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# Rapid recovery of coastal environment and ecosystem to the *Hebei Spirit* oil spill's impact

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ABSTRACT

The 2007 *Hebei Spirit* oil spill (HSOS), the largest in the national history, has negatively impacted the entire environment and ecosystem along the west coast of South Korea. Although many studies have reported the damages and impacts from the HSOS, quantitative assessment evaluating the recovery time and status have not been documented. Here, we first address the recovery timeline of the HSOS, by comprehensive analyses of 10-years accumulated data in quantitative manner. Concentrations of residual oils in seawater, sediments, and oysters rapidly dropped to backgrounds in 16, 75, and 33 months, respectively. Also, damaged benthic communities of intertidal and subtidal areas were fully recovered only after ~6 years. The present results collectively indicated unexpectedly fast recovery of the damaged environment and ecosystem from such a huge oil spill. The high tidal mixing (~9 m tidal height) and intensive human cleanup (~1.2 million volunteers) at the initial cleanup period might have contributed to rapid recovery; cf. 4–5 times faster than the *Exxon Valdez* oil spill. However, potential risk to human health remains unclear. Thus, it is warranted to conduct more in depth epidemiological studies to address chronic health effects associated with the cleanup volunteers as well as the local residents who have been living nearby the oil spill impacted sites.

## 1. Introduction

The 2007 *Hebei Spirit* oil spill (HSOS) severely disturbed the entire ecosystem along the western coast of South Korea (Hong et al., 2014; Yim et al., 2017). The incident released 10,900 tons of three types of crude oil (Iranian Heavy, United Arab Emirates Upper Zakum, and Kuwait Export) into the sea, and contaminated over 200 km of coastline within one month (Hong et al., 2014; Yim et al., 2017). The spilled oil was distributed in intertidal areas, covering oyster farms and natural beaches within one day (Kim et al., 2017). The intertidal ecosystem was severely disturbed, and oil-sensitive organisms were eradicated (Yu et al., 2013; Seo et al., 2014). The local economy, which is highly dependent on subsistence and commercial fisheries, collapsed temporarily.

The degradation of residual oil in the environments was strongly dependent on the media (water, sediments, or porewater) and substrates (grain size, organic carbon contents, etc.) (Natter et al., 2012), microbial community and activity (Lee et al., 2019a,b), natural energy (e.g., tidal flushing) (Hong et al., 2012), and initial cleanup activity (NOAA, 2013). Residual oils in sediments, compared to seawater, are more persistent and can exist for long periods of time in low energy regions (Hong et al., 2012; Yim et al., 2012; Kim et al., 2017). In addition, adverse effects of residual oils on marine organisms are affected by both concentrations of oil and the degree of oil weathering (Hong et al., 2012). In general, as more weathering of oil progresses, the toxicity of residual oil in environmental media on living organisms is

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considered to decrease due to the reduction of bioavailable toxic compounds in oil (Neff et al., 2000; Jonker et al., 2006; Di Toro et al., 2007; Hong et al., 2016). Intertidal organisms appear to have been eradicated initially and then sequentially recolonized from opportunistic species (Yu et al., 2013; Jung et al., 2014; Seo et al., 2014). In terms of environmental management, it is important to make quantitative judgments of ecosystem recovery. However, no clear and easy criteria for judging ecosystem recovery have been documented until now.

After the HSOS, central Korean Government and local authorities immediately responded by placing tremendous efforts on implementing a comprehensive cleanup over several months (details presented in the Table S1 of Supplementary Materials) (MLTM, 2009; Hong et al., 2014). More importantly, there was an intensive human effort (> 2.1 million people), with ~1.2 million volunteers and ~0.9 million residents, military personals, and others, during the cleanup period (Hong et al., 2014). Yet, the contingency plan responses were not sufficiently organized, failing to distribute protective equipment to personnel who participated in the early part of the cleanup (Na et al., 2012). Consequently, many people might have been heavily exposed to toxic oil chemicals (primarily volatile organic chemicals), during the cleanup period; however, follow-up human health studies have been lacking (Sim et al., 2010; Ha et al., 2012; Na et al., 2012; Krishnamurthy et al., 2019).

On developing a national contingency plan, following the designation of a special management area for the oil affected region, the Korean Government initially launched a long-term (10-year) monitoring and restoration project, with a total budget of ~20 million USD. Topics and concerns included the integrated ecosystem monitoring of (i) residual oil in the environment, (ii) residual toxicity, and (iii) recovery of the coastal ecosystem (Yim et al., 2012; Hong et al., 2014; Yim et al., 2017). Until now, over 130 peer-reviewed journal articles have been published relating to the single case of the HSOS incident, advancing our understanding of oil spill science and its global significance. However, a clear quantitative assessment of the resilience status of the coastline in the context of 'recovery' is lacking.

Here, we compile and analyze the highly comprehensive 10-years national monitoring dataset to address the timeline of qualitative and quantitative recovery of the ecosystem from the HSOS. The specific objectives of the present study were to (1) summarize long-term ecosystem monitoring data in aspects of chemistry, toxicology, and ecology, (2) determine recovery time of individual components of ecosystem, (3) assess local economy and human health, and finally (4) suggest future research directions based on the current limitations and knowledge gaps.

## 2. Materials and methods

### 2.1. Sampling strategies and sample collection for multiple environmental media

Seawater (n = 1027) and sediments (n = 1004) were collected from the intertidal and subtidal areas of Taean Region (South Korea) from 2007 to 2016 (Fig. S1). Subtidal seawater samples were collected to large areas (~100 km off coastline) immediately after the HSOS, and from 2008 to 2011 near the coastline (within ~20 km). Sediment samples were collected from the intertidal regions of concern and analyzed for assessing the extent of oil contamination. In particular, spatial and temporal variations in oil-derived substances were investigated. Surface sediments were sampled monthly (7 sites), seasonally (30 sites), and area-wide (70 sites) from December 2007 to December 2008. Thereafter, sediment oil contamination was investigated seasonally, or once a year, beginning in 2009. Based on the results of these surveys, districts with relatively high residual oil levels were selected for surveying the following year.

Sogeunri intertidal (60 sites) and mid-to-low intertidal mudflat porewater (69 sites) samples were collected in October 2012 and July 2013 (locations are shown in Fig. S2 and results are shown in Fig. S3). Thereafter, concentrations of total petroleum hydrocarbon (TPH) in porewater were investigated seasonally, or once a year, from 2014 (Kim et al., 2017). To understand the distribution of oil affecting intertidal sand beaches in more detail, monitoring was conducted at recreational beaches where continuous oil contamination was observed in the previous surveys (results are shown in Fig. S4) (Yim et al., 2012). Residual oil is likely to persist for a long time on boulder-covered beaches, because low-permeability sediments protected the oil from washing and erosion, due to the armor provided by surface boulders and cobbles (Hayes et al., 2010; Nixon and Michel, 2018). Comprehensive investigations were carried out at Garumi and Gurumpo in 2013, where oil was frequently observed (results are shown in Fig. S5). Core sampling was performed after removing surface boulders and cobbles using an excavator to assess subsurface residual oil. TPH in sediments was analyzed to determine the residual oil on boulder-covered beaches. The vertical distribution of subsurface residual oil on armored shorelines was observed at depths of 10–20 cm.

Petroleum-derived polycyclic aromatic hydrocarbons (PAHs) in oysters collected along the Taean Peninsula were analyzed to identify the current impact of the spill and spatiotemporal variation of impact. This investigation was carried out at 32 sites from Garorim Bay to Anmyeondo (oyster, n = 509) from 2007 to 2016 (Kim et al., 2013). The samples were stored in pre-cleaned amber glass bottles (with Teflon lined screw caps) that were combusted at 450 °C for 4 h before use. Collected seawater, sediments, and oyster samples were immediately frozen and stored at −20 °C before analysis.

### 2.2. TPH and PAHs analyses

TPH was analyzed by gas chromatography using a flame ionization detector (GC-FID, Agilent Technologies 7890A GC System, Santa Clara, CA) following liquid–liquid extraction with dichloromethane for seawater or Soxhlet extraction with dichloromethane for sediment (Hong et al., 2012). Bivalve (oyster) samples were Soxhlet extracted and cleaned using a silica-alumina column and high-performance liquid chromatography with a size-exclusion column (Hong et al., 2012). PAHs were analyzed by gas chromatography-mass selected detector (GC-MSD, Agilent Technologies), following methods described previously (Yim et al., 2012; Kim et al., 2017). Chemistry data was partially reported in the previous study (Kim et al., 2017). Method detection limits for PAHs analysis ranged from 0.13 to 3.4 ng $g^{-1}$. Surrogate standard (naphthalene-d8, acenaphthene-d10, phenanthrene-d10, chrysene-d12, and perylene-d12) recoveries in samples ranged from 75 to 125%. In addition, accuracy for PAHs analysis was assessed with standard reference material (NIST 1944, New York/New Jersey Waterway Sediment), and measured concentrations of PAHs in NIST 1944 were within 20% of the certified concentrations.

### 2.3. 7-ethoxy-resorufin O-deethylation (EROD) analysis

Fish were caught in Euhangri, Taean Region, during December 2007 and May 2017 using a fyke net (Figs. S1 and S2). Fish livers were carefully dissected and immediately frozen in liquid nitrogen. The samples were placed in cryotubes and stored at −80 °C. Liver tissue was homogenized in 0.1 M phosphate buffer, pH 7.6 (Jung et al., 2011). The homogenized supernatant was transferred to a fresh tube and stored at −80 °C until analysis. The *O*-dealkylations of ethoxyresorufin were determined in the liver of fish collected from oil spill affected areas using the method described previously (Addison and Payne, 1986). Microsomal protein concentrations were determined using the bicinchoninic acid method (Pierce Chemicals, Rockford, IL) with an autoanalyzer (microplate reader at 550 nm) using bovine serum albumin as the standard. The biomarker data was partially reported in the previous study (Yim et al., 2017).

### 2.4. Toxicity testing

Whole-sediment toxicity tests in amphipods (*Monocorophium uenoi*) were conducted based on standard procedures (Lee et al., 2013). The test sediments were sieved through a 300 μm mesh screen and then homogenized (Fig. S1). The test chambers were constructed with four replicates of 1 L glass beakers containing 175 mL sediment and 800 mL filtered seawater (salinity 32 psu). Twenty individuals of *M. uenoi* (size range 350–500 μm) were placed in each chamber and maintained at 20 ± 1 °C for 10 days. The number of replicates was 4 for each sample. After 10 days, the sediments were sieved through a 300 μm mesh screen to collect live animals. The sediment samples were also collected from the control site (Yeongjong Island), which is located at about 70 km north from the oil spill site and was not affected by the HSOS. The results of toxicity test in Taean regions were compared with those of control site using Dunnett's *t*-test to determine if each sample was significantly toxic. The range of amphipod mortality in control sample was 10–18%. More detail information about toxicity tests was reported previously (Lee et al., 2013).

### 2.5. Macrobenthic community structure analysis

Assessments of the macrobenthic communities in intertidal regions were carried out during 2008–2015 to determine their recovery status after the oil spill. Two random samples for macrobenthos of rocky shores were collected at each site using a 0.0625 $m^2$ (25 × 25 cm) quadrat and eight samples for macrobenthos from soft tidal flats using a 0.025 $m^2$ can core (MLTM, 2009; Yu et al., 2013; Jung et al., 2014). Macrobenthic organisms were fixed in 10% formaldehyde solution and sorted for taxonomic identification using a microscope. Macrobenthic fauna was also collected in the subtidal region from January 2008 to October 2010. Three samples were collected using a Smith-McIntyre grab (covering 0.1 $m^2$). Whole sediments were sieved through a 1 mm mesh screen. Pooled samples were fixed using 10% formalin buffered with seawater (Seo et al., 2014).

### 2.6. Data collection for fisheries and tourism

Fisheries and tourism data were collected from the Korean Statistical Information Service website (http://kosis.kr/index/index.do) and Statistical Yearbook for the Taean Peninsula (http://taean.go.kr/prog/eBook/E01/area/sub06_04/list.do?pageIndex=1&siteCode=area&mno=sub06_04) to investigate the recovery status of the ecosystem and human health after the oil spill (Cheong, 2012a).

### 2.7. Data collection for the incidence of human cancer

Trends in the incidence of human cancer were obtained from the Division of Cancer Registration & Surveillance of the Korean National Cancer Control Institute and the Korean Statistical Information Service website (http://kosis.kr/index/index.do) for 1999–2013 (Choi et al., 2018).

### 2.8. Data analyses

Temporal trends in residual oil, including total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs), in seawater, sediments, and oysters in the Taean area after the HSOS were assessed using exponential decay model in SigmaPlot (Version 10.0, Systat Software GmbH, Erkrath, Germany). The relationship between concentrations of PAHs in sediments and amphipod mortality was investigated using the sigmoid model equation (SigmaPlot). Spatial and vertical distributions of residual oil (e.g., PAHs) in environmental media were visually mapped using GIS-based thematic mapping method (ArcGIS 9.2, ESRI, Redlands, CA). ANOVA test (one-way analysis of variance test) was performed to evaluate the significance of the increase and/or decrease of fisheries production in the oil spilled region before and after the HSOS using SPSS 23.0 software (SPSS Inc., Chicago, IL).

## 3. Results and discussion

### 3.1. Residual oils in seawater, sediments, and biota

The residual oil was monitored at > 1200 locations (> 2500 samples) along the oil spill impacted the coast of Taean, over the past 10 years. The target priority chemicals included TPH and PAHs and their alkylated forms, but not limited to various weathering compounds. Samples of seawater, sediments, and biota (e.g., oysters) were collected from various impacted areas of the intertidal (sand flats, mudflats, and rocky shores) and subtidal zone Figs. 1 and S1). Immediately after the oil spill, great concentrations of TPH in seawater from the intertidal and subtidal areas were found with maximum of > 100,000 μg $L^{-1}$. But the TPH concentrations rapidly decreased and dropped to levels below the Korean water quality guideline (10 μg $L^{-1}$) after 1–2 years only. Since then, seawater has been judged to have fully recovered, accordingly no further monitoring has been made.

In sediments, residual oils were found for a longer period of time compared to those in seawater. The spatial distribution of PAHs in sediments varied widely, both regionally and within the study sites, primarily due to the patchy distribution of spilled oils in the intertidal areas and sediment heterogeneity (Hong et al., 2012). However, the concentrations of the target compounds in intertidal sediments generally decreased over time except for the hotspot area, particularly in the intertidal zone, with relatively great concentrations being recorded in the subsurface layer (Hong et al., 2012, 2014). Several factors were associated with such persistent oiled hotspots; i.e., low tidal energy at some sites, the lack of flushing out residual oils in the upper intertidal zone, and/or delayed cleanups near aquaculture sites (Fig. S3) (Jackson et al., 1989; Hong et al., 2012, 2014). Furthermore, oil weathering, particularly in intertidal benthic hotspots, might have influenced the persistence of residuals and potential toxicities through site-specific exposure conditions associated with the tide (Fig. S4). In particular, residual oil trapped in the bedrock along the rocky shores accumulated over a long period in the bottom layer, due to the lack of natural weathering (Fig. S5). Various bioremediation techniques for recovering oil-contaminated environments such as increasing the activity of oil-degrading bacteria to promote the decomposition of residual oil have been introduced (Lee et al., 2019a,b). It would be also beneficial to use a method of tilling and mixing to allow trapped oils being exposed in the natural environment (Owens and Sergy, 2004). Although cleanup efforts during the initial phase of HSOS have been intensively given, relatively lack of remediation activities were followed. It was fortunate that high tidal mixing under macro-tidal environment in the spilled site seemed to aid natural timely recovery (Kim et al., 2013; Hong et al., 2014). Efforts on both scientific understanding and technical improvement for oil spill remediation method should warrant a wise use of artificial recovery treatment together with natural attenuation of spilled oils.

Immediately after the HSOS, alkylated PAH concentrations in oysters were 40–500 times greater than those measured at the pre-spill site. Thereafter, PAHs in oysters decreased exponentially, and approached pre-spill levels within one year, except at sites where oil remained. Until recently, the central Taean Peninsula exhibited a continuous petrogenic signature of PAHs, whereas other regions showed mixed sources of PAHs from both combustion and petroleum origins (Kim et al., 2013; Hong et al., 2016). Overall, assessment of oil contamination in oysters from the intertidal regions of Taean indicated that the sources of PAHs and their levels are currently fairly similar to those in local resident bivalves collected before the spill (Mondol et al., 2015; Yim et al., 2017). Of note, previous work, as part of the project,

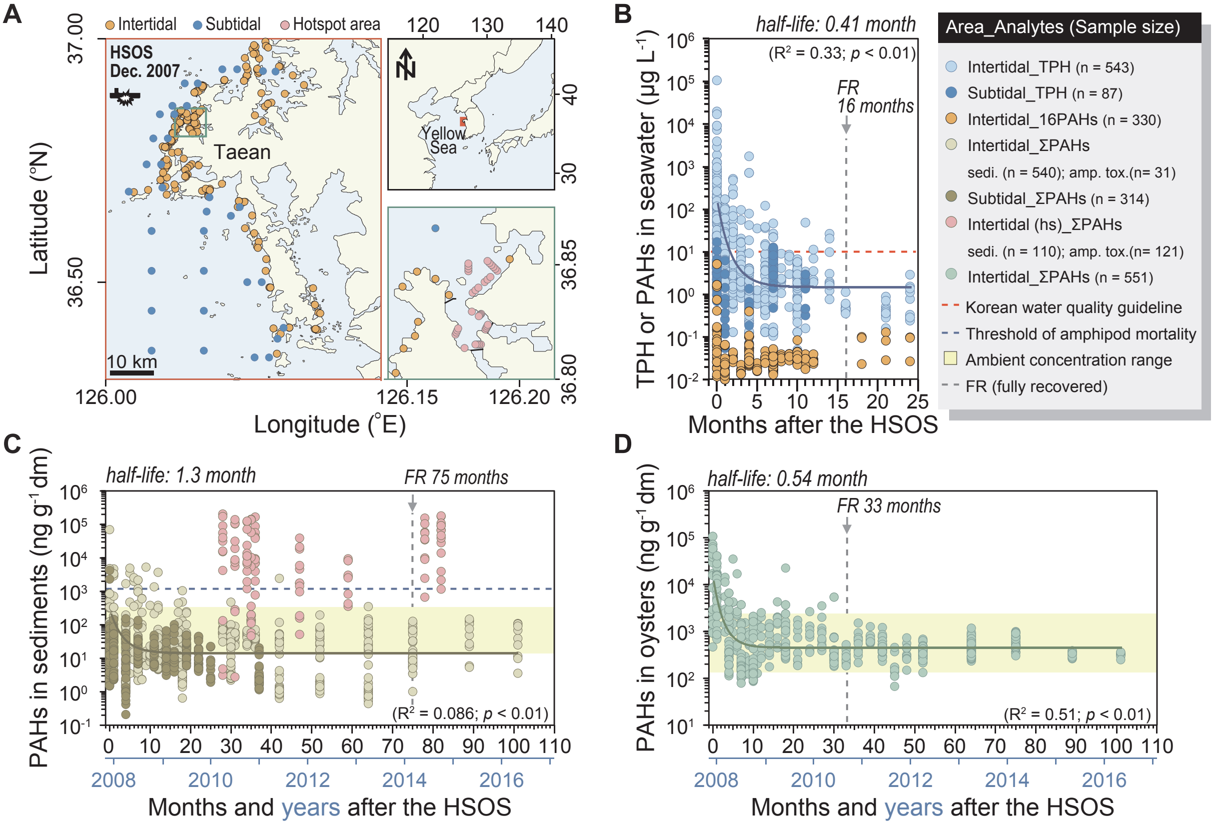

**Fig. 1.** Study area and temporal distribution of residual oil in multiple environmental samples from different sources in Taean Region, South Korea. (A) Map showing the sampling sites in Taean Region, including intertidal and subtidal areas. Intertidal hotspot areas (Intertidal (hs)) are those with high levels of contamination and oil residues persisted over a relatively long period of time. (B) Temporal distribution of TPH and PAHs in seawater collected from the intertidal and subtidal areas of Taean Region. Red dotted lines represent the Korean Water Quality Guideline for TPH (10 μg $L^{-1}$). (C) Temporal variation in PAHs (including alkyl-PAHs) in sediment collected from the intertidal and subtidal areas of Taean Region. Samples from hotspot sites were collected after confirming oil presence. The blue dotted line indicates the threshold concentration that causes 20% amphipod mortality. (D) Temporal variation in PAHs (including alkyl-PAHs) in oysters collected from intertidal areas in Taean Region. Fitted curves were obtained based on residual oil concentrations and the number of months after the oil spill using an exponential decay model (Table S2). Yellow-shaded sections represent the ambient concentration ranges of PAHs in sediments and oysters on the west coast of Korea. Vertical gray dotted lines, denoted as FR, indicate 'fully recovered' status.

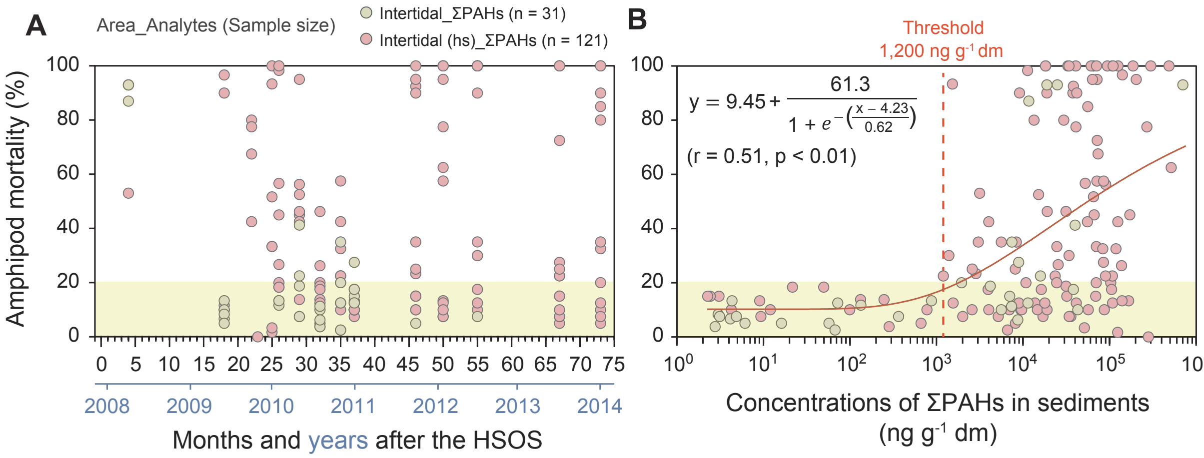

**Fig. 2.** Temporal trends to the ecotoxicity of oil-contaminated sediments. 'Intertidal (hs)' indicates hotspot sites with high levels of oil residues in intertidal sediments and persisted over a relatively long period of time. (a) Amphipod (*Monocorophium uenoi*) mortality after 10 days in the whole-sediment exposure test from 2008 to 2014. (b) Scatter plot of the concentrations of PAHs in sediments and amphipod mortality rates. The sigmoid-fitted curve was obtained from the concentration-response relationship ($p < 0.01$). The threshold concentration was determined as that causing 20% amphipod mortality.

reported that oyster reproduction recovered 2 years after the HSOS (Mondol et al., 2015).

Concentrations of residual oils in seawater (TPH), sediments (PAHs), and oysters (PAHs) have decreased rapidly, with half-lives of 0.41, 1.3, and 0.54 months, respectively (Fig. 1 and Table S2). Concentrations of TPH or PAHs decreased to background levels after 7.7, 14, and 18 months, on average, in seawater, sediments, and oysters, respectively. The environment (target or area) was considered to be 'fully recovered' status when the corresponding concentrations of TPH or PAHs were consistently smaller than the ambient concentrations in all samples. Our data indicated that it took 16, 75, and 33 months for the environment of the seawater, sediments, and oysters in intertidal areas to recover, respectively.

### 3.2. Toxic effects on marine organisms

The toxic effects on living organisms generally reflected heavy, localized, and chronic exposure to environmental residual oils (Jung et al., 2011; Lee et al., 2013). Ethoxyresorufin-*O*-deethylase (EROD) concentrations in local resident fishes (rockfish and marbled flounder) peaked immediately after the HSOS, but thereafter decreased, and finally reached background concentration in about 3–4 years. These data indicated very high levels of direct exposure, with toxicity remaining significant for more than one year (Fig. S6) (Jung et al., 2011; Yim et al., 2017). Furthermore, the whole-sediment exposure test indicated that amphipod (*Monocorophium uenoi*) mortality was elevated over an extended period of time (up to ~70 months), particularly in hotspots with elevated concentrations of residual PAHs (Fig. 2) (Lee et al., 2013). Meanwhile, the hatching rate of fish eggs (*Cyprinodon variegatus*) after porewater exposure showed similar results to the amphipod toxicity tests when evaluating the ecotoxicity of the sedimentary residual oil (Lee et al., 2013). The amphipod toxicity test clearly demonstrated PAH concentration-dependent mortality, with a toxic threshold of 1200 ng $g^{-1}$ dm (Lee et al., 2013). Approximately three years after the HSOS, sedimentary PAHs concentrations in the intertidal areas were shown to reach below the levels of toxicity threshold concentration, except for hotspot sites (Fig. 1C).

Although intertidal hotspots were exposed for extended periods to residual oil, their toxic effects on coastal organisms decreased sharply after 3 years, in most cases (Figs. 1 and 2). Unexpectedly, the Taean Region showed very rapid recovery, in terms of chemical concentrations and toxicities, compared to other oil spill impacted regions (Peterson et al., 2003; Payne et al., 2008; NOAA, 2014). This rapid recovery was collectively attributed to (i) early massive removal of spilled oil (i.e., anthropogenic factor), (ii) the strong tidal circulation of seawater (~9 m tidal range) (i.e., physical factor), (iii) high microbial activities, and (iv) additive effects of natural restoration through bioturbation and/or recolonization (i.e., biological factor) (Clifton et al., 1984; Hong et al., 2012). In contrast to initial predictions where experts mostly estimated recovery time of > 20 years, residual oil concentrations in the given environment, along with the associated adverse toxic effects, returned to background levels within 5–6 years of the HSOS.

### 3.3. Macrobenthic community responses

The community structure of macrobenthos in sandy tidal flats was investigated to address the impact of the oil spill in the aspect of benthic community recovery (Table S3 and Fig. S7). The monitoring of macrobenthos was carried out seasonally in oil-impacted areas, Sinduri and Manlipo, and at one lesser-impacted area, Mongsanpo (Fig. S1 and Table S3). Macrobenthic community structure in the intertidal sandflats showed that Sinduri and Manlipo, which were heavily affected by the spilled oils, had relatively small number of species (Sinduri: 32; Manlipo: 15) and low species diversity index (H′) (Sinduri: 1.7; Manlipo: 1.2) after one year of the HSOS (Table S3). However, the number of species in Sinduri and Manlipo increased to 46 and 22, respectively, in 2013, then corresponding communities were relatively stable thereafter. Of note, compared to Mongsanpo, Sinduri and Manlipo regions have smaller number of species and lower species diversity index (H′). This seems to be the difference in the baseline between the regions. In Sinduri and Manlipo, opportunistic species, such as *Felaniella sowerbyi*, were the most dominant, and the density of these species decreased and the diversity increased as the ecosystem recovered in a timely manner.

In muddy tidal flats, the number of species, density, and diversity of macrobenthos at Sogeunri (oil spill-impacted area) continued to increase after the HSOS, with a strong signal of year-round recovery (Table S4). The opportunistic polychaete species *Perinereis aibuhitensis* was found in the Sogeunri, while opportunistic species did not appear and a large number of *Ruditapes philippinarum* individuals were observed in the Keunso Bay. Since 2012, the Sogeunri tidal flat showed a relatively stable benthic community with consistently greater number of species and species diversity (H′) compared to the past.

Macrobenthos was seasonally monitored on rocky shores in the mid-shore areas of polluted sites at Guryepo and Padori, and at a control site at Yeonpo (Table S5). At the polluted sites, the ecological index (diversity index (H′)) gradually increased after 2009, and minimally fluctuated since 2012, indicating recovery. Of note, the density of the dominant species was higher at the control site compared to the polluted sites. However, in 2014, the density was similar (or higher) at the polluted sites compared to the control site. Based on correlation results between the dominant species, we found that the recovery of *Crassostrea gigas* had important effects on the overall recovery of macrobenthos on rocky shores. In future cases of disturbance to rocky shore ecosystems, the proliferation of *C. gigas* in that area could serve an important indicator of rapid ecosystem recovery.

In subtidal areas, from January 2008 to January 2015, investigations on macrobenthic communities were carried out seasonally (Table S6). These investigations showed that the species diversity index (H′) decreased continuously from spring to summer of 2008, indicating that the spill had affected the health of the macrobenthic community. However, the number of species and their density increased after the summer of 2009 at almost all sites. By July 2012, there were over 40 species and 1769 ind $m^{-2}$. The number of species, density, and diversity of macrobenthos around Hagampo and Manlipo have continued to increase since 2011.

### 3.4. Assessment for recovery of ecosystem

The responses and recovery status of marine benthic organisms to the impact of HSOS were evaluated from the changes in macrobenthos community structures in intertidal and subtidal areas (Fig. 3). It should be mentioned that there were a lack of oil-spill indicative species such as seabirds, marine mammals, and large fishes in Taean, compared to the case of Prince William Sound affected by the *Exxon Valdez* oil spill (EVOS). Instead, the intertidal organisms such as macrobenthos, which provide high commercial values, were assessed to determine recovery status. In general, the macrobenthic community tended to gradually recover in a timely manner with increasing number of species and diversity although the rate and degree varied cross the habitats (Fig. 3).

In the present study, we first suggested four categories of recovery stages based on the number of species and diversity index (H′) obtained from the 10 years of time-series benthic community data; (i) not recovered, (ii) partly recovered, (iii) fairly recovered, and (iv) fully recovered (Fig. 3A). First, 'not recovered' was defined when both the number of species and H′ values were lower than the ambient levels. Second, the 'partly recovered' was defined when the number of species and H′ values were shown to increase and the great abundance of opportunistic species had been observed. Third, the 'fairly recovered' was defined when the number of species generally approached the ambient level, but the variation remained relatively high or H′ values had not reached the moderate level. And finally, the 'fully recovered' was defined when the number of species reached the ambient level and the H′ was shown above moderate level.

The recovery period for macrozoobenthos varied slightly across habitats but generally ranged between 5 and 6 years after the spill for intertidal sandflat (65 months), mudflat (73 months), rocky shore (67 months), and subtidal area (65 months). Interestingly, the threshold recovery time for the benthic communities was similar to that of sedimentary residual oil (75 months) (Fig. 1). In general, our long-term monitoring data indicated that Taean coastal and marine ecosystem

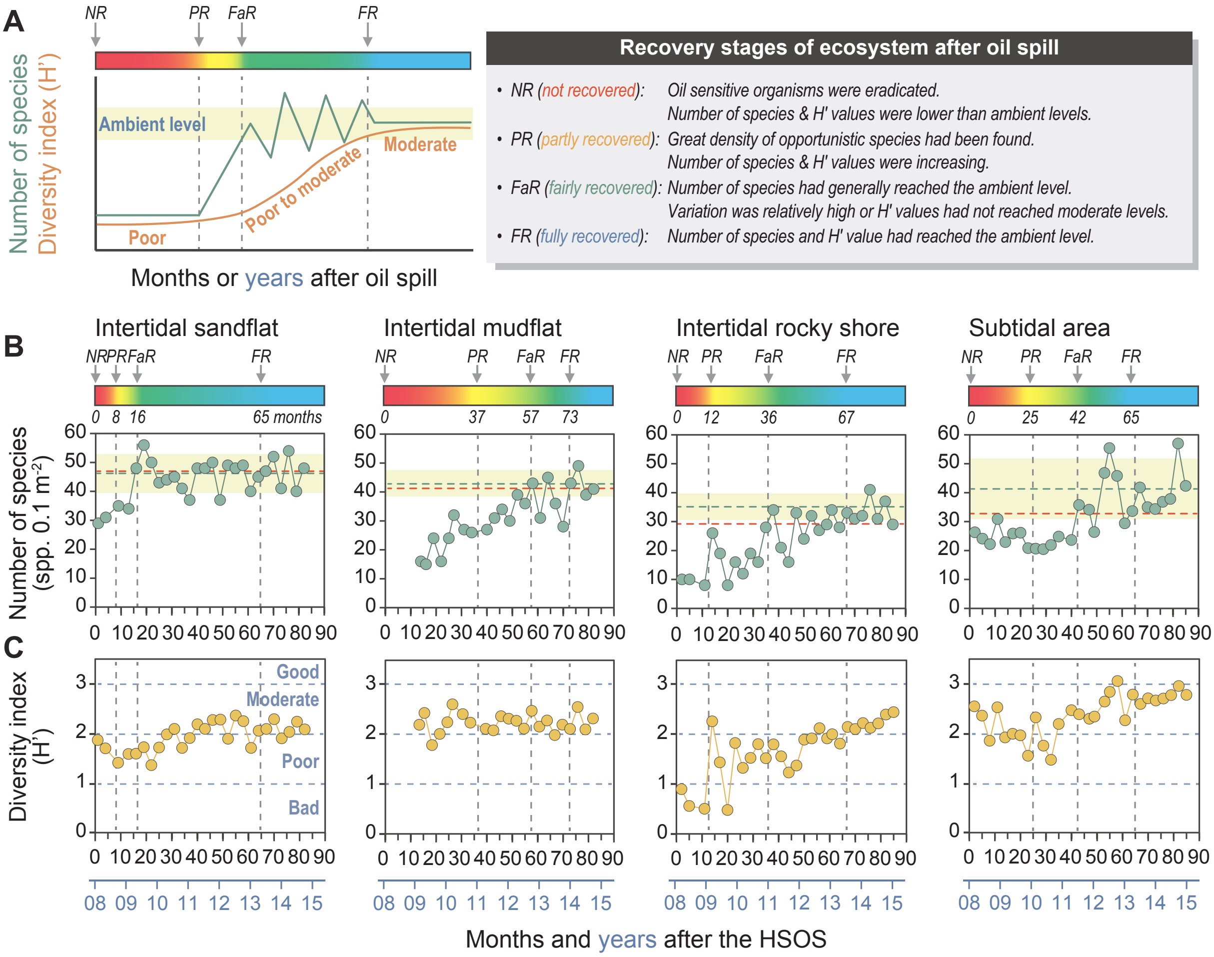

**Fig. 3.** Recovery of macrobenthic communities in the oil spilled coastal area of Taean Region, South Korea. (A) Criteria used to determine ecosystem recovery following an oil spill. Diversity index (H′) values were classified as 'Good', 'Moderate', Poor', and 'Bad', reflecting the status of benthic community health (blue dotted lines). The recovery status of macrobenthic communities was carefully judged based on two endpoints: (i) the number of species and (ii) diversity index values (gray dotted lines). (B) Number of species and (C) H′ of the benthic communities in the intertidal sandflat, mudflat, rocky shore, and subtidal regions over ~7 years after the HSOS. Red dotted lines represent ambient (natural) community levels along the west coast of South Korea. Green dotted lines indicate the mean number of species in the corresponding habitat surveyed during 2014 (January, April, July, and October); standard deviation (yellow-shaded sections) given. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

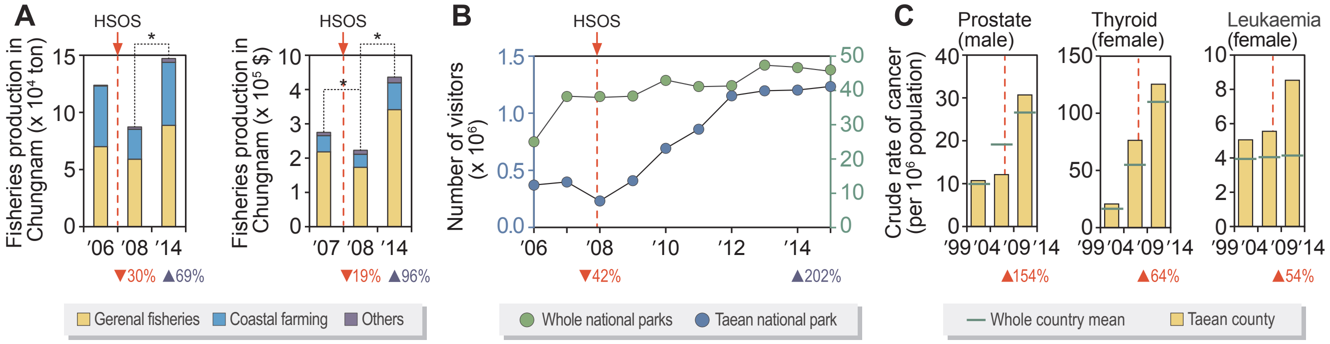

**Fig. 4.** Recovery of the local economy and human health status after the HSOS. (A) Fisheries production (tons and US dollars) in Chungnam Province from 2006 to 2014 (* indicates significant differences, $p < 0.05$). (B) Number of visitors to Taean National Park and all national parks in South Korea from 2006 to 2014. (C) Trend in the incidence of cancer in Taean region before and after the oil spill (national mean given for comparison) (Choi et al., 2018).

seemed to recover much faster compared to other marine oil spill cases; for instance, it was four to five times faster than of the EVOS (NOAA 2014) and approximately twice as fast as that of the *Amoco Cadiz* oil spill (Gesteira and Dauvin, 2000).

The unexpectedly rapid recovery was evidenced in the benthic community in the Taean Region, across intertidal and subtidal areas (Figs. 3 and S7). The dominant intertidal macrobenthos at the spilled sites included several important commercial species, thus the recovery of these species was of great significance to the local residents and economy. However, it should be noted that the impacted benthic ecosystem was slowly recovered with respect to the chemical concentrations and toxicities (Fig. 3). For example, opportunistic species

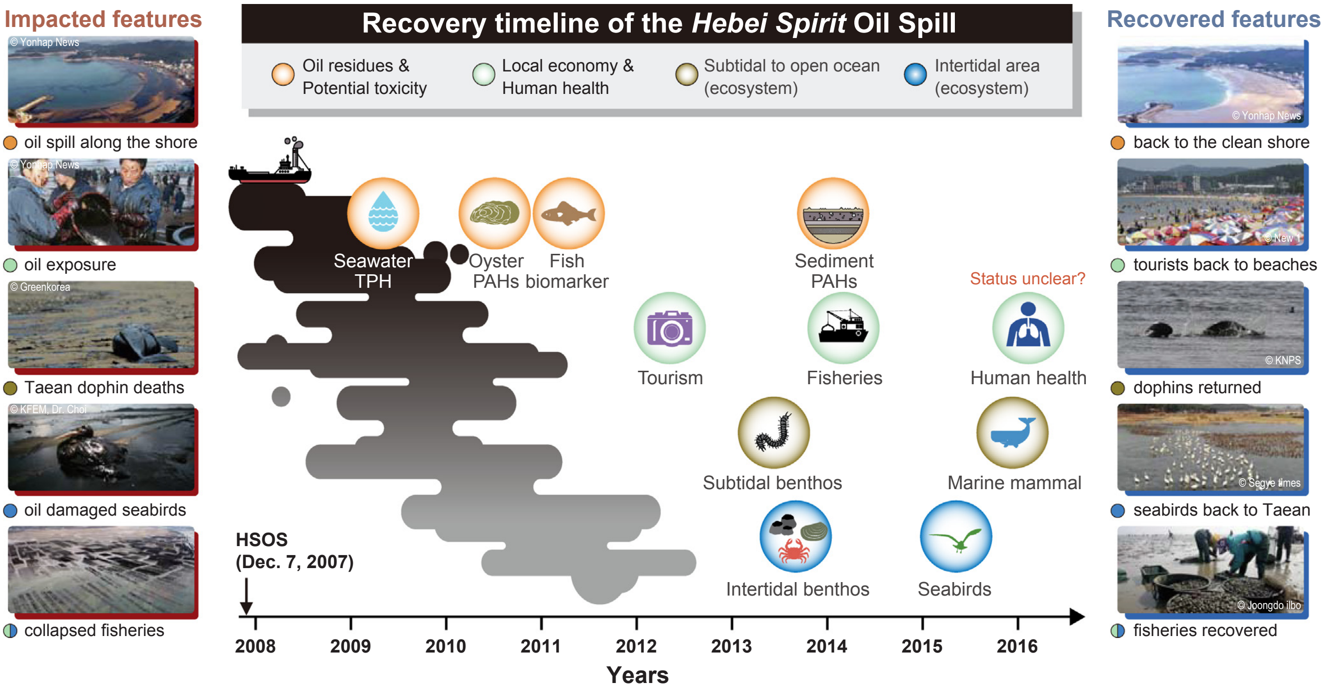

**Fig. 5.** Recovery timeline following the HSOS. Timeline of recovery for various impacted components: local economy (fisheries and tourism), human health (cancer rates), and coastal marine ecosystem (macrobenthic community; intertidal and subtidal areas) after the HSOS (fully recovered environments, habitats, or community structures). The left panel shows impacted features and the right panel shows recovered features.

**Table 1**
Current limitations and future directions. Summary of the key questions that have not been resolved or clarified in current marine oil spill research. Areas of interest and future research directions for each question are suggested.

| Key questions and knowledge gaps | Area of interest | Future research recommendation |
|---|---|---|
| **Q1.** Is the degree of ecosystem recovery associated with the initial response and pollution control methods? | Initial response and pollution control | · Mapping areas sensitive to oil pollution (priority protected areas)<br>· Region-specific pollution control considering coastal uses<br>· Science-based determination of initial pollution control endpoints |
| **Q2.** Are current methods sufficient to identify the substances present in the oil component? | Environmental petroleomics | · Advanced environmental forensics and weathering characteristics<br>· Ecotoxicological effects of unknown toxic chemicals |
| **Q3.** Do we need to use artificial restoration methods for highly oil-contaminated areas? What are some eco-friendly methods? | Environmental restoration | · Restoration methods for highly contaminated areas<br>· Bioremediation methods to promote recovery of oil spill areas |
| **Q4.** How can we accurately assess the recovery of the marine ecosystem? | Ecosystem recovery | · Recovery of marine ecosystem functions in oil spill areas<br>· Habitat-specific criteria for marine ecosystem recovery |
| **Q5.** Were local residents or cleanup participants affected by oil exposure? What measures can reduce such effects? | Human community health | · Epidemiological study of oil exposure to and health of residents<br>· Integrated recovery assessment including the human community |

(*Felaniella sowerbyi*, *Batillaria* spp., etc.) became dominant within 1–2 years. Subsequently, other macrofaunal species gained dominance, reaching a stable state 5–6 years after the HSOS (Hong et al., 2012; Yu et al., 2013).

### 3.5. Recovery of local economy and human health

Of the ~65,000 people in the Taean Region, ~75% are engaged in fisheries. In addition, the Taean coast was designated a 'National Park' in 1978 for its outstanding scenery. As a result, local residents are highly dependent on income from tourism (Kim et al., 2014). Indeed, the HSOS has brought immediate and significant damages to provisioning (fisheries production) and culture services (tourism) (Fig. 4A, B) (Cheong, 2012a). Thus, the unexpected huge collapse of the local economy from the HSOS was of significant concern nationwide. Despite the relatively fast recovery of most fisheries, the coastal aquaculture industry in this region recovered rather slowly (fully recovered in 2014). The number of visitors plummeted after the spill (Fig. 4B), but tourism recovered quite quickly (within 3–4 years) compared to the complete recovery of the coastal ecosystem (viz., ~6 years). The mass media repeatedly issued success stories about the recovery of the Taean Region, with attractive titles, such as 'migratory birds returned' or 'marine mammals back' after 2015. Although debate exists on the recovery timeline from the HSOS, the long-term monitoring data generally support the fast, full ecosystem recovery in this region.

As mentioned earlier, the early massive cleanup by 2.1 million personnel after the HSOS would be one of the most important contributions for the rapid oil spill recovery (Hong et al., 2014). In EVOS case, only 11,000 residents in Alaska (~0.5% of HSOS) worked to clean up the 11 million gallons of crude oil (Maki, 1991). However, the health effects on volunteers, as well as local residents, have not been clearly addressed to date, particularly with respect to chronic recovery (Jung et al., 2017; Choi et al., 2018). Indeed, after the spill (from 2009 to 2013), the rates of prostate cancer (male), thyroid cancer (female), and leukemia (female) in the residents of the Taean region were found to be greater compared to the national average (Fig. 4C). Among them, the incidence rate of prostate cancer in male in Taean was significantly greater compared to those of other coastal areas of South Korea ($p < 0.01$) (Choi et al., 2018). In addition, incidence rates of cancer were greater in residents living in highly exposed areas compared to those living in lower-exposed ones (Choi et al., 2018). Cancer is a chronic disease requiring > 10 years of follow-up checks, thus further study is necessary. Cohort studies of cleanup workers and local residents are in progress and must be continued for a long period of time. There have been numerous conflicts among the impacted parties, leading to the sociopolitical collapse of traditional local communities. Initially, these conflicts occurred between the parties involved in the incident and local residents, and later they occurred between the government and local residents who argued for compensation for the economic losses (Cheong, 2012b). Even though all components of the ecosystem have returned to normal conditions, the human dimension is still being remediated (Fig. 5).

### 3.6. *Implications for future studies*

After the HSOS, there has been a number of large- and small-scale oil spill incidents both nationally and globally. Indeed, our understanding of the science of oil pollutions has advanced over the last decade, including the fields of oil spill environmental forensics (Yim et al., 2011, 2012), compound-specific toxicities (Rhee et al., 2013), weathering characteristics (Joo et al., 2013), and bioremediation (Lee et al., 2018). However, many knowledge gaps remain. Thus, the focus is required on various topics, including unknown toxicities, ecological remediation, and human epidemiology studies (Table 1).

The importance of preparing for and preventing marine oil spills cannot be exaggerated. Today, most member countries of the International Convention on Oil Pollution Preparedness, Response and Cooperation have their own national contingency plans. However, these plans primarily focus on cleanup responses and do not seem to consider recovery from ecosystem threats and/or human health impacts sufficiently. Asian countries are more vulnerable to marine oil spills, because of the high population density in coastal regions and increasing dependence on fisheries and coastal tourism. The coastal area of Korea is widely utilized for tourism, fishing, and commerce, thus it was not possible to leave the spilled oil on the shore. The most important feature of the HSOS was that the government and citizens cooperated with each other to carry out massive initial cleanup activities to collect and remove the spilled oil on the coastal areas. Although the combination of massive emergency cleanup during the key period and favorable natural recovery condition allowed the fast recovery of the ecosystem and its services, the human population continues to suffer from long-term health effects and insufficient compensation (Peters et al., 2017; Sandifer and Walker, 2018). Therefore, the scientific and political focus is required on the coupled human-environment system in oil spill responses and restoration in the future.

## CRediT authorship contribution statement

**Un Hyuk Yim:** Conceptualization, Writing - original draft, Project administration, Funding acquisition, Writing - review & editing. **Seongjin Hong:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Changkeun Lee:** Investigation, Formal analysis, Data curation. **Moonkoo Kim:** Investigation, Formal analysis. **Jee-Hyun Jung:** Investigation, Formal analysis. **Sung Yong Ha:** Investigation, Formal analysis. **Joon Geon An:** Investigation, Formal analysis. **Bong-Oh Kwon:** Investigation, Formal analysis. **Taewoo Kim:** Investigation, Formal analysis. **Chang-Hoon Lee:** Investigation, Formal analysis. **Ok Hwan Yu:** Investigation, Formal analysis. **Hyun Woo Choi:** Visualization, Formal analysis, Data curation. **Jongseong Ryu:** Investigation, Formal analysis, Data curation. **Jong Seong Khim:** Conceptualization, Writing - review & editing, Funding acquisition, Supervision. **Won Joon Shim:** Conceptualization, Writing - review & editing, Project administration, Funding acquisition, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary material

Additional details of sampling sites, spatial and vertical distributions of residual oil, temporal trends of ecotoxicity and macrobenthos in the *Hebei Spirit* oil spill impact area, and other helpful materials are given in the Tables S1–S6 and Figs. S1–S7. Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105438.

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<Environment International>

*Supplementary Materials for*

# Rapid Recovery of Coastal Environment and Ecosystem to the *Hebei Spirit* Oil Spill's Impact

Un Hyuk Yim [1], Seongjin Hong [1], Changkeun Lee, Moonkoo Kim, Jee-Hyun Jung,
Sung Yong Ha, Joon Geon An, Bong-Oh Kwon, Taewoo Kim, Chang-Hoon Lee, Ok Hwan Yu,
Hyun Woo Choi, Jongseong Ryu, Jong Seong Khim*, Won Joon Shim*

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Number of pages: 20

Number of supplementary figures: 7, Figures S1 to S7

Number of supplementary tables: 6, Tables S1 to S6

References

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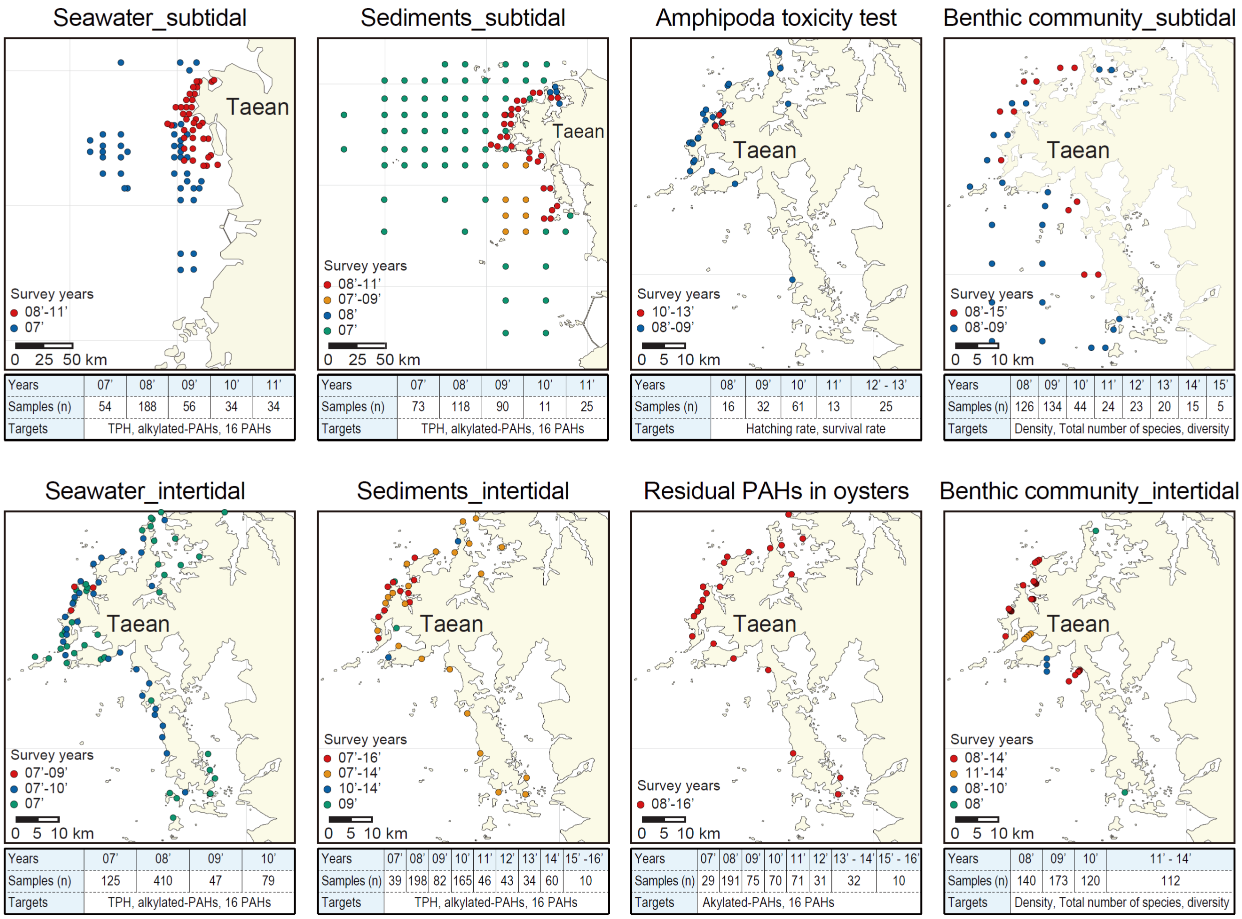
## Supplementary Figures



Seawater_subtidal

| Years | 07' | 08' | 09' | 10' | 11' |
|---|---|---|---|---|---|
| Samples (n) | 54 | 188 | 56 | 34 | 34 |
| Targets | TPH, alkylated-PAHs, 16 PAHs | | | | |

Sediments_subtidal

| Years | 07' | 08' | 09' | 10' | 11' |
|---|---|---|---|---|---|
| Samples (n) | 73 | 118 | 90 | 11 | 25 |
| Targets | TPH, alkylated-PAHs, 16 PAHs | | | | |

Amphipoda toxicity test

| Years | 08' | 09' | 10' | 11' | 12' - 13' |
|---|---|---|---|---|---|
| Samples (n) | 16 | 32 | 61 | 13 | 25 |
| Targets | Hatching rate, survival rate | | | | |

Benthic community_subtidal

| Years | 08' | 09' | 10' | 11' | 12' | 13' | 14' | 15' |
|---|---|---|---|---|---|---|---|---|
| Samples (n) | 126 | 134 | 44 | 24 | 23 | 20 | 15 | 5 |
| Targets | Density, Total number of species, diversity | | | | | | | |

Seawater_intertidal

| Years | 07' | 08' | 09' | 10' |
|---|---|---|---|---|
| Samples (n) | 125 | 410 | 47 | 79 |
| Targets | TPH, alkylated-PAHs, 16 PAHs | | | |

Sediments_intertidal

| Years | 07' | 08' | 09' | 10' | 11' | 12' | 13' | 14' | 15' -16' |
|---|---|---|---|---|---|---|---|---|---|
| Samples (n) | 39 | 198 | 82 | 165 | 46 | 43 | 34 | 60 | 10 |
| Targets | TPH, alkylated-PAHs, 16 PAHs | | | | | | | | |

Residual PAHs in oysters

| Years | 07' | 08' | 09' | 10' | 11' | 12' | 13' - 14' | 15' - 16' |
|---|---|---|---|---|---|---|---|---|
| Samples (n) | 29 | 191 | 75 | 70 | 71 | 31 | 32 | 10 |
| Targets | Akylated-PAHs, 16 PAHs | | | | | | | |

Benthic community_intertidal

| Years | 08' | 09' | 10' | 11' - 14' |
|---|---|---|---|---|
| Samples (n) | 140 | 173 | 120 | 112 |
| Targets | Density, Total number of species, diversity | | | |

**Fig. S1.** Map showing the coverage of long-term monitoring efforts in the Taean region. Filled circles indicate sampling sites in the Taean region, including intertidal and subtidal regions. Over 4,026 samples from > 800 locations were analyzed targeting various endpoints during the 10 years of environmental and ecosystem monitoring.

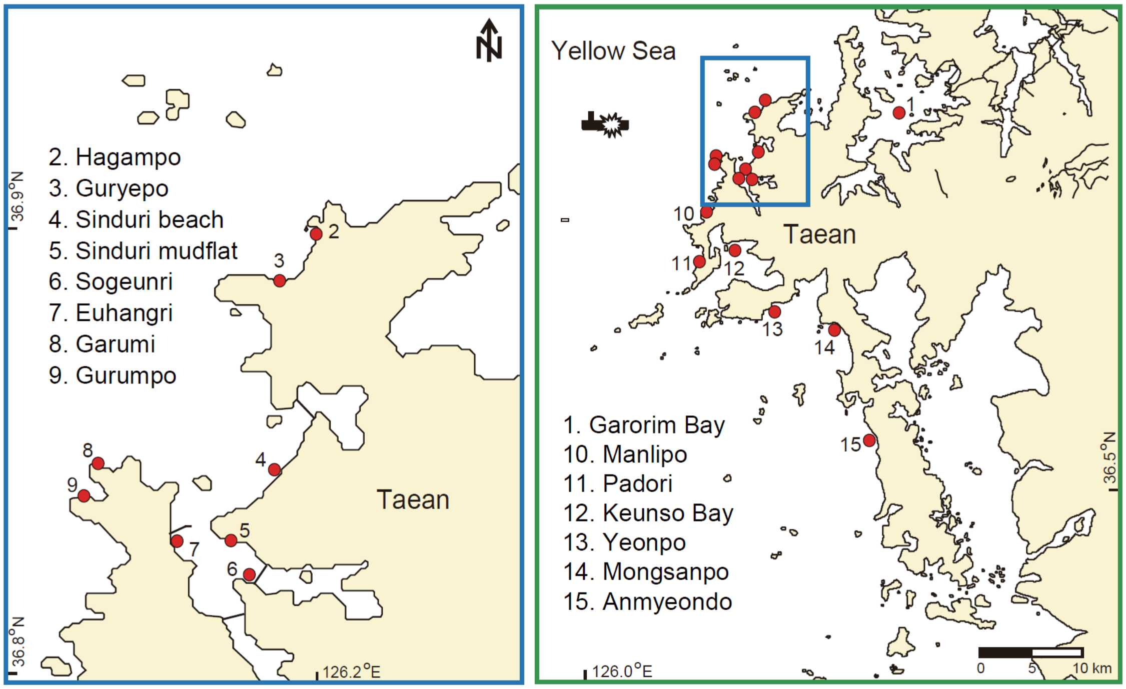


**Fig. S2.** Map showing the place names and locations mentioned in the main text of the Taean region.

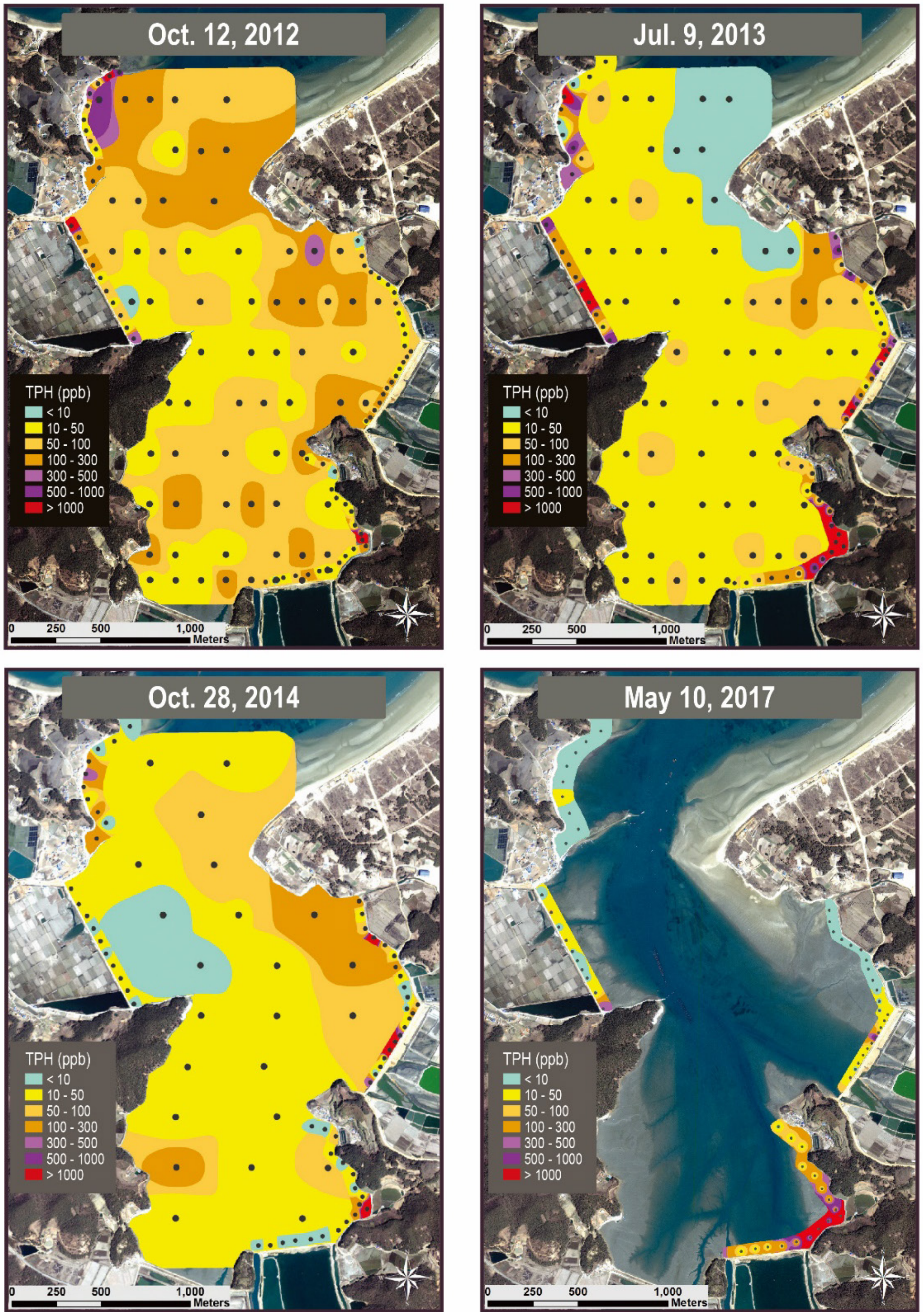


**Fig. S3.** Spatiotemporal distributions of TPH concentrations in porewater samples collected from a mudflat (Sogeunri). Fluorometric porewater analysis was conducted based on a previous study (Yim et al., 2012). The colored area indicates TPH concentrations in porewater samples from the mudflat from October 2012 to May 2017.

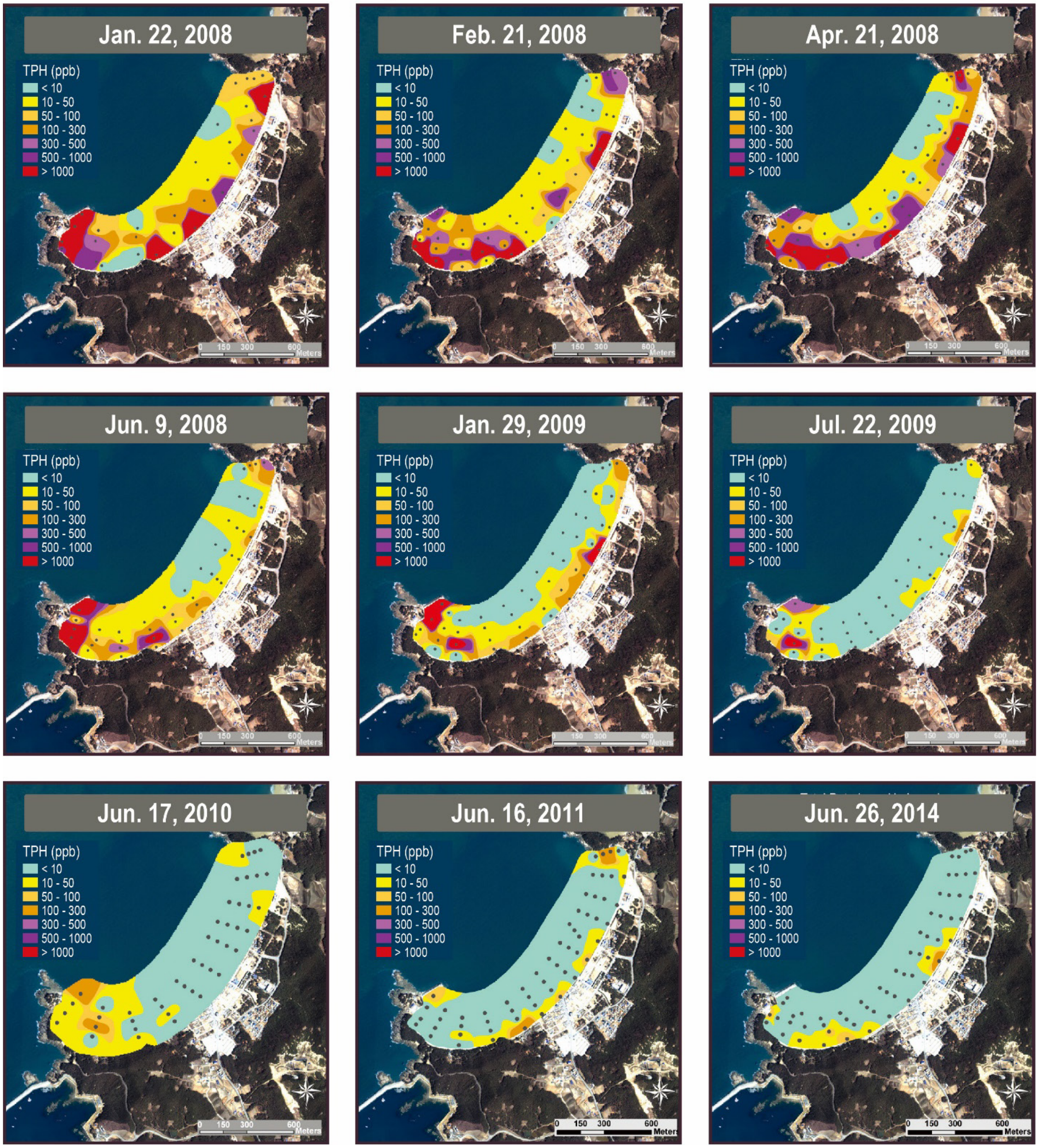


**Fig. S4.** Spatiotemporal distributions of TPH contamination in porewater samples collected from a sandy beach (Manlipo). Fluorometric porewater analysis was conducted based on a previous study (Yim et al., 2012). The colored area indicates the TPH concentrations in porewater samples from the mudflat from January 2008 to June 2014.

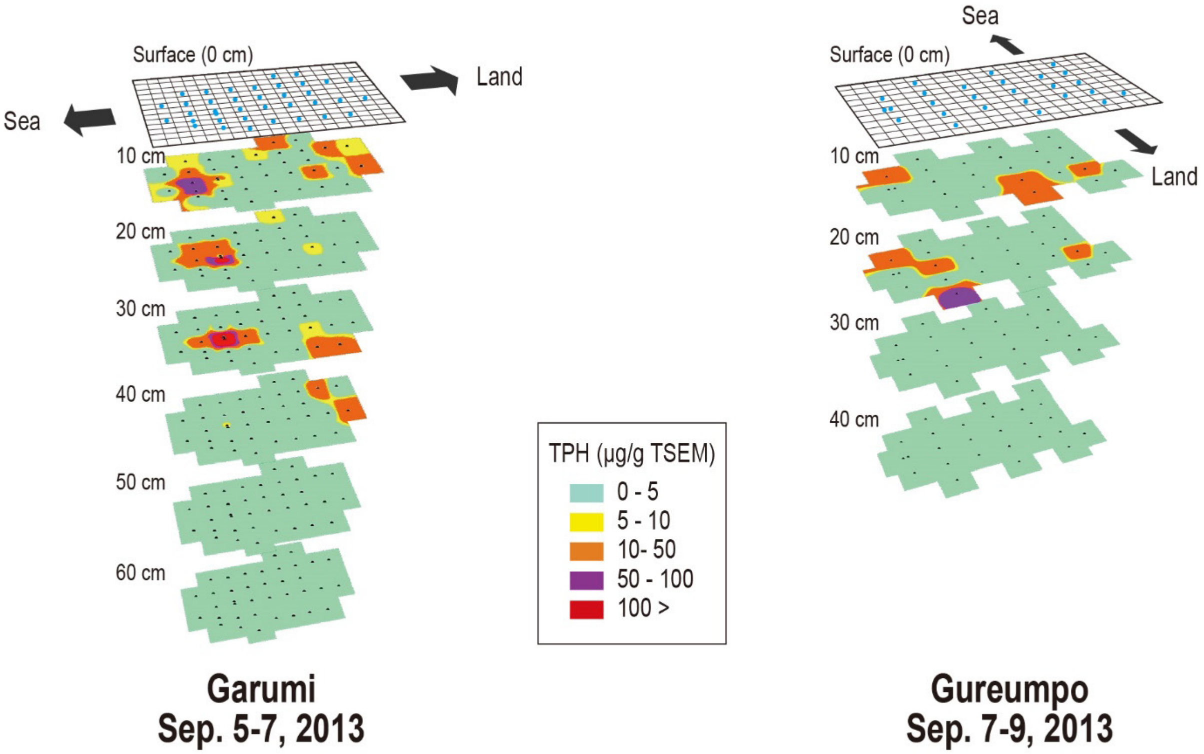


**Fig. S5.** TPH depth profiles of sediments from two different rocky shores (Garumi and Gurumpo). Fluorometric porewater analysis was conducted based on a previous study (Yim et al., 2012). The colored area indicates the TPH depth profiles in porewater samples from rocky shores.

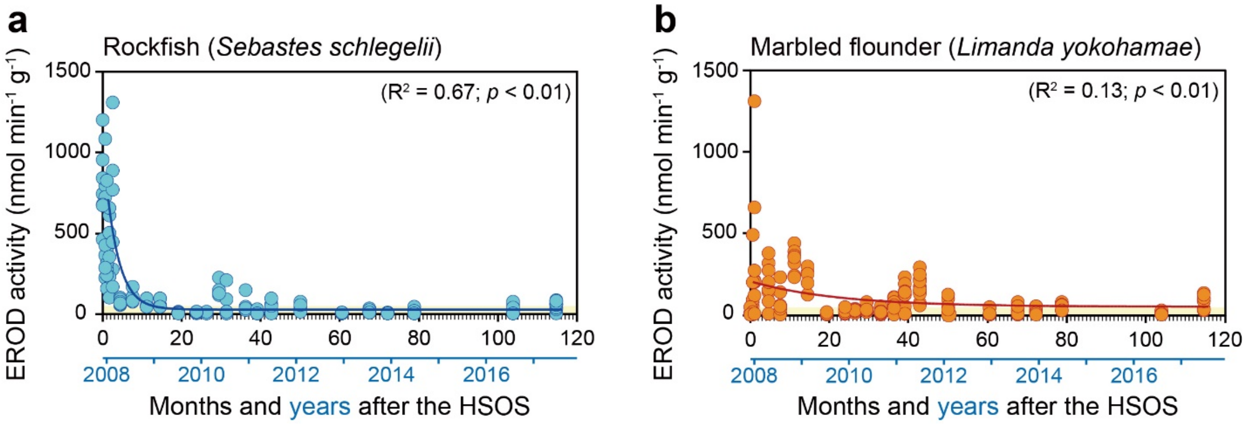


**Fig. S6.** Temporal changes to EROD activity in (a) rockfish and (b) marbled flounder from the Taean area. Yellow-shaded areas indicate EROD activity in fish from the reference site (Boryeong) (Kim et al., 2017; Yim et al., 2017).

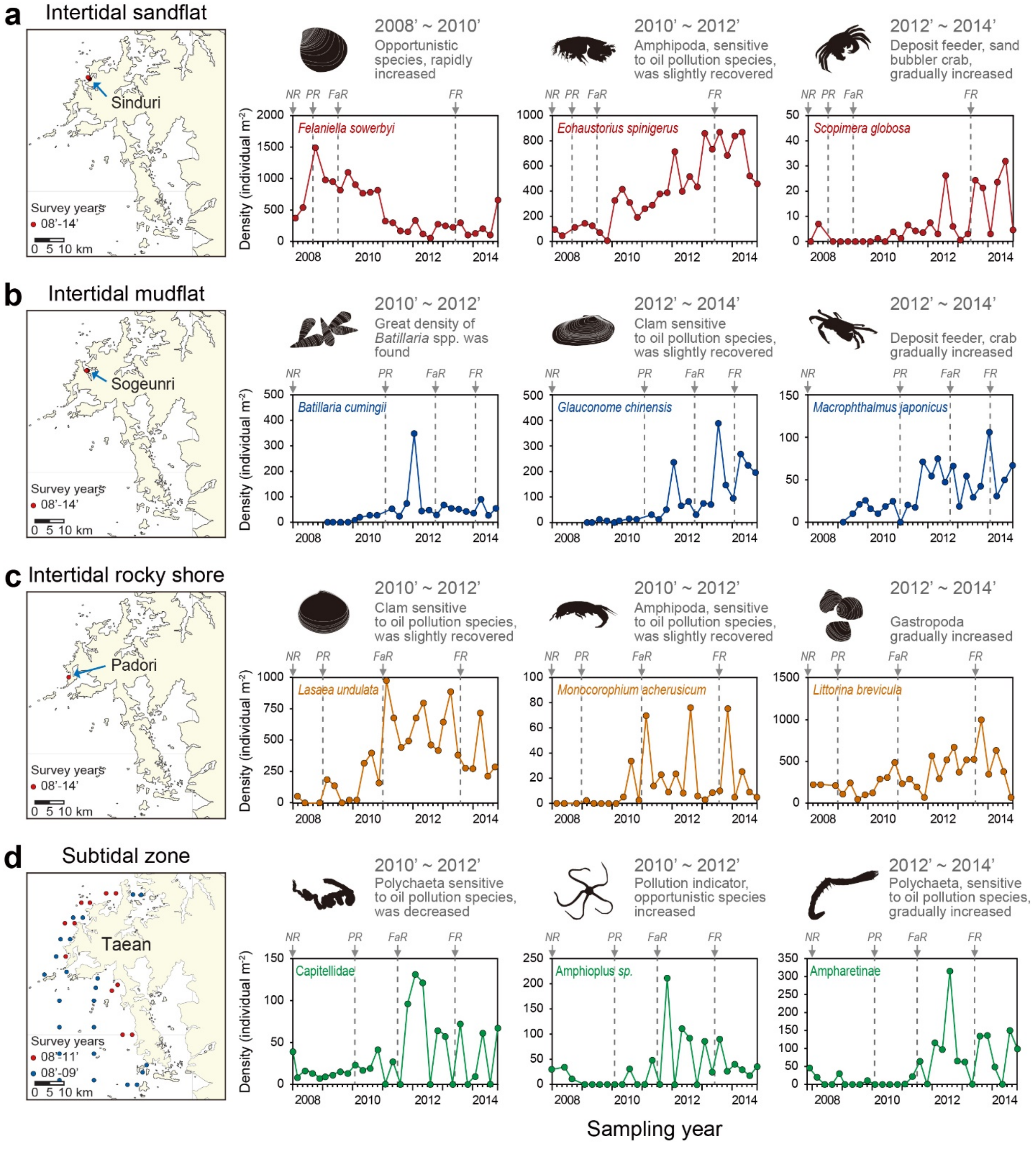


**Fig. S7.** Temporal changes in macrobenthos in the *Hebei Spirit* oil spill impact area. Map showing macrobenthos sampling sites in the Taean region, including (a-c) intertidal and (d) subtidal sites. Each photo shows the dominant macrobenthic species sampled.

## Supplementary Tables

**Table S1.** Summary of the incident and cleanup activities after the *Hebei Spirit* oil spill (modified from a previous study) (Hong et al., 2014).

| | | | |
|---|---|---|---|
| **Occurrence** | Location | ~10 km off Taean | |
| | Month/Day/Year | December/07/2007 | |
| | Amount of spilled oil | 10,900 tons | |
| | Type of spilled oils | Kuwait Export Crude, Iranian Heavy Crude, UAE Upper Zakum | |
| | Polluted areas | 375 km of coastline of west coast of Korea | |
| **Cleanup activities** | Ships | KCG | 6,630 |
| | | KOEM | 889 |
| | | Navy | 723 |
| | | Etc. | 11,968 |
| | | Total (Unit) | 20,210 |
| | Heavy machinery | Truck | 9,991 |
| | | Excavator | 5,559 |
| | | Tractor | 1,304 |
| | | Etc. | 12,119 |
| | | Total (Unit) | 28,973 |
| | Personnel | Volunteers | 1,226,730 |
| | | Residents | 566,343 |
| | | Military personals | 152,695 |
| | | Public officers | 76,684 |
| | | Others | 249,884 |
| | | Total (Individual) | 2,122,296 |
| | Cleanup materials | Oil boom (km) | 47 |
| | | Oil absorbent (kg) | 493,127 |
| | | Dispersant (kL) | 298 |
| **Oil collection** | Liquid oil | at Sea | 2,360 |
| | | on Shore | 1,815 |
| | | Total (kL) | 4,175 |
| | Oil wastes | at Sea | 1,034 |
| | | on Shore | 31,040 |
| | | Total (Tons) | 32,074 |

**Abbreviation.** KCG: Korean Coast Guard; KOEM: Korea Environment Management Corporation.

**Table S2.** Temporal trends in residual oil, including total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs), in seawater, sediments, and oysters in the Taean area after the *Hebei Spirit* oil spill. Equation parameters of the exponential decay model and the half-lives of residual oil are shown.

| **Analytes and equation parameters** | | **Seawater (intertidal)** | **Sediments (intertidal)**[a] | **Oyster (intertidal)** |
|---|---|---|---|---|
| Target analytes | | TPH (μg $L^{-1}$) | PAHs (ng $g^{-1}$ dm) | PAHs (ng $g^{-1}$ dm) |
| Sample size (n) | | 543 | 540 | 551 |
| Parameters[b] | y0 | 0.181 | 1.139 | 2.648 |
| | a | 1.445 | 0.896 | 1.630 |
| | b | 0.560 | 0.306 | 0.381 |
| | $R^2$ | 0.33 | 0.086 | 0.51 |
| | $p$ | < 0.001 | < 0.001 | < 0.001 |
| Initial concentration (y-intercept) | | $4.2 \times 10$ | $1.1 \times 10^2$ | $1.9 \times 10^4$ |
| Half-life (month) | | 0.41 | 1.3 | 0.54 |
| Background level [c] | | 1.6 | $1.4 \times 10$ | $4.5 \times 10^2$ |
| Reaching background level (month) | | 7.7 | 14 | 18 |
| Fully recovered (month) [d] | | 16 | 75 [e] | 33 |
| Year and month of fully recovered | | 2009, 04 | 2014, 03 | 2010, 09 |

[a] Intertidal sediments except in hotspot areas.

[b] Exponential decay model used in this study. Equation: f=y0+a*exp(−b*x).

[c] Background levels of TPH or PAHs were determined from the values of the 'very slow region (stable)' on the exponential decay curves. These values were within the ambient concentrations in regions on the west coast of Korea, on average.

[d] The status 'fully recovered' indicates that concentrations of TPH or PAHs in all samples were below the Korean water quality guidelines or ambient levels.

[e] Except in hotspot areas. Since then, residual oil has been found in sediments of very limited areas (hotspot areas), which continued until artificial removal in 2017.

**Table S3.** Temporal changes of macrobenthic community structures in the intertidal sandflat areas of Taean region.

| Regions | Year | Month | No. of species | Density (ind $m^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Impacted area*** | | | | | | | | | |
| Sinduri | 2008 | Jan. | 29 | 755 | 1.87 | 6.48 | *_Felaniella sowerbyi_ | _Eohaustorius spinigerus_ | _Umbonium thomasi_ |
| | | Apr. | 31 | 942 | 1.70 | 6.88 | *_Felaniella sowerbyi_ | _Umbonium thomasi_ | _Eohaustorius spinigerus_ |
| | | Sep. | 35 | 2272 | 1.41 | 6.70 | *_Felaniella sowerbyi_ | _Pygospio_ sp. | _Umbonium thomasi_ |
| | 2009 | Jan. | 34 | 1578 | 1.58 | 4.66 | *_Felaniella sowerbyi_ | _Umbonium thomasi_ | _Eohaustorius spinigerus_ |
| | | Apr. | 48 | 1632 | 1.59 | 6.10 | *_Felaniella sowerbyi_ | _Umbonium thomasi_ | _Eohaustorius spinigerus_ |
| | | Jul. | 56 | 1373 | 1.72 | 6.18 | *_Felaniella sowerbyi_ | _Umbonium thomasi_ | _Scoloplos armiger_ |
| | | Oct. | 50 | 2073 | 1.36 | 6.51 | *_Felaniella sowerbyi_ | _Umbonium thomasi_ | _Scoloplos armiger_ |
| | 2010 | Jan. | 43 | 2004 | 1.71 | 5.29 | *_Felaniella sowerbyi_ | _Urothoe grimaldii_ | _Eohaustorius spinigerus_ |
| | | Apr. | 44 | 2044 | 1.98 | 5.64 | *_Felaniella sowerbyi_ | _Eohaustorius spinigerus_ | _Pygospio_ sp. |
| | | Jul. | 45 | 2866 | 2.09 | 5.93 | *_Felaniella sowerbyi_ | _Pygospio_ sp. | _Eohaustorius spinigerus_ |
| | | Oct. | 41 | 1499 | 1.71 | 6.98 | *_Felaniella sowerbyi_ | _Eohaustorius spinigerus_ | _Umbonium thomasi_ |
| | 2011 | Jan. | 37 | 1159 | 1.91 | 5.41 | *_Felaniella sowerbyi_ | _Urothoe grimaldii_ | _Eohaustorius spinigerus_ |
| | | Apr. | 48 | 1406 | 2.18 | 6.97 | _Urothoe grimaldii_ | *_Felaniella sowerbyi_ | _Eohaustorius spinigerus_ |
| | | Jul. | 48 | 928 | 2.09 | 5.33 | _Eohaustorius spinigerus_ | *_Felaniella sowerbyi_ | _Urothoe grimaldii_ |
| | | Oct. | 50 | 1503 | 2.27 | 6.27 | _Pygospio_ sp. | _Eohaustorius spinigerus_ | *_Felaniella sowerbyi_ |
| | 2012 | Jan. | 37 | 2280 | 2.28 | 6.48 | _Eohaustorius spinigerus_ | _Urothoe grimaldii_ | *_Felaniella sowerbyi_ |
| | | Apr. | 49 | 2613 | 1.89 | 6.88 | _Pygospio_ sp. | _Eohaustorius spinigerus_ | _Urothoe grimaldii_ |
| | | Jul. | 48 | 2010 | 2.36 | 6.70 | _Eohaustorius spinigerus_ | _Haustorioides indivisus_ | _Pygospio_ sp. |
| | | Oct. | 49 | 1588 | 2.25 | 4.66 | _Eohaustorius spinigerus_ | *_Felaniella sowerbyi_ | _Pygospio_ sp. |
| | 2013 | Jan. | 40 | 1593 | 1.71 | 6.10 | _Eohaustorius spinigerus_ | *_Felaniella sowerbyi_ | _Urothoe grimaldii_ |
| | | Apr. | 45 | 2428 | 2.05 | 6.18 | _Eohaustorius spinigerus_ | _Urothoe grimaldii_ | *_Felaniella sowerbyi_ |
| | | Jul. | 47 | 2338 | 2.09 | 6.51 | _Eohaustorius spinigerus_ | _Urothoe grimaldii_ | *_Felaniella sowerbyi_ |
| | | Oct. | 52 | 1492 | 2.29 | 5.29 | _Eohaustorius spinigerus_ | _Mandibulophoxus mai_ | *_Felaniella sowerbyi_ |
| | 2014 | Jan. | 41 | 1637 | 1.90 | 5.64 | _Eohaustorius spinigerus_ | *_Felaniella sowerbyi_ | _Urothoe grimaldii_ |
| | | Apr. | 54 | 1999 | 2.03 | 5.93 | _Eohaustorius spinigerus_ | _Urothoe convexa_ | *_Felaniella sowerbyi_ |
| | | Jul. | 40 | 1508 | 2.24 | 6.98 | _Eohaustorius spinigerus_ | _Urothoe convexa_ | _Umbonium thomasi_ |
| | | Oct. | 48 | 1805 | 2.08 | 5.41 | *_Felaniella sowerbyi_ | _Eohaustorius spinigerus_ | _Urothoe grimaldii_ |
| Manlipo | 2008 | Jan. | 13 | 208 | 1.59 | 2.25 | *_Felaniella sowerbyi_ | _Thoracophelia mucronata_ | _Umbonium moniliferum_ |
| | | Apr. | 14 | 258 | 1.03 | 2.34 | *_Felaniella sowerbyi_ | _Thoracophelia mucronata_ | _Armandia lanceolata_ |
| | | Sept. | 17 | 1127 | 0.85 | 2.28 | *_Felaniella sowerbyi_ | _Umbonium costatum_ | _Scoloplos armiger_ |
| | 2009 | Jan. | 11 | 376 | 1.16 | 1.69 | *_Felaniella sowerbyi_ | _Archaeomysis vulgaris_ | _Mandibulophoxus mai_ |
| | | Apr. | 23 | 889 | 0.72 | 3.24 | *_Felaniella sowerbyi_ | _Archaeomysis vulgaris_ | _Mandibulophoxus mai_ |
| | | Jul. | 29 | 1413 | 1.07 | 3.86 | *_Felaniella sowerbyi_ | _Umbonium moniliferum_ | _Archaeomysis vulgaris_ |
| | | Oct. | 31 | 1672 | 0.90 | 4.04 | *_Felaniella sowerbyi_ | _Umbonium moniliferum_ | _Armandia lanceolata_ |

*Opportunistic species.

**Table S3.** (continue).

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| Manlipo | 2010 | Jan. | 19 | 827 | 1.24 | 2.68 | **Felaniella sowerbyi* | *Thoracophelia mucronata* | *Haustorioides indivisus* |
| | | Apr. | 20 | 1039 | 0.75 | 2.74 | **Felaniella sowerbyi* | *Mandibulophoxus mai* | *Thoracophelia mucronata* |
| | | Jul. | 27 | 1309 | 1.45 | 3.62 | **Felaniella sowerbyi* | *Umbonium costatum* | *Mandibulophoxus mai* |
| | | Oct. | 27 | 2146 | 1.19 | 3.39 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Urothoe grimaldii* |
| | 2011 | Jan. | 27 | 1418 | 1.19 | 3.58 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Archaeomysis vulgaris* |
| | | Apr. | 23 | 3247 | 0.93 | 2.72 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Thoracophelia dillonensis* |
| | | Jul. | 25 | 3541 | 1.04 | 2.94 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Mandibulophoxus mai* |
| | | Oct. | 21 | 2057 | 1.15 | 2.62 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Urothoe grimaldii* |
| | 2012 | Jan. | 20 | 3480 | 1.36 | 2.33 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Thoracophelia dillonensis* |
| | | Apr. | 25 | 1271 | 1.36 | 3.36 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Thoracophelia dillonensis* |
| | | Jul. | 30 | 2556 | 1.19 | 3.70 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Grandifoxus cuspis* |
| | | Oct. | 20 | 2128 | 1.44 | 2.48 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Urothoe grimaldii* |
| | 2013 | Jan. | 19 | 508 | 1.59 | 2.89 | **Felaniella sowerbyi* | *Urothoe grimaldii* | *Haustorioides indivisus* |
| | | Apr. | 18 | 520 | 1.36 | 2.72 | **Felaniella sowerbyi* | *Urothoe grimaldii* | *Haustorioides indivisus* |
| | | Jul. | 26 | 1863 | 1.39 | 3.32 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Mandibulophoxus mai* |
| | | Oct. | 23 | 1644 | 1.57 | 2.97 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Urothoe grimaldii* |
| | 2014 | Jan. | 26 | 592 | 2.24 | 3.92 | *Haustorioides indivisus* | *Urothoe grimaldii* | *Gnorimosphaeroma noblei* |
| | | Apr. | 28 | 564 | 1.75 | 4.26 | **Felaniella sowerbyi* | *Urothoe grimaldii* | *Thoracophelia dillonensis* |
| | | Jul. | 29 | 1761 | 1.55 | 3.75 | *Haustorioides indivisus* | **Felaniella sowerbyi* | *Haustorioides koreanus* |
| | | Oct. | 32 | 1279 | 1.59 | 4.33 | **Felaniella sowerbyi* | *Haustorioides indivisus* | *Urothoe grimaldii* |
| ***Less-impacted area*** | | | | | | | | | |
| Mongsanpo | 2008 | Jan. | 54 | 826 | 2.75 | 7.89 | *Eohaustorius spinigerus* | *Notomastus latericeus* | *Scopimera globosa* |
| | | Apr. | 55 | 976 | 2.99 | 7.85 | *Eohaustorius spinigerus* | *Nuttallia japonica* | *Lumbrineris latreilli* |
| | | Sept. | 63 | 1173 | 2.88 | 8.77 | *Eohaustorius spinigerus* | *Notomastus latericeus* | *Onuphis* sp. |
| | 2009 | Jan. | 58 | 960 | 3.07 | 8.30 | *Eohaustorius spinigerus* | *Scopimera globosa* | *Magelona japonica* |
| | | Apr. | 67 | 828 | 2.79 | 9.82 | *Eohaustorius spinigerus* | *Notomastus latericeus* | *Scopimera globosa* |
| | | Jul. | 65 | 1661 | 2.78 | 8.63 | *Eohaustorius spinigerus* | *Scopimera globosa* | **Eteone* sp. |
| | | Oct. | 60 | 498 | 2.91 | 9.50 | *Notomastus latericeus* | *Scolelepis* sp. | *Magelona japonica* |
| | 2010 | Jan. | 66 | 1046 | 2.32 | 9.35 | *Eohaustorius spinigerus* | *Nephtys californiensis* | *Notomastus latericeus* |
| | | Apr. | 84 | 1467 | 2.89 | 11.38 | *Eohaustorius spinigerus* | *Notomastus latericeus* | *Magelona japonica* |
| | | Jul. | 81 | 2074 | 3.01 | 10.48 | *Eohaustorius spinigerus* | *Scopimera globosa* | *Armandia lanceolata* |
| | | Oct. | 74 | 1836 | 3.00 | 9.71 | *Eohaustorius spinigerus* | *Pygospio* sp. | **Felaniella sowerbyi* |
| | 2011 | Jan. | 76 | 2097 | 2.83 | 9.81 | *Nuttallia japonica* | *Eohaustorius spinigerus* | *Mactra quadrangularis* |
| | | Apr. | 69 | 2144 | 2.63 | 8.87 | *Eohaustorius spinigerus* | *Nuttallia japonica* | *Mactra quadrangularis* |
| | | Jul. | 73 | 2062 | 2.70 | 9.43 | *Eohaustorius spinigerus* | *Nuttallia japonica* | **Felaniella sowerbyi* |

*Opportunistic species.

**Table S3.** (continue).

| Regions | Year | Month | No. of species | Density (ind $m^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| Mongsanpo | 2011 | Oct. | 83 | 1965 | 2.97 | 10.81 | *Eohaustorius spinigerus* | *Umbonium thomasi* | *Nuttallia japonica* |
| | 2012 | Jan. | 88 | 4833 | 2.96 | 10.26 | *Eohaustorius spinigerus* | *Nuttallia japonica* | *Urothoe convexa* |
| | | Apr. | 69 | 2650 | 2.80 | 8.63 | *Eohaustorius spinigerus* | *Nuttallia japonica* | *Urothoe convexa* |
| | | Jul. | 75 | 2148 | 2.93 | 9.65 | *Eohaustorius spinigerus* | **Felaniella sowerbyi* | *Nuttallia japonica* |
| | | Oct. | 78 | 1519 | 2.61 | 10.51 | *Eohaustorius spinigerus* | *Leonnates persicus* | *Nuttallia japonica* |
| | 2013 | Jan. | 69 | 1829 | 2.83 | 9.05 | *Eohaustorius spinigerus* | **Felaniella sowerbyi* | *Leonnates persicus* |
| | | Apr. | 69 | 1751 | 2.87 | 9.11 | *Eohaustorius spinigerus* | *Urothoe convexa* | **Felaniella sowerbyi* |
| | | Jul. | 68 | 2779 | 2.79 | 8.45 | *Umbonium thomasi* | **Felaniella sowerbyi* | *Eohaustorius spinigerus* |
| | | Oct. | 63 | 1429 | 2.64 | 8.53 | *Eohaustorius spinigerus* | **Felaniella sowerbyi* | *Nephtys californiensis* |
| | 2014 | Jan. | 67 | 1545 | 2.65 | 8.99 | *Eohaustorius spinigerus* | *Urothoe convexa* | **Felaniella sowerbyi* |
| | | Apr. | 64 | 2144 | 2.57 | 8.21 | *Eohaustorius longidactylus* | *Urothoe convexa* | *Nuttallia japonica* |
| | | Jul. | 67 | 2204 | 2.63 | 8.57 | *Umbonium thomasi* | *Eohaustorius longidactylus* | **Felaniella sowerbyi* |
| | | Oct. | 66 | 2886 | 2.10 | 8.16 | *Umbonium thomasi* | *Eohaustorius longidactylus* | **Felaniella sowerbyi* |

*Opportunistic species.

**Table S4.** Temporal changes of macrobenthic community structures in the intertidal mudflat areas of Taean region.

| Regions | Year | Month | No. of species | Density (ind $m^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Impacted area*** | | | | | | | | | |
| Sogeunri | 2009 | Feb. | 16 | 71 | 2.20 | 5.02 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Helicana wuana* |
| | | Apr. | 15 | 48 | 2.44 | 5.07 | *Macrophthalmus japonicus* | *Heteromastus filiformis* | **Perinereis aibuhitensis* |
| | | Jul. | 24 | 366 | 1.79 | 3.87 | *Heteromastus filiformis* | *Micronephthys oligobranchia* | *Laternula gracilis* |
| | | Oct. | 16 | 101 | 2.02 | 5.49 | *Heteromastus filiformis* | *Macrophthalmus japonicus* | *Micronephthys oligobranchia* |
| | 2010 | Jan. | 24 | 100 | 2.25 | 5.30 | *Heteromastus filiformis* | *Macrophthalmus japonicus* | *Batillaria cumingii* |
| | | May | 32 | 163 | 2.61 | 6.15 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Batillaria cumingii* |
| | | Jul. | 27 | 206 | 2.42 | 4.47 | *Heteromastus filiformis* | *Micronephthys oligobranchia* | *Batillaria cumingii* |
| | | Oct. | 26 | 176 | 2.24 | 6.10 | *Heteromastus filiformis* | *Batillaria cumingii* | *Macrophthalmus japonicus* |
| | 2011 | Jan. | 9 | 90 | 0.75 | 5.02 | *Heteromastus filiformis* | *Micronephthys oligobranchia* | *Kuwaita heteropoda* |
| | | Apr. | 27 | 543 | 2.12 | 4.18 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Batillaria cumingii* |
| | | Jul. | 31 | 394 | 2.09 | 5.79 | **Perinereis aibuhitensis* | *Heteromastus filiformis* | *Batillaria cumingii* |
| | | Oct. | 34 | 668 | 2.37 | 6.61 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Batillaria cumingii* |
| | 2012 | Jan. | 30 | 1788 | 2.32 | 5.45 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Sinocorophium japonicum* |
| | | Apr. | 39 | 1020 | 2.28 | 5.60 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Macrophthalmus japonicus* |
| | | Jul. | 36 | 736 | 2.12 | 5.02 | *Heteromastus filiformis* | *Glauconome chinensis* | **Perinereis aibuhitensis* |
| | | Oct. | 43 | 921 | 2.48 | 5.07 | *Heteromastus filiformis* | *Melita shimizui* | **Perinereis aibuhitensis* |
| | 2013 | Jan. | 31 | 818 | 2.16 | 3.87 | *Heteromastus filiformis* | **Perinereis aibuhitensis* | *Glauconome chinensis* |
| | | Apr. | 45 | 1356 | 2.29 | 5.49 | *Grandidierella japonica* | *Heteromastus filiformis* | **Perinereis aibuhitensis* |
| | | Jul. | 36 | 1071 | 1.99 | 5.30 | *Glauconome chinensis* | *Heteromastus filiformis* | **Perinereis aibuhitensis* |
| | | Oct. | 28 | 635 | 2.20 | 6.15 | **Perinereis aibuhitensis* | *Glauconome chinensis* | *Heteromastus filiformis* |
| | 2014 | Jan. | 43 | 1411 | 2.12 | 4.47 | *Heteromastus filiformis* | *Macrophthalmus japonicus* | *Glauconome chinensis* |
| | | Apr. | 49 | 1428 | 2.56 | 6.10 | *Sinocorophium japonicum* | *Glauconome chinensis* | **Perinereis aibuhitensis* |
| | | Jul. | 39 | 1073 | 2.11 | 5.02 | *Heteromastus filiformis* | *Glauconome chinensis* | **Perinereis aibuhitensis* |
| | | Oct. | 41 | 1258 | 2.33 | 4.18 | *Heteromastus filiformis* | *Glauconome chinensis* | **Perinereis aibuhitensis* |
| ***Less-impacted area*** | | | | | | | | | |
| Keunso Bay | 2011 | Apr. | 65 | 1441 | 2.70 | 8.80 | *Ruditapes philippinarum* | *Theora lata* | *Arcuatula senhousia* |
| | | Jul. | 66 | 1820 | 2.79 | 8.66 | *Laternula gracilis* | *Ruditapes philippinarum* | *Heteromastus filiformis* |
| | | Oct. | 71 | 1135 | 2.98 | 9.95 | *Ruditapes philippinarum* | *Heteromastus filiformis* | *Macrophthalmus japonicus* |
| | 2012 | Jan. | 65 | 4110 | 2.70 | 7.69 | *Ruditapes philippinarum* | *Philine orientalis* | *Heteromastus filiformis* |
| | | Apr. | 81 | 2856 | 3.01 | 10.05 | *Cumella somersi* | *Ruditapes philippinarum* | *Philine orientalis* |
| | | Jul. | 71 | 1985 | 2.77 | 9.22 | *Ruditapes philippinarum* | *Ampharete arctica* | *Heteromastus filiformis* |
| | | Oct. | 61 | 990 | 3.03 | 8.70 | *Ruditapes philippinarum* | *Heteromastus filiformis* | *Ilyoplax pingi* |
| | 2013 | Jan. | 51 | 650 | 2.96 | 7.72 | *Ruditapes philippinarum* | *Heteromastus filiformis* | *Nephtys polybranchia* |
| | | Apr. | 61 | 925 | 2.97 | 8.79 | *Heteromastus filiformis* | *Ilyoplax pingi* | *Ruditapes philippinarum* |

*Opportunistic species.

**Table S4.** (continue).

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| Keunso Bay | 2013 | Jul. | 63 | 1498 | 2.91 | 8.48 | *Ruditapes philippinarum* | *Heteromastus filiformis* | *Ampharete arctica* |
| | | Oct. | 55 | 820 | 2.70 | 8.05 | *Heteromastus filiformis* | *Ilyoplax pingi* | *Ruditapes philippinarum* |
| | 2014 | Jan. | 73 | 1721 | 3.12 | 9.66 | *Heteromastus filiformis* | *Diastylis paratricinta* | *Ruditapes philippinarum* |
| | | Apr. | 69 | 1759 | 2.70 | 9.10 | *Ruditapes philippinarum* | *Nippoleucon hinumensis* | *Bullacta caurina* |
| | | Jul. | 56 | 1205 | 2.59 | 7.75 | *Ruditapes philippinarum* | *Heteromastus filiformis* | *Ampharete arctica* |
| | | Oct. | 67 | 1839 | 2.84 | 8.78 | *Heteromastus filiformis* | *Ruditapes philippinarum* | *Ilyoplax pingi* |

*Opportunistic species.

**Table S5.** Temporal changes of macrobenthic community structures in the intertidal rockyshores of Taean region.

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Impacted area*** | | | | | | | | | |
| Guryepo | 2008 | Feb. | 9 | 922 | 0.92 | 1.17 | _Chthamalus challengeri_ | _Littorina brevicula_ | *_Lottia_ spp. |
| | | May | 13 | 340 | 1.12 | 2.06 | _Littorina brevicula_ | _Lasaea undulata_ | _Crassostrea gigas_ |
| | | Nov. | 13 | 175 | 1.47 | 2.32 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | 2009 | Feb. | 20 | 260 | 1.48 | 3.42 | _Littorina brevicula_ | _Lasaea undulata_ | _Crassostrea gigas_ |
| | | May | 13 | 481 | 1.03 | 1.94 | _Littorina brevicula_ | _Lasaea undulata_ | _Crassostrea gigas_ |
| | | Aug. | 9 | 2129 | 1.21 | 1.04 | _Chthamalus challengeri_ | _Littorina brevicula_ | _Lasaea undulata_ |
| | | Nov. | 19 | 400 | 1.12 | 3.00 | _Crassostrea gigas_ | _Lasaea undulata_ | _Littorina brevicula_ |
| | 2010 | Feb. | 18 | 498 | 1.10 | 2.74 | _Littorina brevicula_ | _Crassostrea gigas_ | _Lasaea undulata_ |
| | | May | 24 | 1087 | 1.52 | 3.29 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia spp._ |
| | | Aug. | 23 | 1268 | 1.16 | 3.08 | _Littorina brevicula_ | _Crassostrea gigas_ | _Lasaea undulata_ |
| | | Nov. | 24 | 400 | 1.39 | 3.84 | _Crassostrea gigas_ | *_Lottia_ spp. | _Monocorophium acherusicum_ |
| | 2011 | Feb. | 37 | 1213 | 1.68 | 5.07 | _Crassostrea gigas_ | *_Lottia_ spp. | _Littorina brevicula_ |
| | | May | 21 | 893 | 1.34 | 2.94 | _Littorina brevicula_ | _Crassostrea gigas_ | _Lasaea undulata_ |
| | | Aug. | 23 | 439 | 1.57 | 3.62 | _Crassostrea gigas_ | *_Lottia_ spp. | _Monocorophium acherusicum_ |
| | | Nov. | 25 | 743 | 1.72 | 3.63 | _Crassostrea gigas_ | _Chthamalus challengeri_ | *_Lottia_ spp. |
| | 2012 | Feb. | 26 | 1252 | 2.06 | 3.51 | _Crassostrea gigas_ | _Lasaea undulata_ | _Littorina brevicula_ |
| | | May | 31 | 1160 | 1.91 | 4.25 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | | Aug. | 30 | 997 | 1.97 | 4.20 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | | Nov. | 29 | 474 | 2.18 | 4.54 | _Crassostrea gigas_ | *_Lottia_ spp. | _Hemigrapsus penicillatus_ |
| | 2013 | Jan. | 28 | 1050 | 2.19 | 3.88 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | | Apr. | 33 | 921 | 2.10 | 4.69 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | | Jul. | 28 | 1020 | 2.05 | 3.90 | _Littorina brevicula_ | _Crassostrea gigas_ | *_Lottia_ spp. |
| | | Oct. | 36 | 1093 | 2.10 | 5.00 | _Crassostrea gigas_ | _Littorina brevicula_ | *_Lottia_ spp. |
| | 2014 | Jan. | 31 | 1459 | 1.83 | 4.12 | _Crassostrea gigas_ | _Littorina brevicula_ | *_Lottia_ spp. |
| | | Apr. | 23 | 1277 | 1.83 | 3.08 | _Crassostrea gigas_ | _Littorina brevicula_ | *_Lottia_ spp. |
| | | Jul. | 15 | 1282 | 1.68 | 1.96 | _Crassostrea gigas_ | _Littorina brevicula_ | *_Lottia_ spp. |
| | | Oct. | 18 | 478 | 2.08 | 2.76 | _Crassostrea gigas_ | *_Lottia_ spp. | _Odostomia aomori_ |
| Padori | 2008 | Feb. | 10 | 1175 | 0.02 | 1.27 | _Chthamalus challengeri_ | _Littorina brevicula_ | _Lasaea undulata_ |
| | | May | 10 | 245 | 0.03 | 1.64 | _Littorina brevicula_ | _Nerita japonica_ | *_Lottia_ spp. |
| | | Nov. | 8 | 226 | 0.00 | 1.29 | _Littorina brevicula_ | _Nerita japonica_ | _Monodonta labio_ |
| | 2009 | Feb. | 26 | 737 | 0.21 | 3.79 | _Lasaea undulata_ | _Crassostrea gigas_ | _Littorina brevicula_ |
| | | May | 19 | 1236 | 0.07 | 2.53 | _Chthamalus challengeri_ | _Littorina brevicula_ | _Lasaea undulata_ |
| | | Aug. | 8 | 600 | 0.04 | 1.09 | _Chthamalus challengeri_ | _Littorina brevicula_ | _Crassostrea gigas_ |
| | | Nov. | 16 | 224 | 0.39 | 2.77 | _Littorina brevicula_ | _Crassostrea gigas_ | _Lasaea undulata_ |

*Opportunistic species.

**Table S5.** (continue).

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| Padori | 2010 | Feb. | 12 | 379 | 0.07 | 1.85 | *Chthamalus challengeri* | *Littorina brevicula* | *Crassostrea gigas* |
| | | May | 19 | 1459 | 0.13 | 2.47 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | Aug. | 16 | 1179 | 0.25 | 2.12 | *Lasaea undulata* | *Littorina brevicula* | *Chthamalus challengeri* |
| | | Nov. | 28 | 2812 | 0.21 | 3.40 | *Chthamalus challengeri* | *Crassostrea gigas* | *Littorina brevicula* |
| | 2011 | Feb. | 34 | 2563 | 0.22 | 4.20 | *Lasaea undulata* | *Crassostrea gigas* | *Littorina brevicula* |
| | | May | 21 | 2400 | 0.19 | 2.57 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | Aug. | 16 | 2909 | 0.06 | 1.88 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | Nov. | 33 | 3738 | 0.38 | 3.89 | *Chthamalus challengeri* | *Lasaea undulata* | *Crassostrea gigas* |
| | 2012 | Feb. | 24 | 2325 | 0.17 | 2.97 | *Lasaea undulata* | *Littorina brevicula* | *Crassostrea gigas* |
| | | May | 32 | 1965 | 0.48 | 4.09 | *Lasaea undulata* | *Crassostrea gigas* | *Littorina brevicula* |
| | | Aug. | 27 | 2359 | 0.45 | 3.35 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | | Nov. | 29 | 1847 | 0.36 | 3.72 | *Littorina brevicula* | *Lasaea undulata* | *Chthamalus challengeri* |
| | 2013 | Jan. | 34 | 2110 | 3.08 | 4.31 | *Lasaea undulata* | *Crassostrea gigas* | *Littorina brevicula* |
| | | Apr. | 28 | 2388 | 0.35 | 3.47 | *Lasaea undulata* | *Littorina brevicula* | *Crassostrea gigas* |
| | | Jul. | 33 | 2174 | 1.50 | 4.16 | *Littorina brevicula* | *Chthamalus challengeri* | *Lasaea undulata* |
| | | Oct. | 31 | 2333 | 0.75 | 3.87 | *Littorina brevicula* | *Lasaea undulata* | *Crassostrea gigas* |
| | 2014 | Jan. | 32 | 1397 | 1.45 | 4.28 | *Littorina brevicula* | *Crassostrea gigas* | *Lasaea undulata* |
| | | Apr. | 43 | 2951 | 0.26 | 5.26 | *Lasaea undulata* | *Littorina brevicula* | *Chthamalus challengeri* |
| | | Jul. | 18 | 1129 | 0.40 | 2.42 | *Littorina brevicula* | *Lasaea undulata* | **Lottia* spp. |
| | | Oct. | 24 | 1073 | 1.11 | 3.30 | *Lasaea undulata* | *Crassostrea gigas* | *Chthamalus challengeri* |
| ***Less-impacted area*** | | | | | | | | | |
| Yeonpo | 2008 | Feb. | 24 | 4774 | 0.08 | 2.72 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | | May | 31 | 3892 | 0.11 | 3.63 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | Nov. | 37 | 4037 | 2.34 | 4.34 | *Chthamalus challengeri* | *Lasaea undulata* | *Crassostrea gigas* |
| | 2009 | Feb. | 24 | 426 | 0.33 | 3.80 | *Littorina brevicula* | **Odostomia aomori* | *Nereis heterocirrata* |
| | | May | 36 | 1646 | 0.89 | 4.73 | *Littorina brevicula* | *Lasaea undulata* | *Chthamalus challengeri* |
| | | Aug. | 15 | 6105 | 0.00 | 1.61 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | | Nov. | 22 | 4743 | 0.00 | 2.48 | *Chthamalus challengeri* | *Lunella correensis* | *Hemigrapsus penicillatus* |
| | 2010 | Feb. | 14 | 5961 | 0.01 | 1.50 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | | May | 9 | 7348 | 0.00 | 0.90 | *Chthamalus challengeri* | *Littorina brevicula* | *Crassostrea gigas* |
| | | Aug. | 9 | 15996 | 0.00 | 0.83 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | | Nov. | 18 | 7737 | 0.03 | 1.90 | *Chthamalus challengeri* | *Littorina brevicula* | *Crassostrea gigas* |
| | 2011 | Feb. | 33 | 4717 | 0.37 | 3.78 | *Monocorophium acherusicum* | *Crassostrea gigas* | *Littorina brevicula* |
| | | May | 13 | 4870 | 0.04 | 1.41 | *Chthamalus challengeri* | *Crassostrea gigas* | *Littorina brevicula* |
| | | Aug. | 19 | 2738 | 0.07 | 2.27 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |

*Opportunistic species.

**Table S5.** (continue).

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| Yeonpo | 2011 | Nov. | 27 | 16592 | 0.02 | 2.68 | *Chthamalus challengeri* | *Crassostrea gigas* | *Lasaea undulata* |
| | 2012 | Feb. | 21 | 7694 | 0.02 | 2.24 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | May | 33 | 5231 | 0.13 | 3.74 | *Chthamalus challengeri* | *Littorina brevicula* | *Crassostrea gigas* |
| | | Aug. | 30 | 3711 | 0.08 | 3.53 | *Chthamalus challengeri* | *Lasaea undulata* | *Crassostrea gigas* |
| | | Nov. | 16 | 5101 | 0.00 | 1.76 | *Chthamalus challengeri* | *Littorina brevicula* | *Lasaea undulata* |
| | 2013 | Jan. | 19 | 13174 | 0.00 | 1.90 | *Chthamalus challengeri* | *Lasaea undulata* | *Littorina brevicula* |
| | | Apr. | 13 | 11225 | 0.00 | 1.29 | *Chthamalus challengeri* | *Littorina brevicula* | *Gnorimosphaeroma* sp. |
| | | Jul. | 15 | 10784 | 0.00 | 1.51 | *Chthamalus challengeri* | *Peasiella habei* | *Littorina brevicula* |
| | | Oct. | 10 | 11576 | 0.00 | 0.96 | *Chthamalus challengeri* | *Crassostrea gigas* | *Littorina brevicula* |
| | 2014 | Jan. | 9 | 10058 | 0.01 | 0.87 | *Chthamalus challengeri* | *Littorina brevicula* | *Crassostrea gigas* |
| | | Apr. | 8 | 11715 | 0.02 | 0.75 | *Chthamalus challengeri* | *Littorina brevicula* | *Siphonaria acmaeoides* |
| | | Jul. | 8 | 13080 | 0.01 | 0.74 | *Chthamalus challengeri* | *Littorina brevicula* | *Peasiella habei* |
| | | Oct. | 5 | 11022 | 0.00 | 0.43 | *Chthamalus challengeri* | *Littorina brevicula* | *Siphonaria acmaeoides* |

*Opportunistic species.

**Table S6.** Temporal changes of macrobenthic community structures in the subtidal areas of Taean region.

| Regions | Year | Month | No. of species | Density (ind m$^{-2}$) | Diversity (H') | Richness (R) | Dominant species | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Impacted area*** | | | | | | | | | |
| Subtidal | 2008 | Feb. | 26 | 398 | 2.55 | 2.55 | *Theora lata* | *Sternaspis scutata* | *Lumbrineris longifolia* |
| | | May | 24 | 398 | 2.36 | 2.36 | *Theora lata* | *Amphipholis sobrina* | **Prionospio steenstrupi* |
| | | Nov. | 22 | 389 | 1.85 | 1.85 | *Nephtys polybranchia* | *Theora lata* | *Sternaspis scutata* |
| | | Feb. | 31 | 614 | 2.53 | 2.53 | **Prionospio steenstrupi* | *Nephtys polybranchia* | *Amphisamytha japonica* |
| | 2009 | Feb. | 23 | 304 | 1.92 | 1.92 | *Nephtys polybranchia* | *Lumbrineris longifolia* | *Ampelisca* sp. |
| | | May | 26 | 409 | 1.99 | 1.99 | **Prionospio steenstrupi* | *Nephtys polybranchia* | *Owenia fusiformis* |
| | | Nov. | 26 | 464 | 1.96 | 1.96 | **Prionospio membranacea* | *Theora lata* | *Ampelisca* sp. |
| | | Feb. | 21 | 281 | 1.55 | 1.55 | **Prionospio steenstrupi* | *Urothoe* sp. | *Praxillella affinis* |
| | 2010 | May | 21 | 322 | 2.32 | 2.32 | *Lumbrineris longifolia* | *Heteromastus filiformis* | **Prionospio bocki* |
| | | Nov. | 20 | 279 | 1.75 | 1.75 | **Prionospio bocki* | *Felaniella sowerbyi* | *Lumbrineris longifolia* |
| | | Feb. | 22 | 1131 | 1.47 | 1.47 | *Theora lata* | *Scoloplos armiger* | *Umbonium costatum* |
| | | May | 25 | 337 | 2.19 | 2.19 | *Heteromastus filiformis* | *Urothoe* sp. | *Notomastus latericeus* |
| | 2011 | Apr. | 24 | 416 | 2.47 | 2.47 | *Amphioplus sp.* | *Gammaropsis japonica* | **Mediomastus californiensis* |
| | | Jul. | 36 | 1104 | 2.39 | 2.39 | *Gammaropsis japonica* | *Dimorphostylis brevicaudata* | *Ampharete arctica* |
| | | Oct. | 34 | 1352 | 2.30 | 2.30 | *Ampelisca* sp. | *Euclymene oerstedii* | **Mediomastus californiensis* |
| | 2012 | Jan. | 26 | 1128 | 2.34 | 2.34 | **Mediomastus californiensis* | *Ampharete arctica* | *Euclymene oerstedii* |
| | | May | 47 | 1375 | 2.64 | 2.64 | *Cerapus tubularis* | **Mediomastus californiensis* | *Amphipholis sorbrina* |
| | | Jul. | 55 | 1463 | 2.84 | 2.84 | *Theora lata* | *Ampharete arctica* | *Dimorphostylis brevicaudata* |
| | | Oct. | 46 | 885 | 3.06 | 3.06 | *Euclymene oerstedii* | *Ampharete arctica* | **Mediomastus californiensis* |
| | 2013 | Jan. | 29 | 646 | 2.26 | 2.26 | *Ampelisca* sp. | *Ampharete arctica* | **Mediomastus californiensis* |
| | | Apr. | 34 | 460 | 2.78 | 2.78 | *Lumbrineris japonica* | *Euclymene oerstedii* | *Lepidozona andrijaschevi* |
| | | Jul. | 42 | 939 | 2.59 | 2.59 | *Ampharete arctica* | *Ampelisca* sp. | **Mediomastus californiensis* |
| | | Oct. | 35 | 886 | 2.71 | 2.71 | *Ampharete arctica* | *Amphicteis gunneri* | *Ampelisca* sp. |
| | 2014 | Jan. | 34 | 664 | 2.66 | 2.66 | *Ampharete arctica* | *Ampelisca* sp. | *Euclymene oerstedii* |
| | | Apr. | 37 | 941 | 2.70 | 2.70 | *Owenia fusiformis* | **Mediomastus californiensis* | *Protodorvillea egena* |
| | | Jul. | 38 | 717 | 2.77 | 2.77 | *Ampharete arctica* | *Owenia fusiformis* | *Ampelisca* sp. |
| | | Oct. | 57 | 1184 | 2.95 | 2.95 | *Ampharete arctica* | *Euclymene oerstedii* | *Protodorvillea egena* |

*Opportunistic species.

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