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SPECIAL ISSUE: OCEAN SPILLS AND ACCIDENTS

Environmental Impacts and Recovery After the *Hebei Spirit* Oil Spill in Korea

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Abstract The *Hebei Spirit* oil spill (HSOS) on December 7, 2007 was the worst oil spill recorded in Korea, with the release of approximately 10,900 tons of crude oil and 375 km of coastline polluted along the west coast of Korea. Cleanup operation was conducted by official and contract responders as well as volunteers for massive oil containment and removal of heavy accumulations of stranded oil. Together with the oil cleanup, a long-term environmental impact assessment (EIA) of the HSOS was initiated based on the Marine Environmental Management Act, which covers oil contamination in a multimedia environment, toxic effects on organisms, and ecosystem injury. This review summarizes the long-term monitoring results of HSOS EIA focused on (1) pollution status of seawater, sediment, and bivalves, (2) ecotoxicological effects, and (3) ecosystem recovery. Overall, concentrations of petroleum hydrocarbons in the environment indicated that their concentrations were well down to at or near background or pre-spill contamination levels at most sites after 1 year. The potential toxic effects of residual oils in sediments have decreased to background levels in most coastal areas of Taean. The entire ecosystem in the most affected area of the Taean coasts appear to be considerably, but not fully, recovered at present, namely after 8 years of the HSOS. The presence of lingering oil and elevated contamination levels at several sites still require continuous long-term monitoring.

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On December 7, 2007, the Hong Kong-registered tanker M/V *Hebei Spirit*, laden with 209,000 tons of crude oil, was struck by the crane barge Samsung No. 1 while anchored approximately 10 km off Taean on the west coast of the Republic of Korea (ROK). Approximately 10,900 tons of crude oil spilled into the sea from the *Hebei Spirit*. The collision resulted in punctures to tanks No. 1, 3, and 5 of the oil tanker and three different types of crudes were spilled: Kuwait export crude (KEC), Iranian heavy crude (IHC), and UAE Upper Zakum crude (UZC). The proportional spill volumes of the three cargo oils, KEC, IHC, and UZC, were 43.4, 42.8, and 13.8%, respectively (Yim et al. 2012).

The spilled oil resulted in varying degrees of pollution along the coastline. During a 30-day period, the spilled oil was then rapidly transported over several hundred kilometers of coastline by northwesterly winds and currents (KCG 2008; Kim et al. 2013a). In particular, ~70 km of the Taean shoreline was heavily impacted by thick stranded oil within just 1 day of the spill. The rapid spread of spilled oil resulted in areawide damage to fisheries, mariculture, and beaches along the majority of the west coast of Korea, as well as disruptions to the marine ecosystem (Hong et al. 2014; KCG 2008).

The *Hebei Spirit* oil spill (HSOS) is recorded as the largest marine oil spill in Korean history; thus, it has been of great public and scientific concern in Korea. Based on the Marine Environmental Management Act in the ROK, the responsible party should immediately commence an environmental impact assessment (EIA) through institutes predesignated by the Korean government when the volume of spilled oil is greater than 100 kL (Yim et al. 2012). Oil contamination, toxic effects on organisms, and ecosystem injury were the primary objectives of the HSOS EIA, and they are the main focus of this review. HSOS EIA is planned to continue for 10 years, which is expected to contribute to scientific efforts to reveal the long-term effects of oil spill. This review summarizes the long-term monitoring results of HSOS EIA focused on (1) pollution status for multi-media environment (seawater, sediment, and bivalves), (2) ecotoxicological effects, and (3) ecosystem recovery.

Cleanup Operations

During the initial stage of the HSOS, spilled oil was driven into seawater by high energy physical conditions, which subsequently produced oil-in-water and/or water-in-oil emulsions. Chemical treatment in the pre-approved zone at sea, using approximately 298 kL of oil spill dispersants, further dispersed the surface oil slick into the water column. Approximately 4 days post spill, the spilled crude oil was massively emulsified, resulting in a highly elastic, seemingly stabilized water-in-oil emulsion on the sea surface (Hong et al. 2014).

Cleanup activities at sea were conducted through the use of an oil boom, the recovery of the oil slick in the surface layer, spraying an oil spill dispersant and absorbent using all available ships, and utilizing the man power of all relevant environmental and response agencies and organizations. More than 1.3 million volunteers joined the shoreline cleanup operation for 1 month after the spill (Hong et al. 2014). The shoreline recovered quickly with the help of this unprecedented large number of volunteers, together with the effective physical removal of the solid oil from the environment. A total 4175 kL of oil (not fully separated from water) and 32,074 tons of oiled solid waste, including the disposable response equipment, were collected during the 1-month period. Based on the water content of the recovered liquid oil estimated as 50% by volume and the percentage of oil in the recovered solid waste assumed to be 1% by weight, the total recovered oil was calculated to be roughly 20% of the spilled oil (Yim et al. 2012).

An emergency cleanup operation was conducted by official and contract responders and volunteers, and it involved both massive oil containment and the removal of heavy accumulations of stranded oil, via an operation that lasted until January 2, 2008. A secondary operation was undertaken to remove subsurface oil on beaches and remote islands, and this continued until October 10, 2008 (Yim et al. 2012). Cleanup activities at sea and in the onshore areas of Taean were officially terminated in October 2008. However, lingering oil was found in the deeper layers (>20 cm) of sediments along the heavily affected intertidal areas of Taean (Hong et al. 2012).

Oil Contamination in the Environment

Contamination levels and temporal variations of spilled oil in environmental media were investigated monthly, seasonally, or yearly since the oil spill. Seawater, sediment, and biota samples were collected from intertidal, subtidal, and offshore regions. Heavily contaminated intertidal regions in Taean Peninsula were investigated intensively, and relatively less-disturbed remote areas also were visited periodically. Total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), including US EPA's 16 priority PAHs, and alkylated PAHs were measured in the samples. TPHs were analyzed by GC/FID following the liquid–liquid extraction with dichloromethane for seawater (Kim et al. 2013b) or Soxhlet extraction with dichloromethane for sediment (MLTM 2009). Bivalve samples were Soxhlet extracted and cleaned up by silica-alumnia column and HPLC with size exclusion column (MLTM 2009). PAHs were analyzed using GC/MS following the method described previously in Yim et al. (2007). Target PAH compounds are listed in Table 1.

Water Analyses

Immediately after the spill, its impact was clearly recognized at most sites surveyed. The seawater (unfiltered) TPH concentrations ranged from 1.5 to 7310 μg L^{-1} (equivalent to ppb; parts-per-billion), with an average of 732 μg L^{-1}, which is on average 73 times higher than the marine water quality standard of Korea (Kim et al. 2013a, b). The concentrations appeared to decrease drastically to 2.0–224 μg L^{-1} in 1 month after the spill. 16PAH concentrations in intertidal seawater were as high as 5170 ng L^{-1} (equivalent to ppt; parts-per-trillion) immediately after the spill. Then 16PAH concentrations also decreased drastically to approximately 100 ng L^{-1} 1 month after the spill. The oil component concentrations in seawater then decreased steadily to the range of background contamination levels generally detected in the coastal waters of Korea, with a short-term regional fluctuation due to remobilization of oil by continuing shoreline cleanup operations and subsequent wave/tidal actions (Kim et al. 2010, 2013b).

By 1 year after the spill, the oil content in seawater had clearly declined and seemed to be recovered to ambient concentration level at most sites (Fig. 1a). Although

Table 1 List of the polycyclic aromatic hydrocarbon (PAH) analyzed in each environmental matrices

Matrix	Seawater	Sediment, oyster
No. of analytes	16	36
Acronym	16PAHs	tPAHs
PAHs included	Naphthalene	Naphthalene
	Acenaphthylene	C1-Naphthalenes
	Acenaphthene	C2-Naphthalenes
	Fluorene	C3-Naphthalenes
	Phenanthrene	C4-Naphthalenes
	Anthracene	Acenaphthylene
	Fluoranthene	Acenaphthene
	Pyrene	Fluorene
	Benz[*a*]anthracene	C1-Fluorenes
	Chrysene	C2-Fluorenes
	Benzo[*b*]fluoranthene	C3-Fluorenes
	Benzo[*k*]fluoranthene	Dibenzothiophene
	Benzo[*a*]pyrene	C1-Dibenzothiophenes
	Indeno[1,2,3-*cd*]pyrene	C2-Dibenzothiophenes
	Dibenz[*a*,*h*]anthracene	C3-Dibenzothiophenes
	Benzo[*ghi*]perylene	Phenanthrene
		Anthracene
		C1-Phenanthrenes
		C2-Phenanthrenes
		C3-Phenanthrenes
		C4-Phenanthrenes
		Fluoranthene
		Pyrene
		Benz[*a*]anthracene
		Chrysene
		C1-Chrysenes
		C2-Chrysenes
		C3-Chrysenes
		Benzo[*b*]fluoranthene
		Benzo[*k*]fluoranthene
		Benzo[*e*]pyrene
		Benzo[*a*]pyrene
		Perylene
		Indeno[1,2,3-*cd*]pyrene
		Dibenz[*a*,*h*]anthracene
		Benzo[*ghi*]perylene

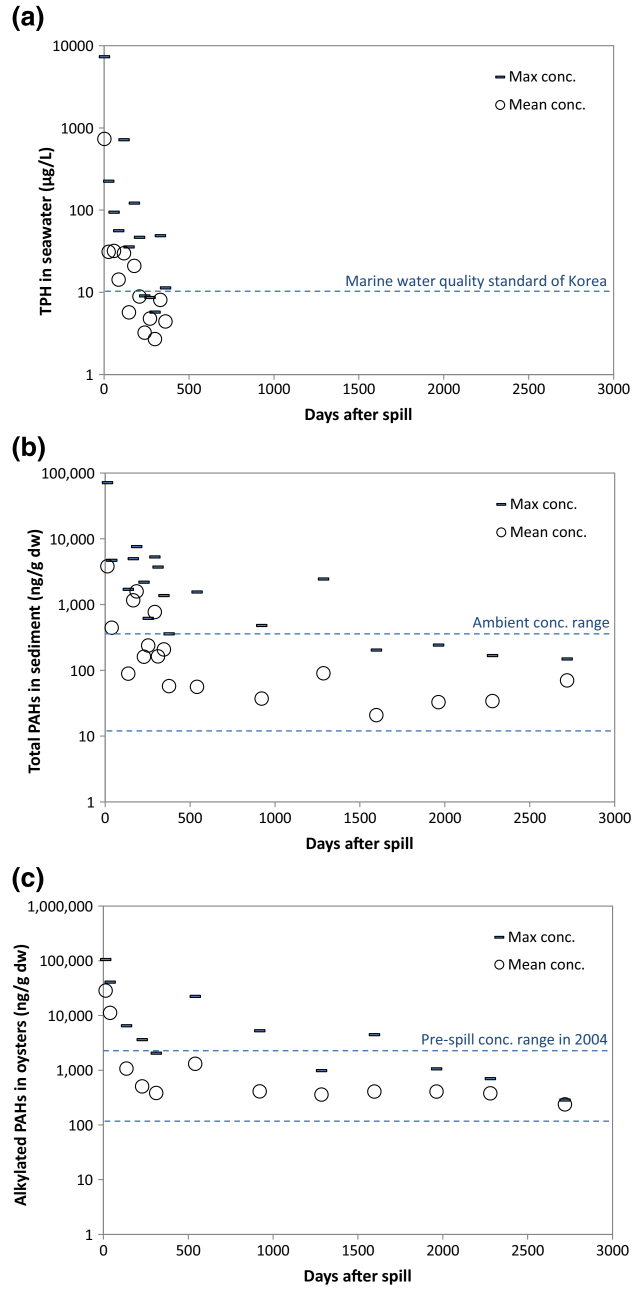

Fig. 1 Temporal trends of oil component concentrations in seawater (**a**), sediment (**b**), and oysters (**c**) for 7.5 years since the *Hebei Spirit* oil spill (December 2007–May 2015). TPH in seawater was monitored only for 1 year (December 2007–December 2008) due to its rapid recovery from the impact of the oil spill. Baseline conditions are marked with *horizontal dashed lines*

elevated levels of hydrocarbon backgrounds have been reported along the heavily populated or industrialized coastlines in Korea due to intensive anthropogenic activities (Yim et al. 2012), the coast of Taean, before the spill, was one of pristine environments with rarely detectable ambient hydrocarbon concentrations. The active tidal/wave mixing in the area, along with various weathering processes, helped to disperse and to degrade petroleum hydrocarbons, resulting in low concentrations below the marine water quality standard in 10 months after the spill. However, TPH concentrations remained higher than the marine water quality standard at some locations until June of 2009 (MLTM 2011). 16PAH concentrations in subtidal regions were approximately 10 ng L^{-1} on average during the entire investigation period, which was approximately twofold lower than the PAH concentrations in the intertidal seawater sampled during the same period (Yim et al. 2012).

Sediment Analyses

In sediment, oil components showed the highest concentrations at the initial spill stage. TPH and tPAHs (sum of the unsubstituted parent PAHs and alkylated PAHs) in the intertidal sediments ranged up to 1630 µg g^{-1} (equivalent to ppm; parts-per-million) and 71,200 ng g^{-1} (equivalent to ppb), respectively, revealing the direct impact of the spill on the intertidal zone (Kim et al. 2017; MLTM 2009). Increases in the concentrations were clearly observed at the sites on Taean Peninsula, which were heavily oiled due to tidal currents and northwesterly wind that transported spilled oil to these locations. Spatial distribution of petroleum hydrocarbons showed substantial variability due to the patchy distribution of spilled oil, cleanup activities, and nonuniform sediment deposition and erosion in the area. Mean and maximum PAH concentrations declined drastically from 3800–88.5 to 71,200–1700 ng g^{-1}, respectively, during the first 4 months (Kim et al. 2017). PAH concentrations highly fluctuated until September of 2008 and then decreased continuously (Fig. 2b).

One year after the spill, the average concentrations of TPH and tPAHs in intertidal sediments had decreased by 40- and 66-fold, respectively, compared with the initial concentrations (Kim et al. 2017; MLTM 2009). Individual PAHs were all decreased in their concentrations but the fractions of C2- and C3-dibenzothiophenes and high molecular weight PAHs relatively increased due to the preferential loss of low molecular weight compounds during the weathering of oil components in sediment. Thereafter, sediment tPAH concentrations have declined close to local background levels at most sites. The storm surge mixing and weathering processes (dissolution, dispersion, microbial degradation, and photooxidation) likely helped to disperse and to degrade PAHs, resulting in low concentrations one year after the spill.

By May 2015 (~7.5 years after the spill), mean and maximum tPAH concentrations decreased by 54 and 481 times, respectively, compared with the peak concentrations (Kim et al. 2017). Due to lack of the analytical data in oil spill-affected areas before the spill, the concentrations of PAHs could not be compared directly, but current concentrations of PAHs at most of coastal areas are comparable with those in other coastal regions of Korea (Khim and Hong 2014; Yim et al. 2007). The sediment PAH concentrations in the monitoring area appeared to have returned to regional background levels. However, relatively elevated concentrations of PAHs were still observed

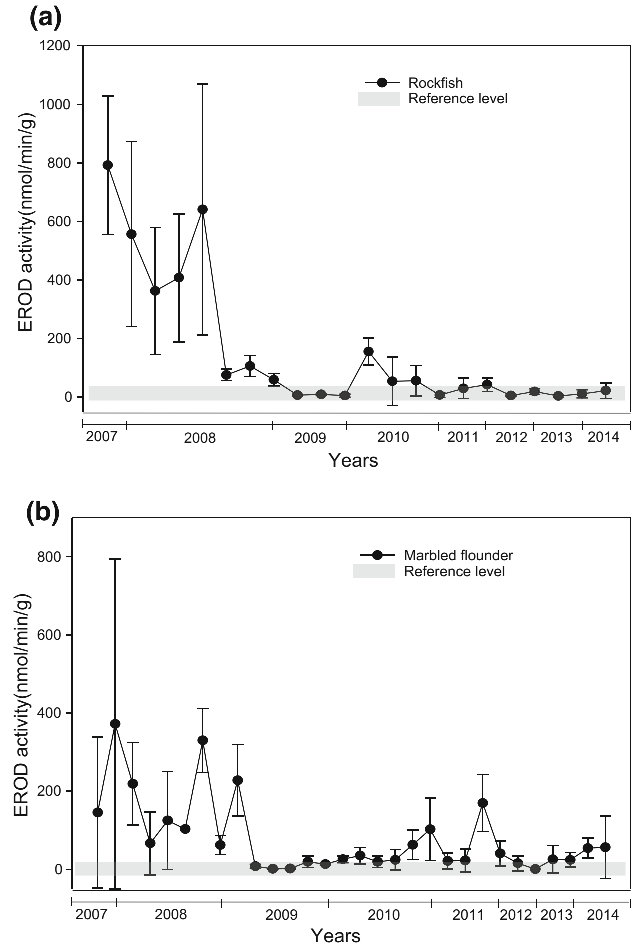

Fig. 2 Temporal changes of EROD activities **a** in Rockfish (*Sebastes schlegelii*), **b** marbled flounder (*Limanda yokohamae*) collected from oil spill sites at Taean. Ranges of reference levels indicate the EROD activity in fish from Boryeong (Reference site). *Error bars* represent standard deviations

at some locations, particularly in fine sediments in the inner part of semiclosed area and boulder-armored beach, due to the lack of flushing under low energy conditions (Hong et al. 2012; MLTM 2012).

Oyster Analyses

The concentrations of parent and alkylated PAHs in oysters increased up to 1200 and 106,000 ng g^{-1}, respectively (MLTM 2009). Alkylated PAHs in oysters collected in the Taean coastal region in December 2007 were approximately 40–500 times higher than those analyzed in the pre-spill site. Source recognition indexes (e.g., alkylated dibenzothiophenes to alkylated phenanthrenes ratios) in the contaminated oyster were similar to those of Iranian heavy and Upper Zakum crude oils, but distinguishable from those of pre-spill or background contaminations, indicating that the source of PAH contamination in the oyster was the spilled oil from the *Hebei Spirit* (MLTM 2009). Alkylated PAH concentrations in oysters decreased exponentially over time and approached pre-spill levels within a year (Fig. 1c), except for sites where oil still lingered (Yim et al. 2012). PAH concentrations in oysters currently show local variations within the pre-spill contamination levels. However, oysters from the sites where oil lingers, such as mud flats and boulder-armored beaches, show slow recovery reflecting the persistence of oil and relatively high PAH concentrations throughout the survey. Bivalve samples from remote areas also had elevated levels of petroleum-derived PAHs after the spill, but there were large variations among the stations.

Overall, concentrations of petroleum hydrocarbons in the environmental media collectively indicated that their concentrations were well down to the background or pre-spill contamination levels at most sites. Their reduction rates (e.g., environmental half-life) were quite comparable to the values reported in other spill cases (Kim et al. 2013a, b, 2017, and references therein). However, the presence of lingering oil and elevated contamination levels at several sites, particularly including mud flats and beaches protected with boulders in the enclosed bay, indicates long-lasting impacts of the spill in the environment. This study suggests the need for continuous long-term monitoring of oil contamination especially at the sites of possible lingering oil to understand and estimate the continuing impact of the *Hebei Spirit* oil spill.

Ecotoxicology

The effects of the spilled oil have been assessed in organisms, as well as at the ecosystem level, from 3 days after the HSOS to the present day. Naturally and/or chemically dispersed oil has affected pelagic ecosystems in the vicinity of the spill site. Biomarker induction in pelagic and benthic fishes exposed to the spilled oil had been monitored following the spill (Jung et al. 2011, 2012). Elevated levels of biliary PAH metabolites and EROD activity were found in fish collected from areas affected by the oil spill immediately after the spill. Biochemical responses based on hepatodetoxification (CYP1A mRNA, CYP1A protein, and EROD) showed a significant relationship with the concentrations of biliary PAH metabolites in resident fish (Jung et al. 2011). The biochemical responses of pelagic and benthic fish to petrogenic PAHs exposure resulting from the HSOS were generally similar to those observed following other large oil spills. The physiological recovery of resident benthic fish was slower than that of pelagic fish (Fig. 2). The slower recovery of benthic fish is possibly due to feeding habits on contaminated benthic organisms.

Laboratory exposure studies have confirmed the adverse toxic effects of one of spilled oil, IHC on resident fish embryos, including novel tail fin defects (Jung et al. 2013, 2015a, b). The impacts of the spilled oil on immune system were also tested in resident fish species. The immune disturbance may have cascading lethal effects including the induction of pathogenicity, and reduction of physiological resistance to the bacterial disease (Kim et al. 2013a, 2014). The fish community in shallow water regions near the heavily impacted shoreline exhibited reductions in the number of species, biomass, and diversity for 2 years after the HSOS compared with the reference site (MLTM 2011).

Even though the massive amount of oil stranded on shoreline was rapidly removed by the cleanup operation, lingering oil contamination in the subsurface of sandy beaches and mudflats caused toxicological effects for several years afterward. Residual crude oil in coastal sediments induced aryl hydrocarbon receptor-mediated activity (Hong et al. 2012, 2015), endocrine disruption (Ji et al. 2011), and genotoxicity (Lee et al. 2011) in an in vitro bioassay conducted 2 years after the spill. Ecotoxicological monitoring of intertidal sediments was performed for 5 years after the spill. Sediment toxicity was observed in an amphipod, *Monocorophium uenoi*, and embryonic fish, *Cyprinodon variegatus*. Sediment toxicity gradually decreased in sandy beaches and to a lesser extent in mudflats during this period, which was generally reflected in the sediment residual PAH concentrations (Lee et al. 2013; MLTM 2013). Overall, the potential toxic effects of residual oils in sediments have declined to background in most coastal areas of Taean. However, some heavily polluted sites and low tidal energy regions still contain lingering oil contamination, in which the specific toxic actions and protagonists in oil are largely unknown (Hong et al. 2014).

Ecosystem

The ecological impacts of the spilled oil in the Taean area have long been a significant issue and concern since the spill due to the contamination in the intertidal and subtidal areas. The adverse effects on the marine organisms in the contaminated water and sediment systems were monitored in a periodic manner from 3 days after the HSOS to recent years. As mentioned earlier, the spilled crude oils reached the southernmost coast of Korea within a month; accordingly the quality of the entire ecosystem in the west coast of Korea was severely degraded. Even though the massive amounts of spilled oils were mostly removed right after the oil spills, residual oils seemed to cause persistent toxic effects on various organisms.

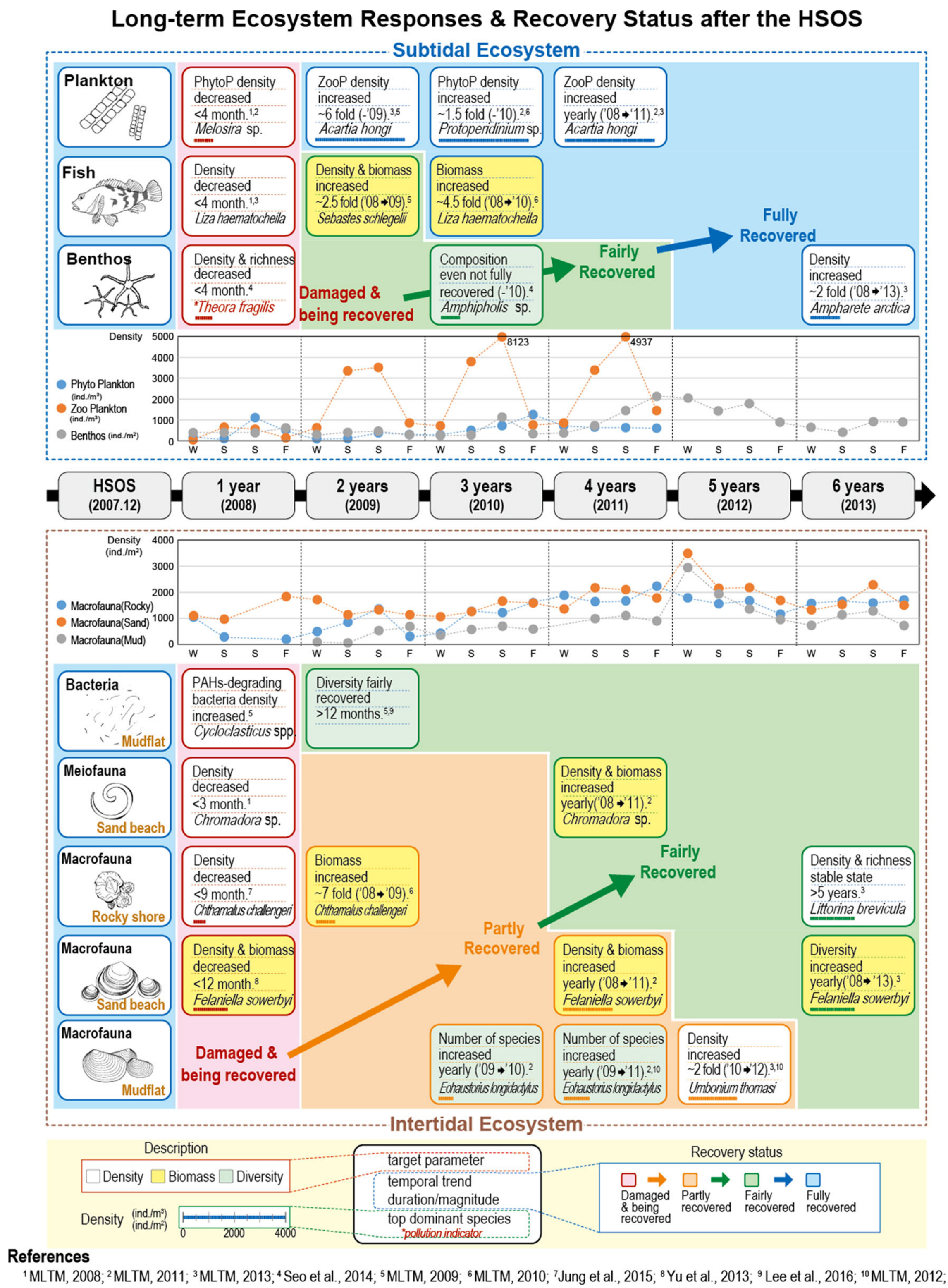

Fig. 3 Long-term ecosystem responses and recovery status in the subtidal and intertidal areas of the Taean coasts, Korea, after the HSOS; target populations of plankton, fish, and benthos for subtidal area and bacteria, meiofauna, and macrofauna for intertidal area. Intertidal macrobenthic community further divided into three type habitats, including rocky shore, sand beach, and mudflat. Recovery status was categorized as four tiers, damaged and being recovered, partly, fairly, and fully recovered based on the meta-data, literature given, and authors communication

As part of this review, we collected meta-data and analyzed the long-term ecological responses at multiple levels of coastal ecosystems encompassing the intertidal and subtidal communities (Fig. 3). Target coastal ecosystems were further divided into major group of targeted populations, i.e., plankton, fish, and benthos for subtidal areas, and bacteria, meiofauna, and macrofauna for intertidal area. Habitat types were further considered for the analysis of intertidal macrofauna responses in rocky shores, sand beaches, and mudflats, as hydrocarbon chemistry in each habitat might vary greatly. Long-term ecological changes in their assemblages including number of species, species composition and abundance, biomass, and diversity were emphasized. Altogether, we tried to address the recovery duration and its degree [i.e., partly (10 to <50%), fairly (50 to <100%), and fully recovered (natural condition, ~100%)] in target populations and/or habitat types. There were certain limitations of the analyses due to the lack of systematic sampling and consistent logistics.

In general, the subtidal community showed relatively fast natural recovery compared with intertidal populations, but the recovery status greatly varied depending on the type of population (Fig. 3). The planktonic populations, both phytoplankton and zooplankton, seemed to be fully recovered 1 year after the spill, with rapid increases of number of species (MLTM 2009, 2010). This result was consistent with the rapid residual hydrocarbons decrease in water column and maintained background levels since the middle of 2008 (Fig. 1a). Fish populations recovered rapidly by density and biomass, with yearly increase of abundance through 2008–2009, reaching the normal population level (MLTM 2009, 2010). Although the subtidal benthic environment seemed to take a longer time for the full recovery, a visual increase of corresponding population after 5 years was evidenced (MLTM 2009; Seo et al. 2014). The steady but slower recovery observed in benthic communities would be attributable to the slow degradation of sedimentary residual hydrocarbons, particularly in soft bottom habitats. Considering the severe injuries both in the subtidal and intertidal ecosystems right after the spill, the recoveries after several years are attributable to tide-derived recolonized populations in combination of abiotic and biotic interactions. The role of key biological factors such as biological behavior, physiology, and reproduction should be recognized in the future study.

The analysis of the long-term changes in intertidal community showed the trend of recoveries across the target populations of bacteria, meiofauna, and macrofauna (Fig. 3). The most sensitive taxonomic group of these organisms was bacteria, where PAHs-degrading bacteria increased drastically in density within a year after the HSOS (Lee et al. 2017). Such rapid change in bacterial populations seemed to indicate faster turnover time compared with higher organisms under the deteriorated benthic condition. The intertidal benthic communities of both meiofauna and macrofauna were slower to recover, i.e., not fully recovered in recent years. However, it is noteworthy that several dominant species showed visual increases across their respective habitats: *Littorina brevicula* (rocky), *Chromadora* sp., and *Felaniella sowerbyi* (sand beach), and *Umbonium thomasi* (mudflat) over years (Jung et al. 2015c; MLTM 2014; Yu et al. 2013). Of note, the visual sign of benthic community response, i.e., recolonization of *Batillaria* spp. after 2 years of the HSOS (December 2009) was reported far earlier, but the study concluded that the most of benthic communities remained unstable and/or unhealthy (Hong et al. 2012).

Altogether, the recovery status of varying coastal ecosystems from the massive oil spills seemed to fluctuate greatly depending on the target populations and habitat types. In general, the recovery status of the Taean coastal ecosystem generally reflected the hydrocarbon chemistry in terms of dose–response relationship. Intertidal benthic communities seemed to require the longest time period for the natural recovery in the contaminated oil spill sites. Overall, the entire ecosystem in the most affected area of the Taean coasts seemed to be considerably recovered at present, namely after 8 years of the HSOS (Hong et al. 2014). Nevertheless, the continuing ecological monitoring would be necessary to address the long-term recovery mechanism and/or potential toxic effects associated with the residual oils, particularly in areas of lingering oil (Hong et al. 2015).

Conclusions

Ever since the *Hebei Spirit* oil spill in December 2007, the largest in Korean history, emergency and continuous national response activities rapidly removed spilled oil and apparently reduced residual oil, thus facilitated restoration of damaged ecosystems. This review summarizes long-term environmental impact assessment results and concluded that the damaged ecosystem has recovered considerably within eight years in terms of oil contamination, ecotoxicological effects, and structural and functional integrity of the ecosystem. There remains an appreciable amount of residual oils in mudflats and beaches protected with boulders in the enclosed bay, indicating potential long-lasting impacts of the spill in the environment. This study suggests the need for continuous long-term monitoring of ecosystem especially at the sites of possible lingering oil to understand and estimate the continuing impact of the *Hebei Spirit* oil spill.

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