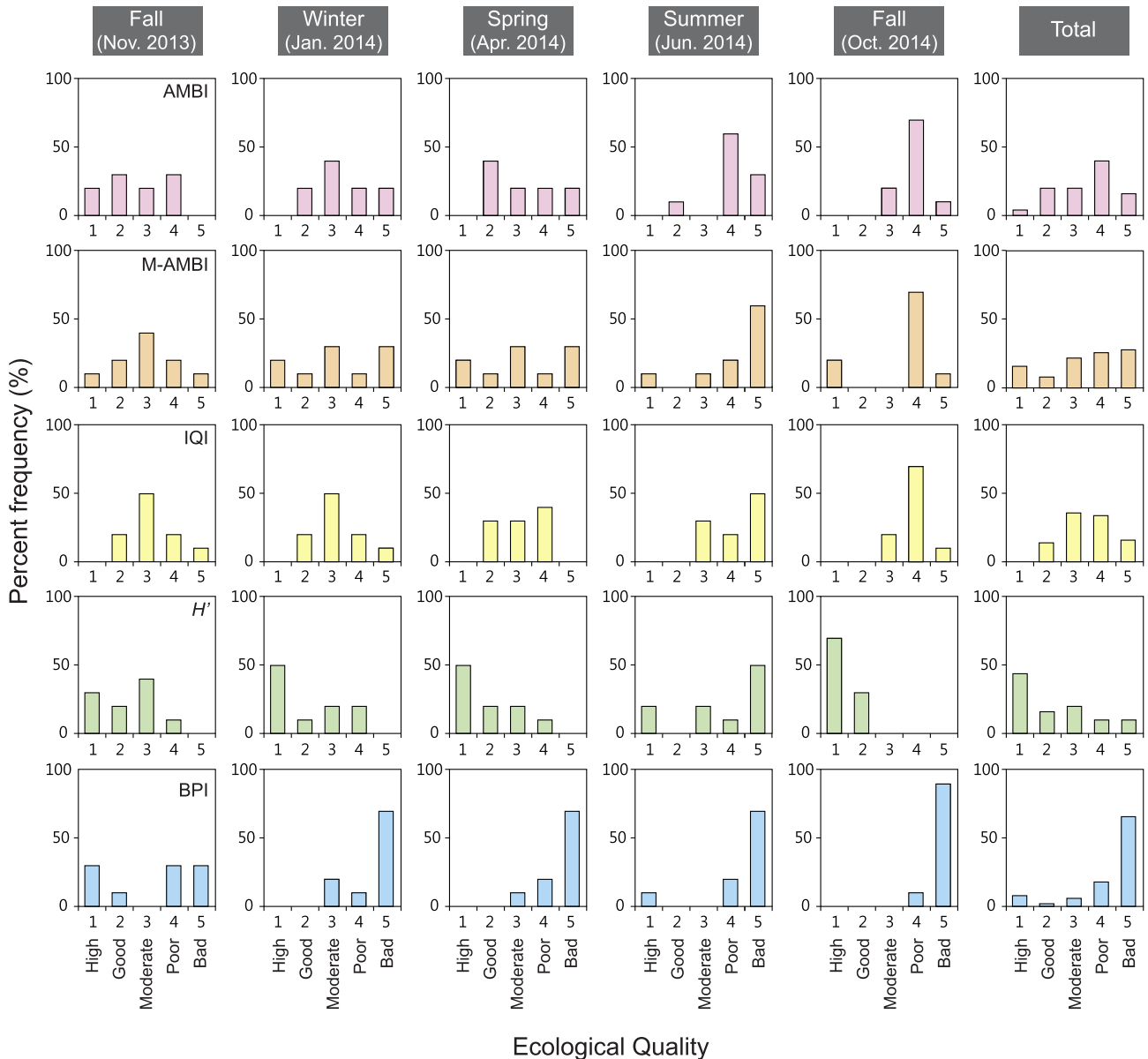
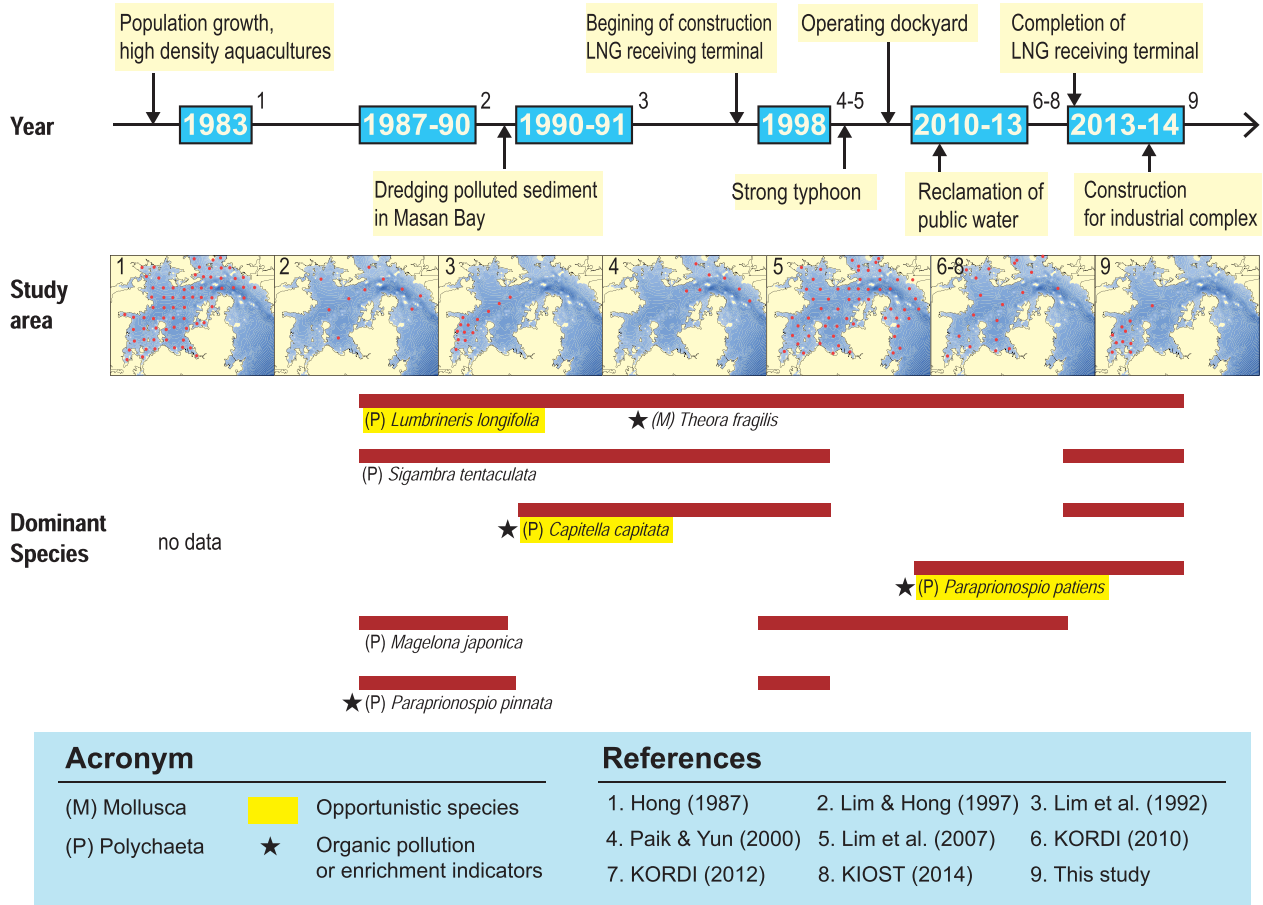


Fig. 4. Percent frequency (%) of EcoQ status based on five benthic indices (AMBI, M-AMBI, EQR,  $H'$ , and BPI) in Jinhae Bay from Nov. 2013 to Oct. 2014.

related to rapid drop of DO in water column, falling down to minimum of  $2.1 \text{ mg O}_2 \text{ L}^{-1}$  (Fig. 3). The sites TB4, TB5, TB7, and TB10 (Group C) generally showed very low species number and abundances of macrozoobenthos throughout the year, indicating the adjacent oyster farming with relatively deeper condition might alter the benthic condition (Forrest et al., 2009). Meanwhile, certain macrozoobenthos species, known as pollution indicators (Shin and Koh, 1990), showed counter-responses to episodic changes in the bottom environment within specific seasons or locations. For example, the peaks of *P. patiens* were observed in many locations in the fall of 2014. These species adapt readily to hypoxic conditions and a great organic matter content in sediments (Pearson and Rosenberg, 1978; Wu, 1982). In this study, a number of *P. patiens* increased suddenly in fall, while other species were barely found. It seems to be caused by ecological characteristics of this species.

Tamai (1996) reported that *P. patiens* has been frequently found in organically enriched area under depleted oxygen concentration in Japanese coastal waters. The larvae of *P. patiens* was

reported to distribute exclusively in water layer with hypoxic condition (Yokoyama, 1995). *P. patiens* was found in Korean coastal waters, mostly shallow mud-dominated bottom, semi-enclosed bay, organic content enriched area, and nearby sewage treatment plant (Yokoyama and Choi, 2010). Larvae of *P. patiens* might have survived in severe environmental condition, depleted oxygen concentration in summer of Jinhae Bay unlike other species. Accordingly, the considerably great total abundance (>90%) of *P. patiens* found at TB2, TB3, TB4, TB5, and TB8 in fall indicated that the very species play an important role as the first recruiters in the given area. However, after summer, the populations seemed to recover to the levels of precedent seasons, though the species compositions in all of the locations had changed substantially. Altogether, the species compositions and their density could be explained generally by time-dependent changes of specific variables in the study area. Overall, the temporally-linked association of macrozoobenthos assemblages with multiple environmental variables would be



**Fig. 5.** Environmental issues and temporal trends of macrozoobenthic communities in Jinhae Bay from 1983 to the present (refer from Hong, 1987; Lim et al., 1992; Paik and Yun, 2000; Lim and Hong, 1997; Lim et al., 2007; KORDI, 2010, 2012; KIOST, 2014; This study). Red lines on the study maps indicate sampling region by literature given. Thick red line represents dominant species reported in Jinhae Bay. No species composition data given from three literatures (Hong, 1987; KORDI, 2010, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

important to resolving their analogous links with varying environmental stressors (Diaz and Rosenberg, 1996).

### 3.5. Ecological quality assessment

The percent frequencies of the five examined ecological indicators  $H'$ , AMBI, BPI, EQR, and M-AMBI demonstrated clear seasonal differences in EcoQ (Fig. 4), as was expected to occur in relation to dynamic seasonal changes in multiple environmental variables. Not surprisingly, the EcoQ indicators were particularly “Bad” in the summer, well reflecting drastic decreases in DO, followed by species populations shifts. The simple biodiversity index  $H'$  seemed to be less sensitive than the other multivariate indicators to sediment pollution. For example, the EcoQ based on  $H'$  was identified as “High” to “Good” in most locations, while that based on most of the other indicators resulted in more “Poor” to “Bad” EcoQ outputs.

In contrast to  $H'$ , the BPI may have overestimated the degree of sedimentary pollution; the EcoQ based on BPI was identified as “Bad” at the majority of locations (Fig. 4). The greatest biodiversity was observed in the spring of 2014, followed by the fall of 2014, although the majority of locations during these periods were identified as having “Poor” or “Bad” EcoQ according to the BPI. Although the BPI was developed and has been utilized in Korea, site-specific application should be considered to minimize such overestimation (Ryu et al., 2016). Overall, the EcoQ results were

useful for demonstrating general ecological conditions and their potential association with sedimentary pollution. However, the agreement between indicators should be recognized.

### 3.6. Comparison with previous studies

The Jinhae Bay area has long been of significant concern due to the repeated reports on the severe contamination in water and sediment qualities being associated with numerous anthropogenic stresses around the coastal areas since the 1980s. The semi-closed highly industrialized bay system with relatively slow seawater circulation allows the accumulated sediment contamination that can deteriorate the benthic environmental conditions. Indeed, a number of macrozoobenthos studies conducted in this region have reported prevailing occurrences of several opportunistic taxa and organic enrichment indicator species over the past couple decades (Fig. 5).

Due to the lack of monitoring study for macrozoobenthos communities during the periods of 1980s–1990s, the long-term changes in benthic ecological qualities could not be fully known. Fortunately, the recent long-term monitoring for 3-year periods has been carried out in Jinhae Bay, which improved our understanding of the seasonal dynamics of macrozoobenthos and annual population changes (KORDI, 2010, 2012; KIOST, 2014). For example, it has been evidenced that the abundance of one opportunistic species of *L. longifolia* was very high with density ranges of 147–417 ind. m<sup>-2</sup>

from those recent studies. They highlighted *L. longifolia* has emerged as dominant species consistently found across seasons and years in Jinhae Bay. *Theora fragilis*, known as representative organic enrichment species, also seemed to occur dominantly for >25 years in the given area. However, it should be noted that the cause effect relationship between specific contamination and macrozoobenthos community changes or alterations has yet to be fully addressed, seemingly due to the dynamic spatiotemporal fluctuations of macrozoobenthos assemblages together with possible integrated species interaction (Woodin, 1974; Waldbusser and Marinelli, 2006).

In the present study, we investigated macrozoobenthos assemblages over five consecutive seasons, focusing on tracking the association of dominant species with environmental variables. The top three dominant species in the present study varied slightly across seasons, but the species that were found to be dominant in this study are consistent with the species reported to be dominant in earlier studies. The repeated occurrence of similar opportunistic species across the bay area over the last 40 years suggests a persistence of environmental stresses in the study area. Although the present study examined macrofaunal associations with environmental changes in representative seasons in varying geographical locations in a general sense, long-term monitoring of the study sites would enable year-round community succession to be fully accounted for, enabling better management of Jinhae Bay in relation to specific concerns.

#### 4. Conclusions

The present study revealed that seasonal macrozoobenthos assemblages in Jinhae Bay was primarily associated with geographical locations which was (in)directly linked to the anthropogenic stresses. The degree of association between spatiotemporal distribution of macrozoobenthos and environmental parameters greatly varied both in time and space. First, the shifts on peak abundances of some dominant species were closely related with the degree of pollution including heavy metals. Summer species distinct was associate with deterioration of bottom water quality, say anoxic condition in the corresponding periods. All the environmental parameters seemed to be responsible for the long-term community changes in location-specific manner. Several locations close to reclamation area, industrial complexes, and oyster farming areas showed relatively bad ecological qualities, which broadly support the direct association between them. In particular, the organic-rich bottoms influenced by the oyster farming area seemed to provide favoring habitat condition to some opportunity species, such as *Capitella* sp. and *P. patiens*. Overall, the macrozoobenthos community in Jinhae Bay has long been exposed to severe environmental pollution with varying anthropogenic stresses, owing to the rapid and continuing development over the past 40 years. The addition of present data to existing meta-data of macrofaunal assemblages would provide better understanding of the long-term ecological changes and characteristics that associated with historical pollution in the given area.

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#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.chemosphere.2016.12.112>.

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## **Impacts of environmental and anthropogenic stresses on macrozoobenthic communities in Jinhae Bay, Korea**

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Table S1. GPS positions of study area sites.

Station	Latitude	Longitude
TB1	34°56'43.47"N	128°25'58.89"E
TB2	34°55'36.55"N	128°26'30.86"E
TB3	34°54'23.34"N	128°25'54.39"E
TB4	34°57'41.35"N	128°27'26.90"E
TB5	34°57'07.10"N	128°28'03.83"E
TB6	34°55'46.75"N	128°27'35.85"E
TB7	34°58'33.22"N	128°28'53.06"E
TB8	34°55'32.60"N	128°28'53.12"E
TB9	34°54'24.47"N	128°28'50.36"E
TB10	35°00'30.50"N	128°32'23.27"E

Table S2. Summary of benthic indices with information including algorithms, remarks, and references.

Biotic indices	Algorithms	Remarks	References
<b><i>Ecological index</i></b>			
Simpson's diversity index ( $1 - \lambda$ )	$1 - \lambda = 1 - N(N - 1) / \sum n(n - 1)$		
Shannon-Wiener diversity index (H')	$H' = - \sum p_i \ln(p_i)$		
<b><i>Multivariate index</i></b>			
AMBI (AZTI Marine Biotic Index)	$AMBI = \{(0 \times \%GI) + (1.5 \times \%GII) + (3 \times \%GIII) + (4.5 \times \%GIV) + (6 \times \%GV)\} / 100$	Organic matter enrichment considered	Borja et al. (2000)
BPI (Benthic pollution Index)	$BPI = \{1 - (a \times N_1 + b \times N_2 + c \times N_3 + d \times N_4)\}$	Feeding type considered	KORDI (1995)
IQI (Infaunal quality index)	$IQI = \{(2 \times (1 - (AMBI/7)) + (1 - \lambda')) / 3\} \times \{((1 - (1 / A)) + (1 - (1 / S))) / 2\}$		Borja et al. (2004)
M-AMBI (Multivariate-AMBI)	$M-AMBI = K + (a \times AMBI) + (b \times H') + (c \times S)$		Muxika et al. (2007)

N: Total number of individuals

S: Number of species

For the AMBI: %GI, relative abundance of disturbance-sensitive species; %GII, relative abundance of disturbance-indifferent species; %GIII, relative abundance of disturbance-tolerant species; %GIV, relative abundance of second-order opportunistic species; %GV, relative abundance of first-order opportunistic species.

For the BPI: N<sub>1</sub>, filter or suspension feeders and large carnivores; N<sub>2</sub>, surface deposit feeders and small carnivores; N<sub>3</sub>, subsurface deposit feeders; and N<sub>4</sub>, opportunistic species and pollution indicators

Table S3. Seasonal variations in environmental variables and macrozoobenthic communities in Jinhae Bay from Nov. 2013 to Oct. 2014.

	Fall (Nov. 2013)	Winter (Jan. 2014)	Spring (Apr. 2014)	Summer (Jun. 2014)	Fall (Oct. 2014)	Mean
<b><u>Environmental variables</u></b>						
Cr (mg kg <sup>-1</sup> dw)	49.3	41.8	42.1	40.5	39.1	42.5
Cu (mg kg <sup>-1</sup> dw)	30.3	25.8	23.5	18.1	19.3	23.4
Pb (mg kg <sup>-1</sup> dw)	18.6	15.3	16.1	13.7	13.5	15.4
Zn (mg kg <sup>-1</sup> dw)	101.9	83.9	82.0	71.5	71.3	82.1
Ni (mg kg <sup>-1</sup> dw)	22.6	19.1	19.5	18.6	18.0	19.6
Li (mg kg <sup>-1</sup> dw)	81.0	72.0	76.5	72.3	71.7	74.7
Cd (mg kg <sup>-1</sup> dw)	0.4	0.3	0.3	0.3	0.2	0.3
As (mg kg <sup>-1</sup> dw)	4.4	4.0	3.4	2.6	2.6	3.4
Hg (μg kg <sup>-1</sup> dw)	3.4	3.3	2.4	2.3	2.4	2.8
OC (%)	2.5	2.4	2.2	2.2	2.0	2.3
TN (%)	0.3	0.3	0.3	0.3	0.3	0.3
δ <sup>13</sup> C (‰)	-20.6	-20.6	-21.1	-21.0	-20.9	-20.8
δ <sup>15</sup> N (‰)	7.0	7.1	7.4	7.1	7.7	7.3
DO (mg O <sub>2</sub> L <sup>-1</sup> )	7.3	10.8	9.3	3.6	6.0	7.4
Temperature (°C)	15.6	6.0	10.6	20.2	20.4	14.6
<b><u>Number of species</u></b>						
Total	63	88	105	70	63	166
<b><u>Mean density (ind. m<sup>-2</sup>)</u></b>						
Total	469	823	1124	64	77	765
1 <sup>st</sup> : TB 1	211	368	254	371	284	297
2 <sup>nd</sup> : TB 9	91	327	499	254	230	280
3 <sup>rd</sup> : TB 2	112	31	27	0	65	47
<b><u>Dominant species (ind. m<sup>-2</sup>)</u></b>						
1 <sup>st</sup> : <i>Lumbrineris longifolia</i>	182	220	299	34	24	255
2 <sup>nd</sup> : <i>Paraprionospio patiens</i>	2	0	0	0	26	52
3 <sup>rd</sup> : <i>Capitella</i> sp.	1	16	174	5	0	49

Table S4. Characteristics of environmental variables measured in seawater and sediment samples from Jinhae Bay, mean values given over the five seasons, from Nov. 2013 to Oct. 2014.

	TB1	TB2	TB3	TB4	TB5	TB6	TB7	TB8	TB9	TB10
Temperature (°C)	14.5	15.9	14.9	14.5	14.5	14.5	14.3	14.9	15.1	11.4
Salinity	32.6	32.6	32.7	32.9	32.8	32.8	32.9	32.9	33.0	32.6
pH	8.3	8.2	8.0	8.0	8.0	8.0	8.4	8.1	8.1	8.2
DO (mg/L)	8.1	7.4	7.8	7.0	7.3	7.7	6.8	7.5	7.1	8.7
Depth (m)	11	16	14	20	20	17	23	16	19	24
Grain size	4.0	9.8	9.7	10.1	10.1	9.8	10.1	9.8	3.5	10.0
OC (%)	1.0	2.9	2.3	2.3	2.8	2.6	2.3	2.1	2.4	1.7
TN (%)	0.1	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.1	0.2
Cr (mg/kg)	24.9	35.0	42.4	50.0	52.0	50.3	51.0	45.6	24.9	49.2
Cu (mg/kg)	19.8	21.2	24.8	24.8	31.0	24.3	24.7	27.1	15.3	21.0
Pb (mg/kg)	14.9	14.7	16.4	15.7	15.0	17.6	17.0	16.3	9.1	17.4
Zn (mg/kg)	74.0	69.8	83.1	84.0	98.6	96.0	94.3	84.2	48.4	88.9
Ni (mg/kg)	10.4	16.0	18.7	23.6	24.6	23.2	24.9	24.5	5.7	24.1
Li (mg/kg)	74.4	68.7	93.4	85.8	81.1	80.2	83.0	76.0	21.6	82.8
Cd (mg/kg)	0.1	0.4	0.3	0.4	0.5	0.4	0.3	0.3	0.1	0.2
As (mg/kg)	2.7	4.8	4.3	3.1	3.4	3.7	2.9	3.4	2.9	2.3
Hg (µg/kg)	5.0	1.5	2.3	2.0	2.0	1.8	2.3	3.2	2.9	4.6
δ <sup>13</sup> C (‰)	-22.3	-20.6	-20.7	-20.7	-20.6	-20.4	-20.7	-20.5	-21.1	-20.7
δ <sup>15</sup> N (‰)	6.4	6.8	6.9	7.2	7.5	7.6	7.8	7.6	8.4	6.6

Table S5. Spatial-seasonal variation of bottom dissolved concentration (mg O<sub>2</sub>L<sup>-1</sup>)

<b>Station</b>	<b>Fall (Nov. 2013)</b>	<b>Winter (Jan. 2014)</b>	<b>Spring (Apr. 2014)</b>	<b>Summer (Jun. 2014)</b>	<b>Fall (Oct. 2014)</b>
TB1	8.8	10.5	9.7	5.5	6.2
TB2	7.4	10.4	9.3	5.9	5.9
TB3	7.4	13.7	9.2	3.2	5.7
TB4	6.3	10.2	9.8	2.7	6.0
TB5	7.4	10.6	9.6	2.8	6.1
TB6	7.2	10.8	9.5	4.5	6.4
TB7	6.5	10.5	9.2	2.1	5.7
TB8	7.8	10.6	9.0	3.8	6.1
TB9	6.7	10.5	8.7	3.5	5.8
TB10	7.3	10.5	9.0	2.1	6.0

Table S6. Complete list of macrozoobenthos from Jinhae Bay (n=10) for 5 seasons. The densities of each species is given (ind. m<sup>-2</sup>).

Taxa	TB1	TB2	TB3	TB4	TB5	TB6	TB7	TB8	TB9	TB10	SUM
<i>Lumbrineris longifolia</i>	1457	108	4	2	1	1	1		979		2553
<i>Paraprionospio patiens</i>	20	125	201	11	16	1		140	5		519
<i>Capitella capitata</i>	90	2	372		3	10			18		495
<i>Sigambra tentaculata</i>	65	21	41			6	3	20	156	5	317
<i>Polydora</i> sp.	34	13	6	1		5	2	3	175	1	240
<i>Theora fragilis</i>	27	23	8	22	21	8	12	8		73	202
Gammaridea 1	5	15	16		1	1	6	8	132	1	185
Gammaridea 2	6	1	15	1		5	2		124	1	155
<i>Corophium</i> sp.	5						5		137		147
<i>Armandia lanceolata</i>		1					1		145		147
<i>Notomastus</i> sp.	113	4							14		131
<i>Praxillella affinis</i>	98	10	1		1	1		3	9		123
<i>Dorvillea</i> sp.	12	14	1			1			84		112
<i>Chone teres</i>	38		1			7			60		106
<i>Mediomastus</i> sp.	66	23							12		101
<i>Macoma</i> sp.	82		4	1		1				1	89
<i>Paraprionospio coora</i>	59	2	5	1				3	6	6	82
<i>Heteromastus filiformis</i>	62	9			1				9		81
<i>Salpa</i> sp.	1	3				4		1	71		80
<i>Prionospio membranacea</i>	22	30					1	4	18		75
<i>Marphysa</i> sp.	55	6							1		62
Paraonidae	42	1	4						13	1	61
<i>Euchone</i> sp.	9	5		1	1	9		7	25	3	60
<i>Prionospio</i> sp. 2	42								16		58
<i>Glycera chirori</i>	24	4						1	23		52
<i>Mesochaetopterus</i> sp.	4	2		2	1		4	5	20	12	50
<i>Musculus senhausia</i>	13			1		1			34	1	50
<i>Euchone analis</i>									48	1	49
<i>Polydora carunculata</i>		1	2				1		43		47
<i>Ophiodromus</i> sp.	6	8		3	1			1	24		43
<i>Praxillella pacifica</i>	43										43
<i>Prionospio</i> sp. 1	17		6	1	1		1		13	2	41
<i>Nephtys polybranchia</i>	35							3	3		41
<i>Nicomache minor</i>									39		39
Thaliacea			10			2		3	23		38
<i>Polydora ciliata</i>									35		35
Decapoda sp.	18	1	8				1	1	4		33
<i>Eunice aphroditois</i>	30										30
Nemertinea	19	1	1						9		30
Stomatopoda sp.	2	1	1	12	7	1	3	1		1	29
Alpheidae	2	6	6			3		4	6	1	28
<i>Praxillella praetermissa</i>	28										28
Gammaridea 7	27										27
Nematoda	26										26
<i>Oratosquilla oratoria</i>		1	2	5	10		5	1			24
<i>Aricidea simplex</i>	6	4	1					2	10		23

<i>Eteone</i> sp.	8	1						14		23	
<i>Moerella</i> sp.	23									23	
<i>Praxillella</i> sp.	9	1			1	6		6		23	
<i>Gaprella</i> sp.	1	1	9				1	2	5	1	20
<i>Caprella</i> sp.	13	2	5								20
Gammaridea 3				1					19		20
Gammaridea 5	1								19		20
Platyhelminthes	11	1	1					1	6		20
<i>Maldane cristata</i>	18										18
<i>Mytilus</i> sp.				1	1				14		16
<i>Tharyx</i> sp.	6							2	8		16
Polynoidae	5		1	1		2	2		4		15
<i>Chone</i> sp.	14										14
<i>Heterospio</i> sp.									14		14
<i>Thelepus</i> sp.	5	1	4		1	3					14
<i>Cirratulus cirratus</i>	1	3							8		12
<i>Nectoneanthes multignatha</i>	5								4	3	12
<i>Amaeana</i> sp.	10	1				1					12
<i>Amphitrite</i> sp.	11										11
<i>Anaitides</i> sp.	3	1	4						3		11
<i>Eunice</i> sp.	10								1		11
Gammaridea 4								2	9		11
Cirripedia								4	6		10
<i>Glycinde</i> sp.	8			1						1	10
<i>Magelona japonica</i>									10		10
Mytilidae	3								7		10
<i>Pista</i> sp.	10										10
<i>Pseudopolydora</i> sp.	4		3			2			1		10
<i>Ruditapes philippinarum</i>								1	9		10
Cumacea							1		8		9
<i>Aricidea hartleyi</i>			4						5		9
Ostracoda									9		9
<i>Glycera onomichiensis</i>	8								1		9
Bivalvia 1	6	2									8
<i>Terebella</i> sp.	4							1	3		8
<i>Eunice indica</i>	7										7
Sabellidae	4								3		7
Tanaidacea						5		1	1		7
<i>Amaeana trilobata</i>	2		2			2					6
<i>Anaitides maculata</i>	3								3		6
<i>Dorvillea rubrovittata</i>	6										6
Gammaridea 6	1			3		1					5
Holothuroidea	1	3							1		5
Ophiuroidea	5										5
<i>Syllis</i> sp.		1							4		5
<i>Amphisamytha</i> sp.									4		4
<i>Eulalia</i> sp.			4								4
Gastropoda									4		4
<i>Paraprionospio</i> sp.										4	4
Sipunculida									4		4
Spionidae				1			2				3

<i>Arcuatula senhousia</i>	3									3
<i>Balanus</i> sp.		3								3
Bivalvia 8	3									3
<i>Chaetozone setosa</i>							3			3
<i>Crepidula gravispinosa</i>								3		3
Fulviamutica	1							2		3
<i>Goniada</i> sp.	2	1								3
<i>Phylo</i> sp.					3					3
<i>Pugettia quadridens</i>		1						2		3
<i>Pista cristata</i>	1					1				2
Anthozoa							1	1		2
Asterozoa	1						1			2
Bivalvia 12	1							1		2
Bivalvia 2								2		2
Bivalvia 9								1	1	2
Carditidae								2		2
<i>Glycera capitata</i>	2									2
<i>Glycera</i> sp	2									2
<i>Haloa</i> sp	2									2
<i>Nephtys ciliata</i>	1							1		2
<i>Pagurs</i> sp.			1					1		2
<i>Poecilochaetus johnsoni</i>	1	1								2
<i>Polydora cardalia</i>	2									2
<i>Protodorvillea</i> sp.	2									2
<i>Protothaca jedoensis</i>	2									2
<i>Spio</i> sp.	2									2
Bivalvia 4						1				1
<i>Amage</i> sp.								1		1
Ammonotheidae								1		1
<i>Anaitides koreana</i>								1		1
<i>Arca</i> sp.								1		1
<i>Atrina pectinata</i>								1		1
Bivalvia 10								1		1
Bivalvia 11								1		1
Bivalvia 13								1		1
Bivalvia 14								1		1
Bivalvia 15								1		1
Bivalvia 3								1		1
Bivalvia 5	1									1
Bivalvia 6	1									1
Bivalvia 7	1									1
Brachyura					1					1
<i>Brada</i> sp.								1		1
<i>Ceratonereis erythraeensis</i>	1									1
<i>Diopatra bilobata</i>								1		1
Eunicidae								1		1
Goniadidae			1							1
<i>Haploscoloplos elongatus</i>								1		1
<i>Hydroides</i> sp.								1		1
<i>Lagis bocki</i>						1				1

<i>Lima</i> sp.									1		1
<i>Macroschisma</i> sp.									1		1
Maldanidae				1							1
<i>Megacardita</i> sp.	1										1
<i>Micropodarke</i> sp.	1										1
<i>Neanthes caudata</i>									1		1
<i>Nereis longoir</i>				1							1
<i>Nereis multignatha</i>									1		1
<i>Petrama pusilla</i>									1		1
<i>Pherusa plumosa</i>									1		1
<i>Pherusa</i> sp.									1		1
<i>Prionospio steenstrapi</i>	1										1
<i>Pseudopolydora antennata</i>									1		1
<i>Pseudopotamilla ocellata</i>									1		1
<i>Scolelepis</i> sp.	1										1
<i>Spiophanes bombyx</i>	1										1
<i>Terebellides horikoshii</i>	1										1
<i>Upogebia</i> sp.							1				1
Veneridae									1		1

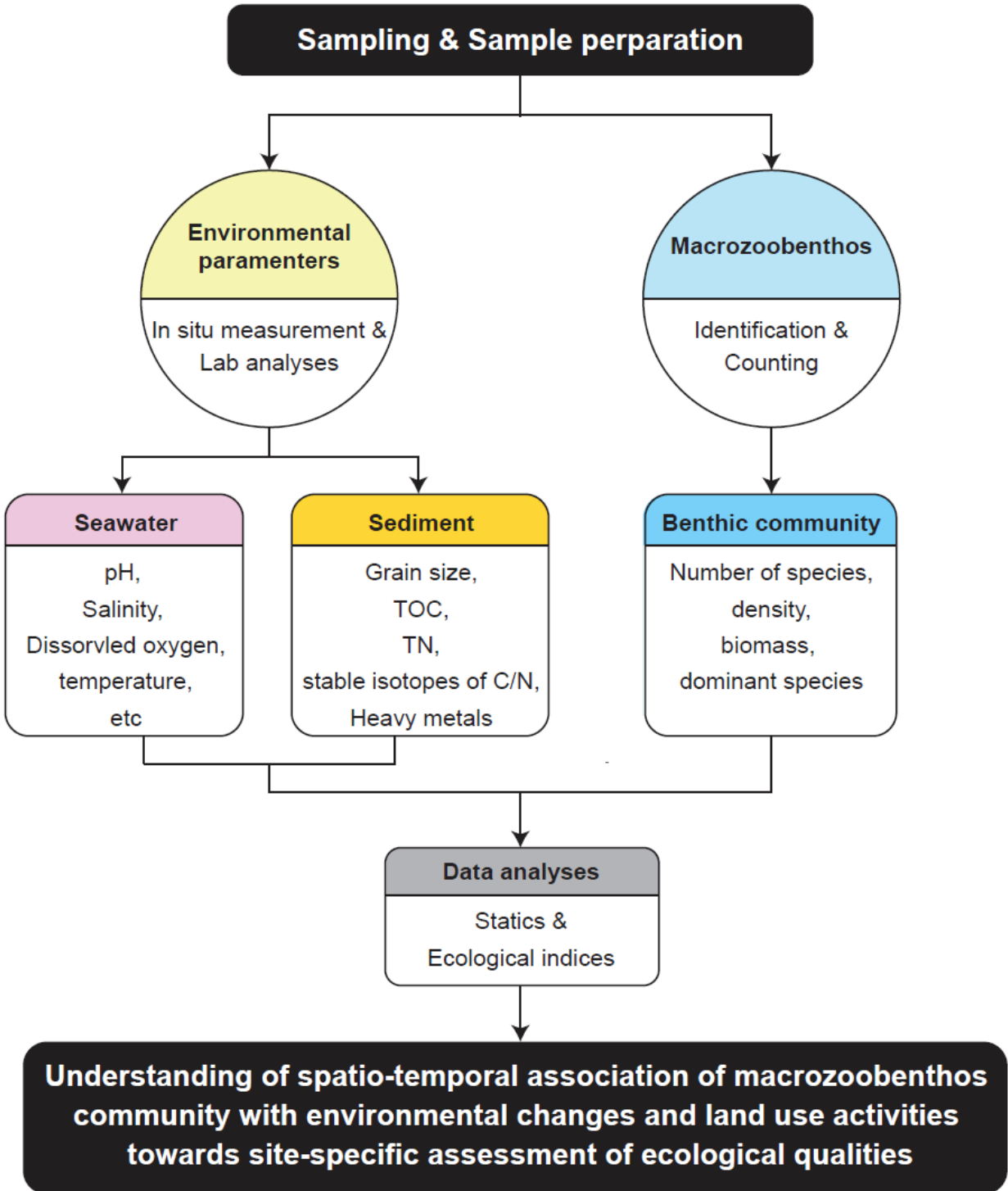


Fig. S1. Flowchart showing the study design and detailed target endpoints.

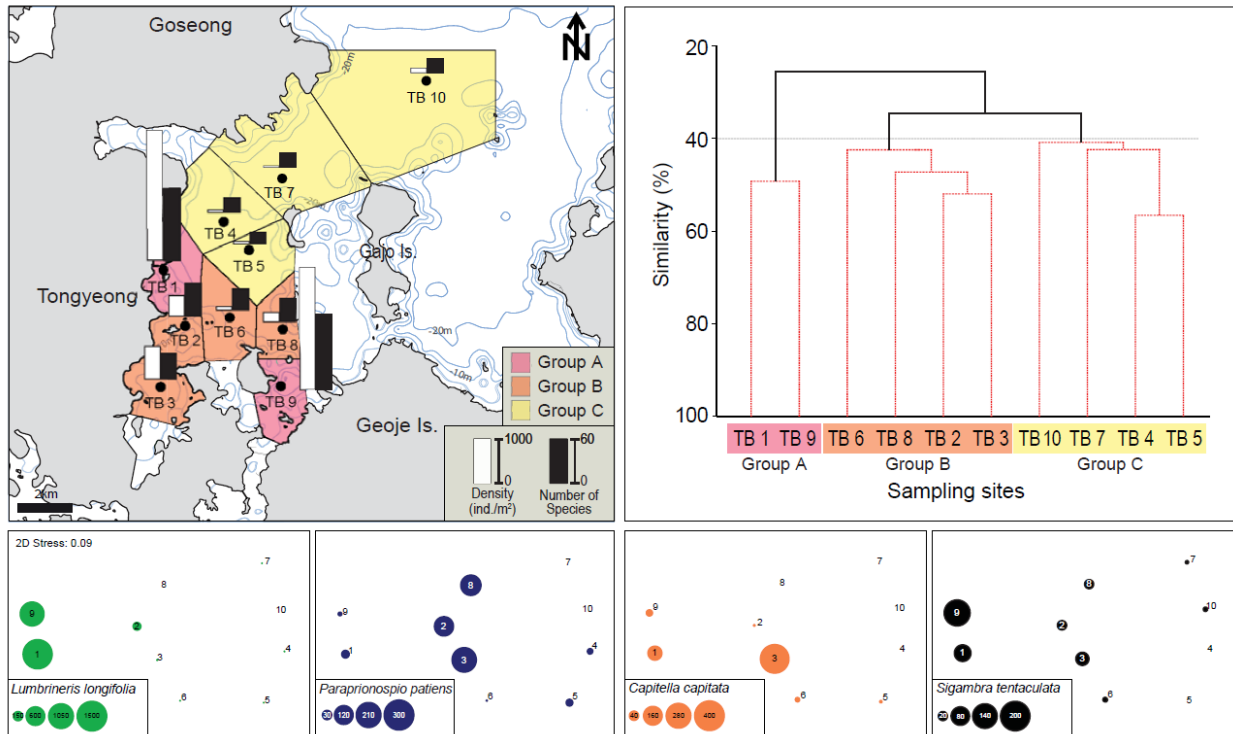


Fig. S2. Cluster analysis and non-metric MDS ordination of 10 locations in terms of macrofaunal species composition and abundance, focusing on the four dominant species in Jinhae Bay from Nov. 2013 to Oct. 2014

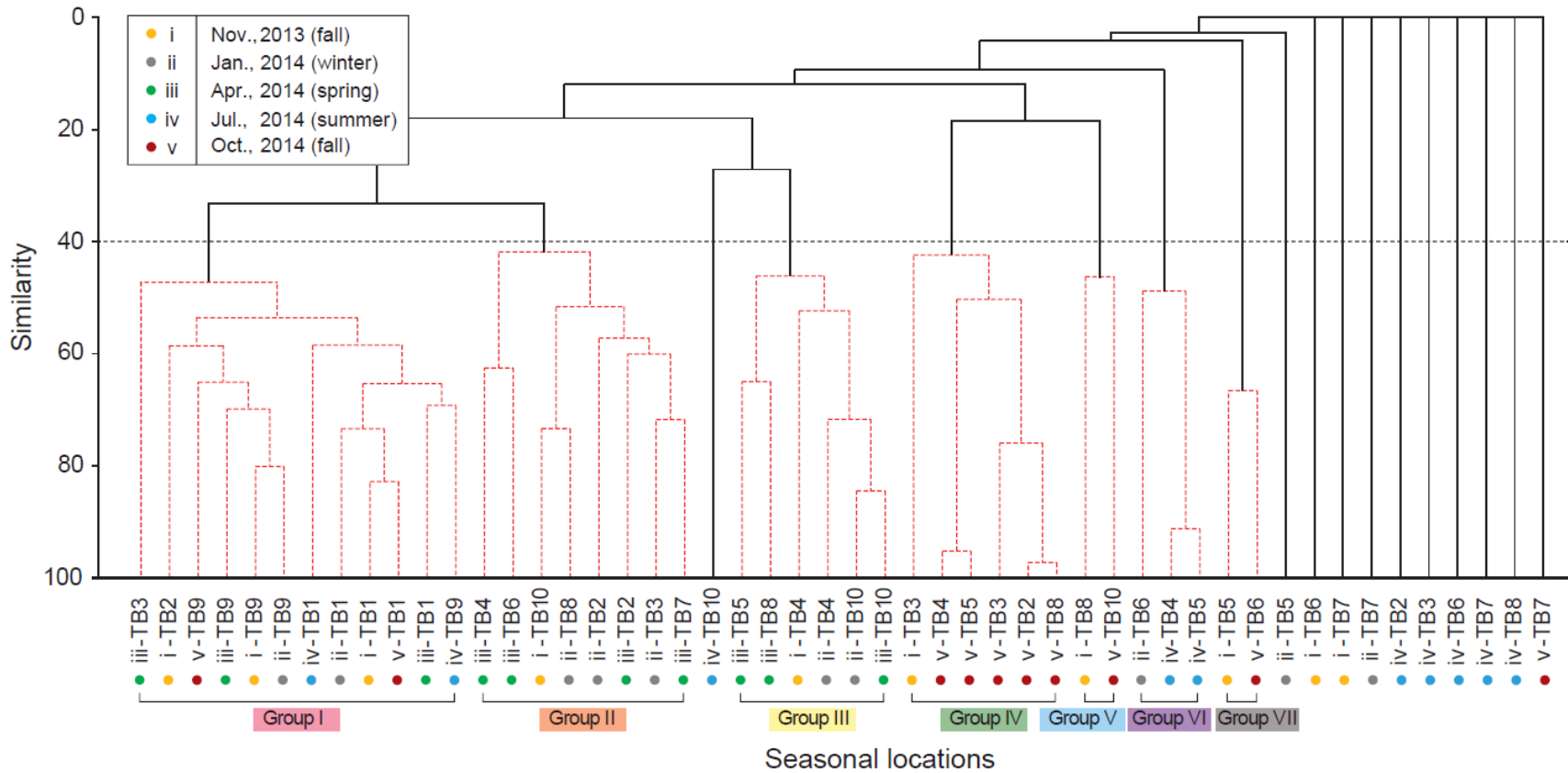


Fig. S3. Cluster analysis of all 50 datasets (10 locations  $\times$  5 seasons) in terms of macrofaunal species composition and abundance in Jinhae Bay from Nov. 2013 to Oct. 2014.