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Environmental and ecological effects and recoveries after five years of the *Hebei Spirit* oil spill, Taean, Korea

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ABSTRACT

The *Hebei Spirit* oil spill (HSOS) in December 7, 2007 spilled approximately 10,900 tons of crude oil in about 10 km off the Taean coasts in South Korea. We first summarize and overview, in the present study, the current status of environmental and ecological effects of the HSOS focusing on i) pollution status for surrounding environment (water, sediment, and porewater), ii) biological effects on living organisms, iii) potential toxic effects *in vitro* and *in vivo*, and finally iv) human health risk. In particular, ecological impacts followed by the recoveries of coastal ecosystem are intensively addressed. Water quality seemed to be rapidly recovered considering the background levels of oil pollution indices, while oil impacted sediments experienced fairly long history of contamination. Meanwhile, the benthic epifauna mapping in the worst impacted area of Taean indicated that the coastal organisms are fairly recovered after five years of the HSOS. However, it should be noted that residual oils are still found in some inner part of small bays and mud dominant regions in Taean area which would cause the potential toxic effects on coastal organisms. Finally, the current understandings and limitations of such effects from the HSOS are further discussed highlighting, i) long-term effects of residual oils, ii) identification of certain toxic chemicals in residual oils, iii) weathering characteristics of spilled oils, iv) possible effects from the unknown hydrocarbons in oils, and v) recovery of community level responses to the HSOS.

1. Introduction

1.1. *Hebei Spirit* oil spill

On December 7, 2007, the oil tanker M/V *Hebei Spirit*, which was carrying 209,000 tons of crude oil, was collided by a crane barge, Samsung No.1, near Taean (~10 km off the west coast), South Korea (Kim et al., 2010; Yim et al., 2012). Approximately 10,900 tons of crude oil (mixtures of Kuwait Export Crude, Iranian Heavy Crude, and UAE Upper Zakum Crude) from the oil tanker was spilled into the sea (Yim et al., 2012). The spilled oil was then rapidly extended over several hundred kilometers of coastlines during 30 days by northwesterly winds and currents driven (KCG, 2008; Kim et al., 2013) (Fig. 1). In particular, ~70 km of the Taean shoreline was heavily impacted by thick stranded oil within only one day post-spill.

The rapid spread of spilled oil certainly resulted in area-wide damages (~350 km^2) to fisheries, maricultures, and beaches in most of the west coast of Korea, as well as total disruption to the marine ecosystem (KCG, 2008), as expected. The *Hebei Spirit* oil spill (HSOS) is recorded as the biggest marine oil spill in the Korean history, amount of spilled oil was two times greater than those of the Sea Prince oil spill, the former worst one, in South Sea of Korea in 1995. The HSOS was the recent largest oil spill at sea in the world prior to the Deepwater Horizon oil spill in the Gulf of Mexico in April 2010 and about 1/3 in size compared to the *Exxon Valdez* oil spill (EVOS), the worst oil spill accident in the world, in 1989, thus of great public and scientific concerns in Korea (Yim et al., 2012).

1.2. Initial responses

Immediately after the HSOS, Korean Coast Guard (KCG) could not take any action for prevention of oil spill from the oil tanker due

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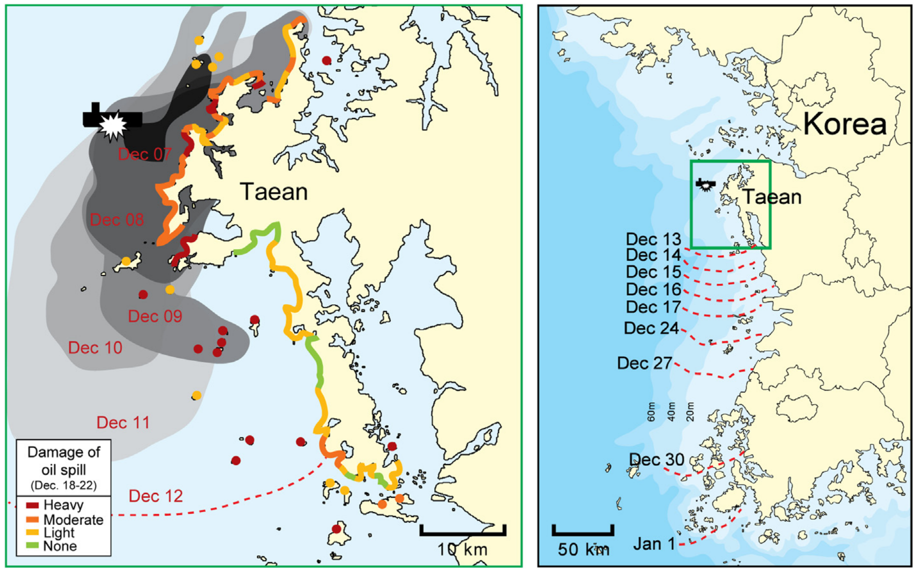

Fig. 1. Spread of spilled oil and damage of oil spill along the shoreline at initial stage of the *Hebei Spirit* oil spill accident (KCG, 2008; MLTM, 2008).

to the inclement weather conditions. For example, it was not until two days after that break-hole part of vessel was blocked as emergency responses (KCG, 2008), which could have accelerated the rapid environmental damage, if any. In high physical energy condition at initial stage of the HSOS, spilled oil was mixed with seawater and subsequently produced oil-in-water and/or water-in-oil emulsion. Chemical treatment in the pre-approved zone at sea using about 298 kL of oil spill dispersants (Table 1) dispersed surface oil slick into water column. Approximately four days post spill, the spilled crude oil was massively emulsified, resulting in highly elastic stabilized water-in-oil emulsion on sea surface.

The KCG organized the National Disaster Prevention and Countermeasures Headquarters (NDPCH) with associated agencies and organizations and local authorities based on the National Contingency Plan, and set the response activities by use of ships, helicopters, and heavy equipment (Table 1). At the initial stage, the NDPCH set up priority plans including blocking the release from oil tanker and prevention of oil input to the sensitive areas such as those for fisheries, maricultures, and enclosed bay regions. The NDPCH organized three teams including Coastal Response Team, Marine Response Team, and Logistics Team which were in charge of planning of response strategies, support and management of equipment and volunteers, and oil waste disposal, respectively.

1.3. Cleanup activities

Cleanup activities at sea were conducted by use of oil boom, recovery of oil slick in the surface layer, spraying of oil spill dispersant and absorbent by use of all available ships and manpower of every related agency and organization (Table 1). Total of 20,210 ships were mobilized, about 47 km of oil boom were installed, and 493 tons of oil adsorbent were used for both at sea and on shore cleanup. It should be highlighted that more than 1.2 million volunteers had joined the shoreline cleanup operation for more than one month after the spill. The shoreline had recovered fast with help of a large number of volunteers together with the effective physical removal of the solid oil in the environment (Yim et al., 2012). Total 4,175 kL of oils (not fully separated from water) and 32,074 tons of oiled solid waste including the disposable response equipment were collected during the one month period.

Emergency cleanup operation had been conducted by official and contract responders and volunteers for massive oil containment and removal of heavily stranded oil, until January 2, 2008.

Table 1
Cleanup activities in marine and coastal area after the *Hebei Spirit* oil spill. Mobilizations of ships, cleanup materials, heavy machinery, and personnel and collecting waste oil (KCG, 2008).

Occurrence		
Location	~10 km off Taean	
Month/Day/Year	December/07/2007	
Amount of spilled oil	10,900 tons	
Pollution	375 km of coastline	
Type of oil	Kuwait Export Crude, Iranian Heavy Crude, UAE Upper Zakum	
Cleanup activities		
Ships	Total (Unit)	20,210
	KCG[a]	6,630
	KOEM[b]	889
	Navy	723
	Etc.	11,968
Heavy machinery	Total (Unit)	28,973
	Truck	9,991
	Excavator	5,559
	Tractor	1,304
	Etc.	12,119
Personnel	Total (Ind.)	2,132,322
	Volunteer	1,226,730
	Resident	563,896
	Etc.	341,696
Cleanup materials	Oil boom (km)	46.77
	Oil adsorbent (kg)	493,127
	Dispersant (kL)	298
Recoveries		
Liquid oil[c]	Total (kL)	4,175
	at Sea	2,360
	on Shore	1,815
Oil wastes	Total (Tons)	32,074
	at Sea	1,034
	on Shore	31,040

[a] KCG: Korean Coast Guard.
[b] KOEM: Korea Marine Environment Management Corporation.
[c] Not fully separated from water.

Next, secondary fine response operation had been done to remove sub-surface oil on beaches and remote islands, until October 10, 2008 (Yim et al., 2012). Cleanup activities at sea and on shore areas of Taean have been terminated officially in October of 2008. However, lingering oils have been often found in deeper layer (>20 cm) of sediments along the heavily affected intertidal areas of Taean (Hong et al., 2012).

1.4. Legal authorities and environmental surveys

Environmental survey for marine pollution effect after the HSOS was carried out based on the Marine Environment Management Act of 2007 (MEMA). The purpose of this Act is originally to prevent any danger and injury due to either damage of marine environment or marine pollution and create a clean and safe environment (MLTM, 2010). Scientific surveys by the government should follow the "Article 77: Marine Pollution Effect Investigation" of the MEMA, guided as, "*… pollutant substances … is discharged from a vessel or maritime facility to the ocean, an owner of the vessel or maritime facility shall execute marine pollution effect investigation through a marine pollution effect investigation institution. The marine pollution effect investigation institution … shall be designated by the Minister …. Where a person who has conducted the marine pollution effect investigation … does not perform … or it is acknowledged to be necessary for an emergency investigation …, the Minister may select separately an investigation institution to execute the investigation…*"

Environmental survey for marine pollution effects of the oil spill should be conducted by the representatives owning research vessels and/or survey facilities. The environmental survey for the impact assessment of the HSOS was carried out by the Korea Institute of Ocean Science & Technology (KIOST) (previously named Korea Ocean Research and Development Institute, KORDI), as one of the public institutes. Originally, the environmental survey was comprised of monitoring for i) natural environment, ii) life environment, and iii) socio-economic environment, however, the KIOST survey was somehow limited to the field monitoring of natural environment among those. In anyhow, the technical reports have been published annually entitled "Environmental Impact Assessment and Environmental Restoration of the *Hebei Spirit* Oil Spill: Technical Report" since 2008. About hundred researchers (one institute, five universities, and two companies) have been participated to this project of which research funds are about 2.5 billion Korean won (ca. 2.3 million USD) per year supported from the government. The project has been conducting the assessment of oil pollution, ecosystem monitoring, and ecotoxicological risk assessment.

In addition, as individual level efforts, many researches have been studying the various aspects of the environmental damages and impacts relating to the HSOS during the last five years. Altogether, such extra work could support the missing elements for the environmental impact assessment of the HSOS and could contribute the broad spectrum of environmental quality monitoring and assessment up to date. While, much of the oil pollution status in terms of "damage" are studied and known after the HSOS, the changes of natural environment and surrounding ecosystem in aspect of "recovery" have not been yet documented. In fact, after the HSOS, about 30 papers have been published in domestic and international journals, thus we reviewed all the previously published data and summarized those findings focusing on the historic environmental damages and current status towards "recovery" aspect, in the present review. Also, as part of the collection, we provided our own data, say the habitat mapping result of benthic epifauna to track the evidence of ecological response and recovery of the HSOS in timely manner. The detailed review process including data collection and analysis are presented as below.

2. Data collections and analysis

After the HSOS, the governmental projects and individual researches on the oil pollution and its various environmental impacts followed by assessments have addressed the multiple lines of evidences towards ecological recoveries against environmental damages. Major issues for oil pollution cover occurrence and distribution of residual oils in environmental media including water, porewater, sediment, and biota in and around oil spill site, especially targeting the area of worst impacted coasts of Taean (Fig. 1). Meantime, the initial response and recovery of ecosystem focusing on biological effects against the HSOS at varying ecological levels from molecular and cell, individual, population, community, and further human health have been collectively studied.

In the present study, key findings of the previous studies on pollution status, in terms of "damage" and biological effects of the HSOS, in aspect of "recovery" were scrutinized and the current understandings are carefully delivered. As part of review, we collected the monitoring data of residual oils in sediments around the coastal areas of Taean and analyzed the spatial and temporal changes of their major components including polycyclic aromatic hydrocarbons (PAHs) and alkyl-PAHs (MLTM, 2012) (presented in Fig. 3). By comparing their concentrations with background levels of PAHs and alkyl-PAHs and/or their environmental quality guidelines, the selected regions are categorized as four groups, say i) not recovered, ii) partly recovered, iii) fairly recovered, and iv) fully recovered, addressing recovery status. Meanwhile, the damage and its recoveries of macrobenthic communities in the intertidal areas were highlighted based on the epifauna mapping techniques, viz. visual assessment of benthic assemblages in target areas, including beach, tidal flat, and rocky shore of Taean coasts in July 2008, December 2009, and July 2013 (shown in Fig. 4).

Altogether, the degree of recoveries in the viewpoints of water quality, sediment quality, bioaccumulation, potential toxicity, and benthic community was carefully indexed into four categories, which encompasses, i) not recovered ($<\sim$20%), ii) partly recovered ($\sim$20–$\sim$50%), iii) fairly recovered ($\sim$50–$\sim$80%), and iv) fully recovered ($>\sim$80%), to quantitatively address the current status of the HSOS damage and recovery (presented in Fig. 5).

Finally, research efforts after the HSOS were analyzed into five categories based on the subjects, which includes studies on i) oil residues, ii) biological effects, iii) ecological concerns, iv) human health, and v) social concerns and policy, then the results were compared to those of the EVOS case (given in Fig. 6). This was done to comparatively analyze the research efforts and future directions regarding the post evaluation process against large scale oil spill accidents, highlighting case-specific assessment, if any.

3. Environmental damages

As crude oil is introduced into the environment, it undergoes dissipation and degradation through an oil weathering process. Weathering encompasses a variety of physical, chemical, and biological transformation such as evaporation, dissolution, emulsification, photo-oxidation, and microbial degradation over periods of days, months, or even many years (Harayama et al., 1999; Prince et al., 2003; Hong et al., 2012). According to the environmental conditions, the amount of spilled oil would gradually decrease upon such processes.

As for the HSOS case, the half-life of spilled oil was calculated to be 2.6 months in the early stages of weathering (Yim et al., 2011). Most of stranded oil samples on intertidal zone after 8 months the

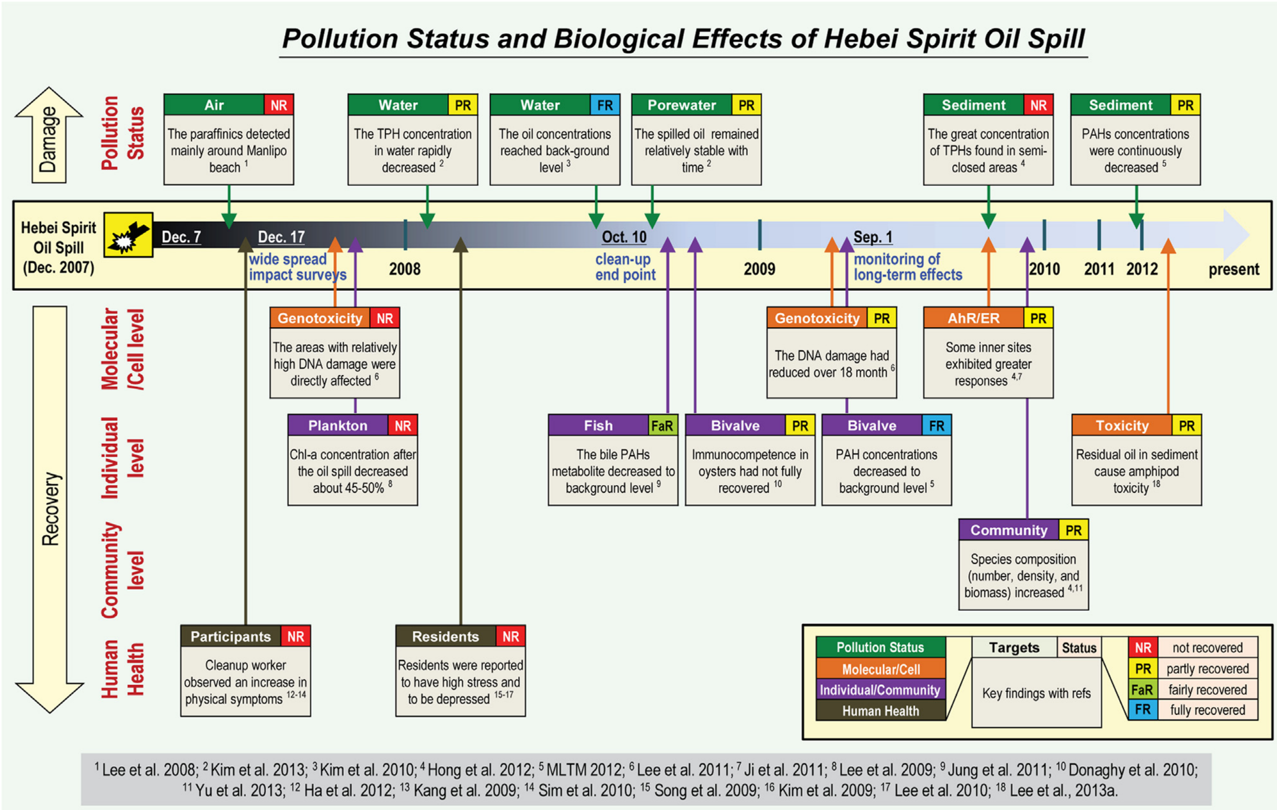

Fig. 2. Summary for key findings of studies on pollution status and biological effects after the *Hebei Spirit* oil spill.

HSOS were categorized into either the advanced or extreme weathering stage (Yim et al., 2011). However, some higher molecular weight compounds and non-degradable ones in crude oil are more resistant to weathering and oils in deeper layer of sediments or soils can persist for longer period of time, which have a potential for causing long-term adverse effects on marine and terrestrial ecosystems (Wang and Fingas, 1995; Peterson et al., 2003). The degree of oil weathering generally tends to increase with exposure time (air or water), although the rates of dissipation and transformation are site-specific due to regional or temporal differences in light, wind, waves, tidal flushing, strength of currents, and microbial activities (Lee et al., 2008; Taylor and Reimer, 2008).

Gradual increase in more persistent toxic component along with compositional change of chemicals in the residual oil through various environmental media during weathering emphasizes the need for adaptive eco-toxicological approaches (Yim et al., 2011; Hong et al., 2012). In this section, we summarized the previous findings on occurrence, distributions, and environmental fate and transport, if any, through varying environmental media, including water, sediment, and porewater to fully understand the current status of oil pollution related to the HSOS.

3.1. Water

For a couple days after the spill, most of the intertidal seawater was covered by rainbow/brown sheens and/or thick crude oil (Kim et al., 2010). After one to two weeks, the visible sheens on surface seawater were mostly removed, however, the great concentrations of total petroleum hydrocarbon (TPH) were detected ranging from 1.5 to 7,310 μg L^{-1} (mean = 732 μg L^{-1}, $n = 23$) in intertidal zone (Kim et al., 2010, 2013). The TPH concentrations appeared to decrease drastically to 2.0–224 μg L^{-1} in one month of the spill. The concentrations of residual oils in seawater were fluctuating with time because of the remobilization of oils by the cleanup activities and subsequent wave/tidal actions (Kim et al., 2010, 2013).

Concentrations of TPH in seawater were much greater at high tide than those at low tide, which seemed to be associated with the tidal resuspension of stranded oil on the upper tidal zone (Kim et al., 2013). Oil concentrations in seawater clearly decreased at most sites, of which concentrations were found at the level below the Korean Marine Water Quality Standard (10 μg L^{-1}) in 10 months of the spill (Kim et al., 2010). Overall, water quality of Taean area seemed to be fairly recovered within 1 year after the HSOS.

3.2. Sediment and porewater

The spilled oil was relatively resistant to bottom layers of sediment and porewater in the intertidal area compared to seawater environment (Kim et al., 2010; Hong et al., 2012; MLTM, 2012). One month after the oil spill, the oil concentrations in porewater in most coastal area were found to be relatively low, however, the elevated oil concentrations (TPH > 1,000 μg L^{-1}) were detected in several porewater samples from the heavily impacted area (Kim et al., 2010). Concentrations of residual oil in porewater did not show clear decreasing trends in highly affected areas until three months after the spill, due to slow exchange rate of materials therein (Kim et al., 2010). At highly impacted area by the HSOS, the residual oils could be dissolved into porewater and/or adsorbed onto the sediments which can be slowly released back into the seawater, continuing the steady impacts on surrounding marine environment and habitat (Kim et al., 2010).

In sediment, oil-derived toxic substances, PAHs showed the greatest concentrations at initial stage (MLTM, 2012). The sedimentary PAHs continuously decreased in most of the coastal areas,

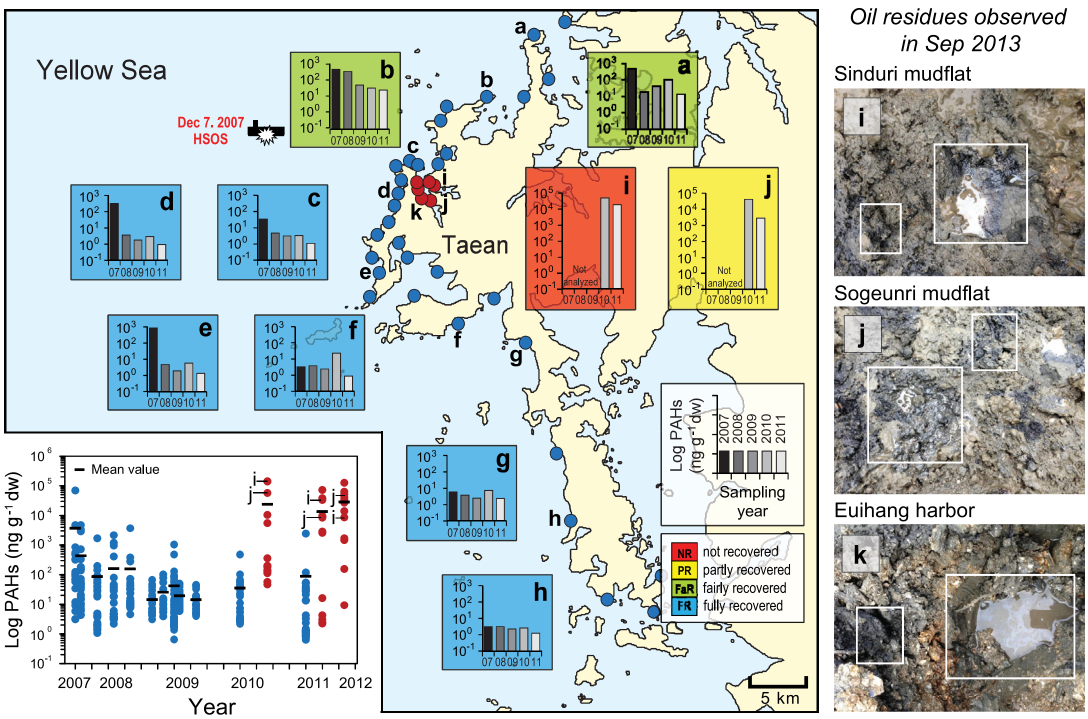

Fig. 3. Spatio-temporal distribution of total PAHs (parents and alkyl- PAHs) in coastal sediments during 2007–2011. Photos of residual oils observed in September 2013 taken from heavily polluted areas of Taean.

of which process was relatively slow compared to those in seawater and porewater (Fig. 3). Because of lack of the analytical data in oil spill-affected area before the HSOS, the concentrations of PAHs could not be compared directly, but current concentrations of PAHs at most of coastal areas are comparable with those (~several ppb level) in other areas of the Korean coasts reported previously (Yim et al., 2007; Khim and Hong, 2014). However, the elevated concentrations of oil-derived PAHs were yet found at some locations, particularly in the inner part of semi-closed area, possibly due to the lack of flushing under low energy conditions (Hong et al., 2012; MLTM, 2012).

In Taean area, sand beach is dominant along the shoreline and tidal range is relatively high (4–8 m), thus such high energy conditions together with coarse particle properties of sand bottom would bring the rapid removal of oil residuals in sedimentary environment, compared to other regions. In addition, the rapid response along the shoreline prevented the beaches from massive penetration and burial of stranded oils to sub-surface of sediments. However, it should be noted that relatively great concentrations of oil-derived PAHs were still found in fine sediments in the inner part of semi-closed area and boulder-armored beach, due to the limited clean-up operations and/or the lack of flushing under low energy conditions (Hong et al., 2012; MLTM, 2012) (Fig. 3). Bioavailability, specific toxic mechanisms, and the effects of agonists/antagonists of residual oil components are still largely unknown, thus their distribution and transport during weathering process cross the areas and/or compounds should be further identified to fully address their environmental fate.

4. Biological effects and recoveries

Crude oil contains large number of toxic substances with varying components that can cause adverse effects on marine and terrestrial ecosystems including human health (Harwell and Gentile, 2006). Two major classes of damages such as physical injuries and biochemical impacts would be generally considered (US EPA, 1999) for the oil spill pollution. At the initial stage, plants, water birds, and other marine wildlife could be physically affected by the spilled oil, such that plants and animals are completely covered and smothered by crude oils. Crude oil not only destroys the insulating properties of animal fur and bird feathers, which can lead to hypothermia, but it also impairs animals' abilities to fly and swim, sometimes causing oiled animals to drown (NOAA, 2013). For instance, about 30,000 dead birds (>90 species) were found in the oil spilled areas during the months after the EVOS (Piatt et al., 1990).

Crude oil also has harmful effect on living organisms due to its chemical constituents that is a complex mixture of thousands of chemicals with various known mechanisms including aryl hydrocarbon receptor (AhR) associated toxicity (Harwell and Gentile, 2006). For example, VOCs and PAHs are well known major toxic components of crude oil (Page et al., 2002). VOCs including benzene, toluene, ethylbenzene, and xylene readily evaporate into the air which are generally acutely toxic and potentially cancer-causing when inhaled (Leusch and Bartkow, 2010). Air-breathing marine mammals, residents, and cleanup workers could be exposed to VOCs particularly right after the oil spilled because of their volatile properties. In contrast, PAHs would persist in the environment for many years because of long residence time, in some cases continues to cause long-term adverse effects on aquatic organisms after the oil spill (Peterson et al., 2003).

4.1. Potential toxic effects of residual oils

After the HSOS, several potential toxic effects including AhR-mediated activity, endocrine disruption, and genotoxicity in residual crude oil in costal sediments were intensively studied (Fig. 2). For example, after two years the spill, AhR-mediated activity in oil contaminated coastal sediments was assessed using *in vitro* H4IIE-luc bioassay (Hong et al., 2012). The AhR-mediated

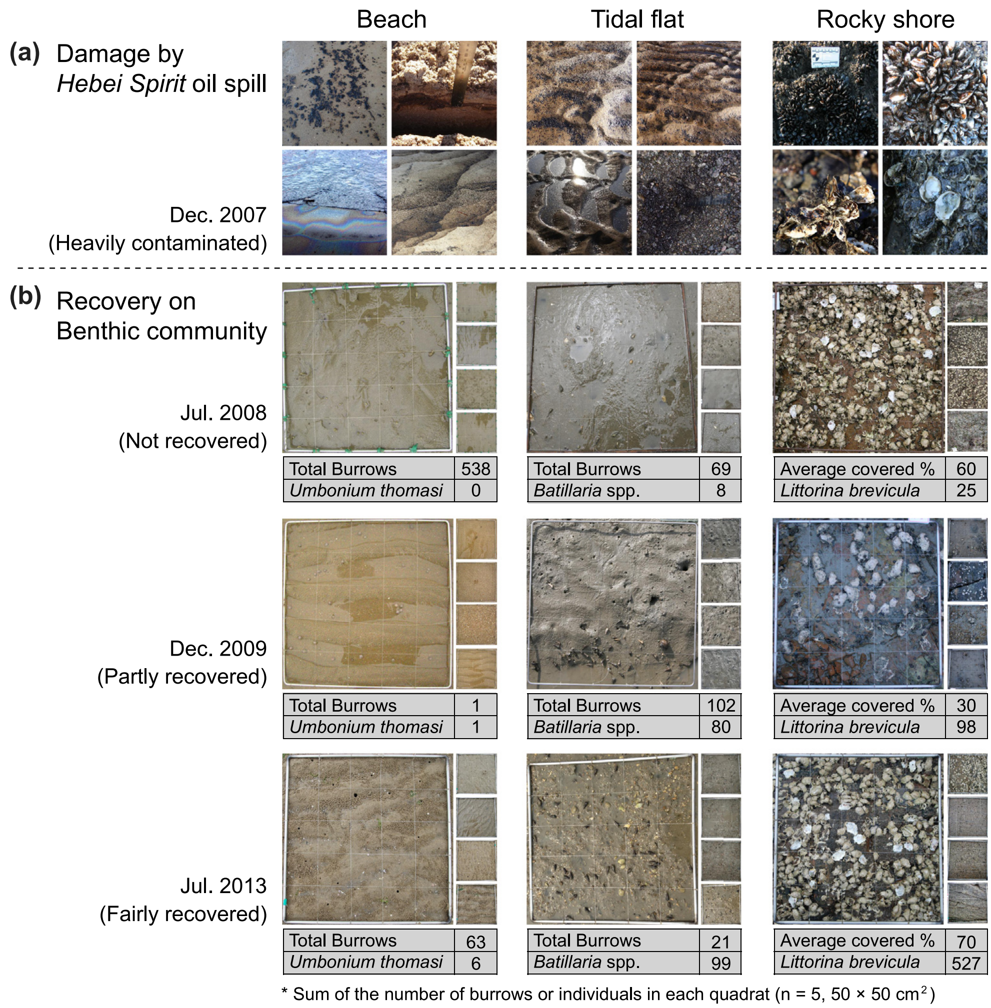

Fig. 4. Quadrat photos for observation of recoveries of benthic communities after the *Hebei Spirit* oil spill from intertidal area such as beach, tidal flat, and rocky shore in December 2007, July 2008, December 2009, and July 2013. Photos were taken from Taean coasts.

activities were significantly induced in organic extracts of sediments collected from inner regions (semi-enclosed low energy condition), indicating the presence of large amount of AhR-active compounds. Elevated concentrations of crude-derived hydrocarbons were primarily found in muddy bottoms, particularly in subsurface layers (>20 cm depth). More weathered samples containing greater fractions of alky-PAHs exhibited increased AhR activity, due to the occurrence of recalcitrant AhR agonists present in residual oils (Hong et al., 2012).

Similar to dioxin-like activities found in the H4IIE-luc assay, significant endocrine disruption potentials were observed in the H295R cell assay after exposure to most of the organic extracts of sediments of Taean coasts after two years of the HSOS (Ji et al., 2011). Among the 22 sediment extracts, nine samples significantly altered transcription of at least one gene relative to that of the solvent control. The fact that the exposure to both crude and artificially weathered oil extracts resulted in greater 17-β-estradiol (E2) production by the H295R cells suggests that the observed potential endocrine-disrupting effects in the sediment of Taean area might be linked to the oil spill (Ji et al., 2011).

At molecular level response, the genetic toxicity in coastal sediments collected from initial stage (December, 2007) and 18 months after the oil spill (June, 2009) was determined by the comet assay (Lee et al., 2011). The high DNA damage was found in sediments of initial stage, but the response was significantly reduced over 18 month periods. The result of the comet assay indicated that the adverse molecular level effects in oil contaminated sediments seemed to be rapidly weakened from the oil pollution.

While, as for *in vivo* test looking for biological effects at individual level organism, the oil contaminated intertidal sediments collected from the shoreline of Taean area were shown apparent toxic effects on amphipod survival in laboratory condition after a year of the HSOS (Lee et al., 2013a). Sediment toxicity gradually decreased in sand beach and lesser extent in mudflat during this period, which was generally agreed with the sedimentary residual concentrations of PAHs (Lee et al., 2013a). Also, relatively long-term adverse effect by the oil spill was evident, for example, residual oil in sub-surface of mud and muddy sand bottoms from the enclosed bay showed amphipod toxicity even after five years of the HSOS (MLTM, 2013).

Overall, potential toxic effects of residual oils in sediments have been fairly recovered in the most of coastal areas of Taean. However, some heavily polluted sites and low tidal energy regions still contained lingering oils of which specific toxic actions and agonists in oil are largely unknown. In particular, it should be noted that the PAHs and related breakdown compounds during the weathering process could not fully explain the total induced toxicity in residual

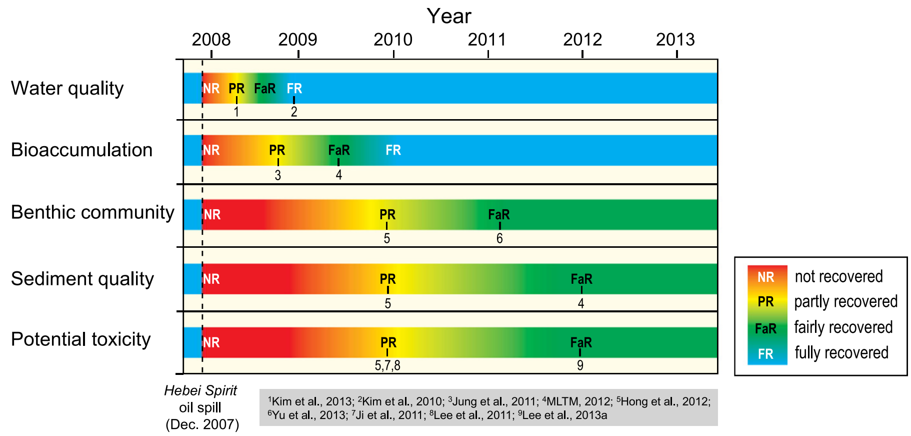

Fig. 5. Environmental and ecotoxicological recoveries after the *Hebei Spirit* oil spill regarding five viewpoints including water quality, sediment quality, bioaccumulation, potential toxicity, and benthic community based on the published data and personal communication with experts.

oils. Thus, continuing research efforts towards identification of source and effect and their relationship would be necessary to fully address the toxic mechanisms of oils, by multiple assessments of instrumental determination and bioanalytical characterization.

4.2. Damage and recovery of the subtidal organisms

Right after the HSOS, numerous and varying coastal and marine organisms inhabiting the Taean coastal areas, particularly for subtidal and intertidal ones, were severely affected by the crude oils. Phytoplankton and zooplankton in water column and benthic microalgae in bottom sediment would not be exception for this biological damage. One recent study investigated the phytoplankton community by measurement of chlorophyll-*a* concentrations between before and after the HSOS *in situ* by use of satellite remote sensing technique (Lee et al., 2009). After the HSOS, chlorophyll-*a* concentration in water column decreased about 45–50% compared to the natural condition, say before the oil spill. The decrease of phytoplankton community mass continued for ~2 weeks, and then slightly increased (Lee et al., 2009). These results indicated that phytoplankton community was largely affected by the spilled oil and then quickly recovered, which might be associated with rapid turn-over of the phytoplankton community and decreased number of zooplankton (MLTM, 2008).

In case of fish, biological responses including PAHs metabolisms and biomarker induction in pelagic and benthic fishes to spilled oil exposure have been monitored for one year following the HSOS (Jung et al., 2011, 2012). Concentrations of PAHs in fish muscle showed the greatest level in five days after the spill, and then the concentrations decreased rapidly to the background levels in eleven months after the spill (Jung et al., 2011). Elevated biliary PAHs metabolites concentrations were found in fish collected from oil spill affected area immediately after the HSOS, which shows rapid detoxification process. The process seemed to be declined steadily, but the concentrations were observed still above those found in reference site for a year after the HSOS. Biomarker responses (e.g., CYP1A) in both pelagic and demersal fish collected from near mouth and inside of enclosed bay were also observed similarly to the biliary PAHs metabolites, implying their continuing exposure to residual PAHs. In terms of spatial distribution, fish biomarker responses were higher in the vicinity of the heavily oiled sites than those in reference and/or off-shore sites (Jung et al., 2012). Laboratory comparison study of zebra fish embryo toxicity for Iranian Heavy Crude oil from the HSOS and Alaskan North Slope crude from the EVOS demonstrated similar cardiovascular toxic effects (Jung et al., 2013).

In general, subtidal organisms in oil spill affected area had shown the adverse effects such as decreasing number of individuals, induction of biomarkers, and bioaccumulation of oils at initial stage after the HSOS. Subtidal environment and organisms seemed to be partly affected by not only dissolved fraction of oils but also mechanically and chemically dispersed oils. Although somewhat slow the biological responses of subtidal organisms compared to planktons in terms of recovery, their responses indicated a gradual recovery in response to the rapid decrease of oil concentrations in seawater in Taean area.

4.3. Damage and recovery of the intertidal organisms

While macrobenthic populations in the heavily oiled intertidal zone were almost eradicated immediately after the HSOS (Hong et al., 2012), organisms have been recovered slightly one year after the spill (Yu et al., 2013) (Fig. 4). The mean density and biomass of macrobenthic fauna in oil spill affected area significantly increased after one year of the spill, however, species diversity index did not significantly change compared to those of initial stage (Yu et al., 2013). Two years after the oil spill, crabs (*Helice* spp., *Ilyoplax* spp., *M. japonicus*, and *M. dilatatus*), gastropods (*Umbonium thomasi*, *Batillaria* spp., and *Lunatia fortunei*), sea stars (*Asterina pectinifera*), and polychaetes (*Periserrula leucophryna*) were frequently found in the intertidal zones (Hong et al., 2012) by recolonization. In particular, certain species *Felaniella sowerbyi* and *U. thomasi* were present with high density in sandy beach after two years of spill, indicating full recovery of their populations (Hong et al., 2012; Yu et al., 2013).

Overall, biomass and species density data suggested that two years after the HSOS the macrobenthic communities started to show a signal of recovery in both soft- and hard-bottom intertidal zones. However, physiological functions of certain intertidal organisms could not be fully recovered, particularly in severely affected area by the oil spill (Donaghy et al., 2010). For example, the hemocyte parameters including granulocyte population, phagocytic capacity, and reactive oxygen species production in oysters exposed to crude oil during 13 months were depressed compared to the unexposed control oysters (Donaghy et al., 2010).

Intertidal zone showed slightly different trend compared to subtidal one, where the long-term potential adverse effects on marine organisms were evident due to a relatively long residence time of spilled oil in sediments. In particular, physical energy such as tidal current could not reach to the bottom layer of muddy sediment where the oil degradation of microbial activity is dominated (Jeon et al., 2009). Transformation of oil by microbial activity

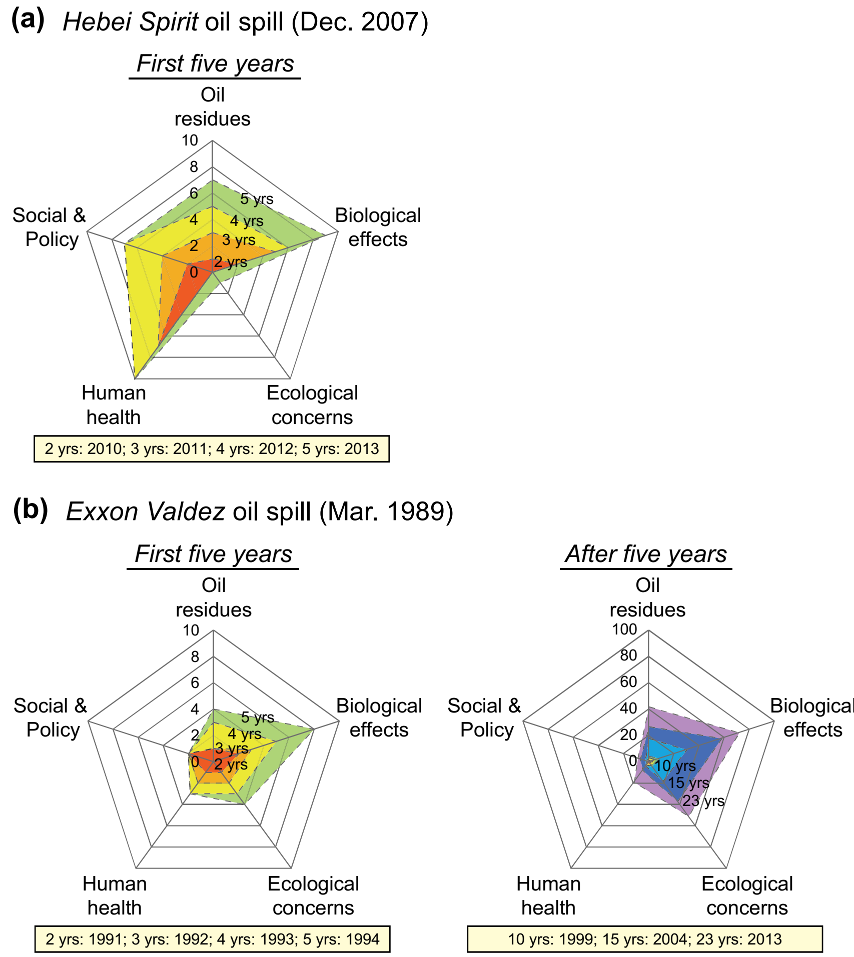

Fig. 6. Radar plots for comparison of study efforts after the (a) *Hebei Spirit* oil spill (in 2007), (b) and (c) *Exxon Valdez* oil spill (in 1989), based on the number of publications (SCOPUS, www.scopus.com). Papers were classified into five groups of study interests including oil residues, biological effects, ecological concerns, human health, and social and policy.

in sediment selectively affects to certain chemicals (Leahy and Colwell, 1990; Atlas, 1995; Venosa et al., 1996), thus the composition and concentration of residual oils in sediments are dependent on the microbial community and activity. However, specific mechanisms of residual oil in sediments by microbial activity and changes of toxic effects are not yet fully understood. Overall, the long-term and integrated monitoring would be required to assess the specific biological effects of oil pollution on the intertidal macrobenthic community this time.

4.4. Acute human health effects: cleanup participants and residents

Acute health effects on cleanup volunteers (more than 1 million) affected by exposure to crude oil at initial stage would be of primary concerns. Ha et al. (2012) reported that volunteers participated for longer period of cleanup work suffered from physical symptoms including visual disturbance, nasal and bronchus irritation, headaches, heart palpitations, fatigue and fever, memory and cognitive disturbance, and abdominal pain. Urinary concentrations of VOC and PAHs metabolites in 105 volunteers were significantly greater in samples after cleanup activity than those before participation (Ha et al., 2012). Also, Sim et al. (2010) reported that residents and volunteers engaged in the HSOS cleanup operation experienced acute health problems including back pain, skin lesions, headache, and eye, neurovestibular, and respiratory symptoms. Exposure to crude oil during cleanup work was also associated with a significant low value in peak expiratory flow (Kang et al., 2009). These health effects were mainly due to a lack of personal protective equipment and safety education to volunteers during cleanup activity at initial stage of the oil spill (Sim et al., 2010). Duration of health problems in cleanup participants such as eye symptoms, headaches, skin symptoms, and neurovestibular symptoms were found to continue during the longer periods, 9.7 month, 8.4 month, 8.3 month, and 6.9 month (mean duration), respectively (Na et al., 2012). Considering the significant health problems in volunteers reported in the previous studies, the monitoring of the long-term health effects should be warranted.

Kim et al. (2009) evaluated the resident health effects to exposure to BTEX (benzene, toluene, ethylbenzene, and xylenes) in the Taean area after the oil spill. They suggested that exposure to crude oil-derived BTEX is correlated with an increased risk of health effects among pregnant women. Also, the residents of Taean suffered from the psychological disorder, when compared with unexposed groups in the general population. Another set of data suggested that the residents of Taean showed 6.5 times greater stress and 9.4–9.7 times more depressed condition than control groups (Song et al., 2009). The residents of highly contaminated area in Taean were more engaged in cleanup activities and have a greater chance of oil exposure at initial stage of the oil spill. Meantime, the indices of anxiety and depression were found to be higher among the residents of the heavily and moderately oiled areas. Adverse effects on human health effects by the HSOS also includes the increased risks of headache, nausea, dizziness, fatigue, tingling of limb, hot flushing, sore throat, cough, runny nose, shortness of breath, itchy skin, rash, and sore eyes were significant (Lee et al., 2010). Altogether, these results suggested that various acute health problems of cleanup participants and residents were associated with crude oil exposure in Taean area after the HSOS. Further long-term monitoring effort should also be delivered to address chronic health effects in residents of Taean area and/or cleanup participants.

4.5. Current status in viewpoint of "recovery"

Rapid temporal changes in oil contamination cross the coasts of Taean during the first quarter of year post the spill indicates that ephemeral data collection was crucial to understand oil spill impacts on ecosystem and human health at initial stage. Fortunately, intensive environmental impact assessment for the HSOS case during the initial stage has brought general identification of the range, extent, and duration of the impact so far. Rapid clean-up response at initial stage of the spill as well as geographical features in the spill sites resulted in relatively quick recovery of oil contamination and injured ecosystem in the coastal environments compared to other oil spill cases. In general, concentrations of PAHs reported by the environmental survey performed by KIOST and other individual works during the last five years collectively indicated that their concentrations were well down to the background levels in water and biota (Fig. 3). However, lingering oil could be found in coastal waters from sub-surface sediments of mudflat and boulder-armored beach area in the enclosed bay, particularly Sinduri and Sogeunri mudflats and Euihang harbor. This result is well agreed with the sediment toxicity test data where the samples collected from such heavily impacted areas showed relatively great biological responses.

Meanwhile, populations of sensitive species and community structures have demonstrated a good signal of recovery about one and a half year post the spill. However, the number of species, species density, and biomass of macrobenthic animals in the heavily oiled intertidal zone were still smaller than those of pre-spill periods or reference site. In addition, several reports suggested that environmental levels of residual oils in water and biota were almost fully recovered after 1–2 years of the oil spill (Fig. 5). Overall, the Taean area seemed to be fully recovered in terms of water quality and bioaccumulation, but not fully recovered as for benthic community, sediment quality, and potential toxicity related with sedimentary residuals of oil spill components.

5. *Hebei Spirit* oil spill vs. *Exxon Valdez* oil spill

To simply compare the size in environmental damages, we selectively compared several components including backgrounds, effects, and responses between worst Korean oil spill of the HSOS and world worst oil spill accident of the EVOS (Table 2). Magnitude of oil spill of the EVOS was about 3 times greater than that of the HSOS, but cleanup coast was ~6 fold greater for the EVOS. However, the manpower served for the cleanup activity was much great for the HSOS compared to that for the EVOS, indicating labor-intensive cleanup effort might compensate the technical cost for the HSOS. Such differences would also come from the geographical setting of the spilled site, where manual cleanup was more appropriate to effectively remove the residual oils along the ria-type coasts of Taean, west part of Korea. In anyhow, about half of the spilled oils for both the HSOS and EVOS have been physically removed from the sea by the cleanup activities, in turn the last of spilled oils would have brought long-term environmental damages and impacts.

Table 2
Comparison between the *Exxon Valdez* oil spill and the *Hebei Spirit* oil spill.

Contents	*Exxon Valdez* oil spill	*Hebei Spirit* oil spill
Backgrounds		
Location	Prince William Sound, Alaska, USA	Taean, Yellow Sea, South Korea
Date	24 March, 1989	7 December, 2007
Tons	38,000 tons	10,900 tons
Effects		
Shoreline impacted	2,100 km	375 km
Total area	28,000 km^2	1,300 km^2
Responses		
Cleanup cost	US $2,000 million	US $330 million
Equipment	85 aircraft and 1,400 vessels	13 helicopters, 17 airplanes, and 327 vessels
Personnel	>11,000	1,037,000 (during 33 days)
Results	>25,000 tons of oil was collected (end of the 1989)	4,175 kL of oil was collected (Jan, 2008)
Research fund	~US $6 million a year (20 yr, total ~ $120 million)	~US $2.3 million a year (10 yr, total ~ $23 million)

After the oil spill accidents, large amount of research money have been allocated with varying environmental surveys including national level monitoring and individual scientific researches until yet. Research funds relating to the HSOS reaches about 2.3 million dollars per year which is a bit lower compared to that for the EVOS but still high for a single subject issue, in Korea. However, it should be mentioned that the research efforts on the HSOS, based on the number of publications introduced in the international journals, over doubled compared to the EVOS, during the same period of 5 years post the oil spills (Fig. 6). It is noteworthy that, however, the research activities regarding the EVOS are still occasionally found until now, where various subjects are yet under consideration.

By analyzing the composition of subjects related to those oil spills, we found relatively great study efforts on human health and social and policy were given for the HSOS, while majority of research for the EVOS focused on the biological effects and ecological concerns. The apparent differences in research directions for two cases would come from the characteristics of damages and risk together with people's recognition and concerns in each country. Also, the differences in geophysical features of oil spilled sites and cleanup activities for both cases would influence the study interest and research directions. Currently, it has passed already six years since the HSOS, thus more studies on ecological concerns in terms of "recovery" would be worthy of subject as other concerns have been relatively well addressed.

6. Future research directions

Environmental fate of crude oils and their ecotoxicological consequences have been fairly well addressed by the intensive scientific efforts towards targeted monitoring followed by the environmental assessment during the last five years after the HSOS. However, there could be many other subjects that need to be further addressed, particularly sediment associated process and mechanism. For example, alkyl-PAHs consist of major proportion of crude oils in sediment and biota, but their potential toxic effects were not well documented yet. In addition, crude oil has thousands of hydrocarbons, while only a few hundreds of known compounds can be resolved by instrumental quantification, and further their combined effects between known and/or unknown would be missing. Thus, it should be recognized that there would be still a big uncertainty to state toxic effects on un-resolved and unidentified hydrocarbons in crude oils.

However, for timely decision making in the oil spill response and restoration, it is required to establish environmental criteria for oil derived hydrocarbons to protect aquatic life and human health in time-dependent manner. At present, it is not clearly known that a long-term weathering process of lingering oils which were trapped in sub-surface sediment of mudflat and boulder-armored beach, accordingly their bioavailability and toxic effects on mudflat organisms are largely unknown. Weathering behavior and toxic effects of the spilled oil with dispersants were recently studied (Baek et al., 2013; Joo et al., 2013; Lee et al., 2013b), but the role of different types of dispersants used in the response for enhancing dissolution of toxic components in crude oils with different weathering stage would be worthy of study. Although with such limitations and weakness in scientific knowledge and understanding for the HSOS, the timely action and policy generation with currently available data would warrant proper and/or cost-effective assessment and management for the HSOS.

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