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MARINE BIODIVERSITY IN KOREA: A REVIEW OF MACROZOOBENTHIC ASSEMBLAGES, THEIR DISTRIBUTIONS, AND LONG-TERM COMMUNITY CHANGES FROM HUMAN IMPACTS

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Abstract The present review provides a historical overview of the macrozoobenthos that supports Korean marine biodiversity set against a regional introduction to the oceanography and diverse marine habitats of Korean seas. We constructed a comprehensive meta-dataset of Korean macrozoobenthos to provide an up-to-date ecological inventory. In particular, we address faunal characteristics with respect to species occurrence, composition, and distributions along the Korean coasts. The ecology of the Korean macrozoobenthos is described in order of the West Sea, South Sea, and East Sea following the regional description of oceanography settings, in a consistent manner. Later, the impacts of anthropogenic pressures, such as coastal reclamation and oil spills, on long-term benthic community changes are also highlighted. We accounted for a total of 1915 macrozoobenthos species, belonging to 17 phyla, in the Korean marine environments. The most dominant phylum was Mollusca (670 species), followed by Annelida (469 species), Arthropoda (434 species), and Cnidaria (103 species). The most diverse communities inhabit the South Sea (1103 species), followed by the West Sea (829 species) and the East Sea (621 species). The highest regional numbers in each sea are comparable, in the West Sea (Taean: 510 species), South Sea (Jejudo: 511 species), and East Sea (Ulleungdo: 562 species). Subtidal areas, especially in the West Sea and South Sea, constituted the habitats with the greatest faunal occurrence, including predominantly soft bottom invertebrates. Polychaetes were the most widely distributed taxa, followed by bivalves, across the three seas. In general, the faunal assemblages and distributions seemed to reflect the typical habitat profiles for the environments, including well-developed tidal flats in the West Sea, rocky shoreline in the East Sea, and mixed features in the South Sea. Interestingly, the remote island of Jejudo was found to have a distinct faunal composition among the South Sea coastal areas, presumably as a consequence of its geographical and ecological isolation. Case analyses of the ecological impacts of coastal reclamations revealed long-term benthic community alterations in Lake Sihwa and the Saemangeum tidal flats. An analysis of faunal distributions over decadal periods showed substantial community alterations, particularly during periods of new dike construction. Signs of benthic community deterioration were evident in both areas, including the increased occurrence of opportunistic species and enriched organic indicators, which persisted even after the completion of dike construction. Although water quality seems to have recovered recently in Lake Sihwa owing to seawater circulation, the Saemangeum flats have yet to recover. Finally, we demonstrate the long-term ecological impacts of the 2007 Hebei Spirit Oil Spill (HSOS), the largest spill in South Korean national history, by analyzing 10 years of monitoring data. The HSOS disaster collapsed the entire marine ecosystem along the Taean coast and in nearby habitats, particularly mud bottoms. Although recovery pace varied across localities, the benthic community fully recovered after ~6 years, except

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for the limited hotspots, reaching ambient species baseline levels in terms of population, composition, abundance, and diversity index. The relatively fast recovery of marine ecosystem in Taean coast, say compared to the Exxon Valdez case, might suggest that the macrotidal West Sea coastal ecosystem is quite resilient. Overall, the present review supports the conclusion that Korea retains high marine biodiversity despite severe human impacts on coastal ecosystem sustainability. Although South Korean government agencies have long practiced ecosystem-based management efforts, their success has been limited to some extent by a fragmented approach. In the future, a holistic management strategy and framework for protecting organisms and habitats, as one ecosystem, would support the conservation of high marine biodiversity around the Korean Peninsula and elsewhere in the adjacent seas of East Asia.

Keywords: Biodiversity, Biogeography, Ecological checklist, Marine benthic invertebrates, Human impacts, Management and conservation

Introduction

Backgrounds and overview

South Korea (from here forward, Korea for simplicity) is located in the far eastern part of the Eurasian continental mass, between China and Japan; it is protected from the open Pacific Ocean by Japan (NGII 2016). The three-sided coasts of the Korean Peninsula, with west-, south-, and east-facing coastlines abutting the West Sea, South Sea, and East Sea, respectively, have some unique topographical and geographical characteristics (representative seascapes of the Korean coasts described in Table 1). Because the Korean economy and culture rely heavily on marine products, including artisanal and commercial fisheries and aquafarming sectors, the socioeconomic value of marine resources is highly significant (Koh & Khim 2014). The seas around Korea are affected by distinct regional natural conditions, including seasonal changes associated with the monsoon climate and dynamic oceanographic settings shaped by local macrotidal environments and the active mixing by warm and cold currents.

The dynamic marine environments around the Korean Peninsula are associated with high marine biodiversity. The 2015–2020 national marine ecosystem monitoring survey conducted in the three seas surrounding Korea catalogued the presence of 7619 marine species (MEIS 2021). These findings are consistent with the prior Census of Marine Life (Costello et al. 2010) in which the exclusive economic zone of South Korea was ranked as the most species-rich region in the world with some 32.3 species per unit area. Our recent reviews further highlighted high marine biodiversity for marine invertebrates in the Korean tidal flats along the western coast of Korea (Park et al. 2014a) and around the island of Dokdo (Song et al. 2017).

A notable unique feature of the Korean coastal waters is the convergence of diverse microhabitats from the three surrounding seas into a dynamic ecosystem. For example, along the upper intertidal zone of the West Sea, well-developed salt marsh beds with various halophytes, such as *Phragmites* and *Suaeda* plant species, provide nursery grounds for many marine organisms. Frequent blooms of microphytobenthos inhabiting the soft bottoms of the West Sea also support the upper trophic ecosystem. Our recent studies indicated that benthic primary production in the West Sea was quite high from a global perspective, supporting the high marine diversity in Korea-adjacent seas (Kwon et al. 2020). The rocky shoreline environment that prevails along the East Sea coast is home to diverse hardbottom plants and animals. Our recent review reporting the high occurrence of macrozoobenthos in the remote island of Dokdo (578 species; Song et al. 2017) revealed a major global biodiversity hotspot, with diversity comparable to that reported for the entire coastal span of the West Sea (624 species) (Park et al. 2014a), while the biodiversity on the South Sea, including the coastline of the island of Jejudo, has not been yet documented systematically.

Marine biodiversity is an index of ocean health that represents both species richness and habitat diversity. The maritime health status of South Korea, according to the 2019 Ocean Health Index

Table 1 General oceanographic conditions and socioeconomic information of Korean[a] coastal areas

Environmental characteristic	West Sea	South Sea	East Sea
Coastal landform	Submerged coast (Rias type)	Submerged coast (Rias type)	Emerged coast
Bottom topography	Sea bed gently slopes seaward (west to east) with tidal flats	Sea bed slopes gently seaward (northwest to southeast) with many islands	Sea bed deepens sharply from coast to seaward (east to west)
Coastal Location	126–127°E, 34–37°N	126–129°E, 34–35°N	128–129°E, 35–38°N
Coastline length, km	2450	2484	687
Tidal range, m	Megatidal (4.0–10.0)	Mesotidal (1.3–4.3)	Microtidal (0.2–0.5)
Ocean currents	Kuroshio Warm Current	Kuroshio Warm Current	Kuroshio Warm Current, Liman Cold Current
Seawater parameters			
Depth, m[b]	51 (124)	71 (198)	1497 (2985)
Transparency, m	1.6 (0.1–14)	5.4 (0.0–20)	9.4 (0.5–26)
Temperature, °C	14.3 (1.06–33.1)	15.8 (1.75–32.4)	10.6 (1.23–33.1)
Salinity, ‰	31.9 (27.7–91.0)	33.4 (12.4–36.1)	33.8 (28.9–36.7)
pH	8.06 (6.73–8.82)	8.10 (6.07–9.98)	8.04 (0.18–8.93)
DO, mg L^{-1}	8.62 (3.40–16.6)	7.85 (1.73–15.0)	8.60 (4.28–13.8)
COD, mg L^{-1}	1.25 (0.02–8.98)	1.01 (<0.01–8.29)	0.88 (0.01–6.36)
NH_3-N, μg L^{-1}	21.4 (<0.01–1030)	18.6 (<0.01–1060)	19.3 (<0.01–337)
NO_2-N, μg L^{-1}	7.18 (<0.01–117)	6.66 (<0.01–442)	3.98 (<0.01–224)
NO_3-N, μg L^{-1}	113 (<0.01–626)	64.5 (<0.01–1720)	66.4 (<0.01–579)
DIN, μg L^{-1}	142 (0.80–1080)	89.5 (<0.01–1800)	89.5 (0.80–597)
TN, μg L^{-1}	381 (67.4–2500)	286 (15.0–2520)	215 (16.0–1590)
DIP, μg L^{-1}	16.9 (<0.01–163)	14.7 (<0.01–524)	12.7 (<0.01–207)
TP, μg L^{-1}	47.1 (5.50–686)	31.2 (<0.01–2510)	26.8 (1.70–1010)
SiO_2-Si, μg L^{-1}	300 (<0.01–1730)	335 (3.80–2710)	266 (3.80–1680)
SS, mg L^{-1}	35.0 (0.10–512)	11.3 (0.10–200)	4.63 (<0.01–31.6)
Chl-*a*, μg L^{-1}	2.83 (<0.01–67.2)	1.81 (<0.01–61.4)	1.16 (<0.01–25.2)
Provinces (population size)	Gyeonggido (13.7 M), Chungnamdo (2.1 M), Jeollabukdo (1.9 M), Jeollanamdo[c] (1.9 M)	Jeollanamdo[c] (1.9 M), Gyeongsangnamdo (3.4 M)	Gyeongsangbukdo (2.7 M), Gangwondo (1.6 M)

[a] Data were collected along South Korean coasts, except for those from North Korea, from 1997 to 2019.

[b] Water depths are reported as mean (maximum); other parameters are given as mean (range).

[c] Jeollanamdo region is located across west and south coasts.

Abbreviations: DO, dissolved oxygen; COD, chemical oxygen demand; NH_3-N, nitrogen ammonia; NO_2-N, nitrite; NO_3-N, nitrate; DIN, dissolved inorganic nitrogen; TN, total nitrogen; DIP, dissolved inorganic phosphate; TP, total phosphate; SiO_2-Si, silica dioxide; SS, suspended solid; Chl-*a*, chlorophyll-*a*; M, million.

(OHI) assessment, was ranked 48th (76 points) in the world out of 221 countries and territories (global mean = 71 points) (OHI 2019), while the neighbouring three countries showed relatively low ranking in comparison: Japan 125th (66 points); China 158th (63 points); and North Korea 193rd (58 points) (Figure 1). It is noteworthy that Korea also received a higher biodiversity index ranking (5th, 96 points) than other East Asian countries.

Sustainable management of coastal habitats should be acknowledged as an important contributing component for preserving high marine diversity. However, it is obvious that large areas of Korean coastal habitats have been undergoing long-term anthropogenic destruction. Representative

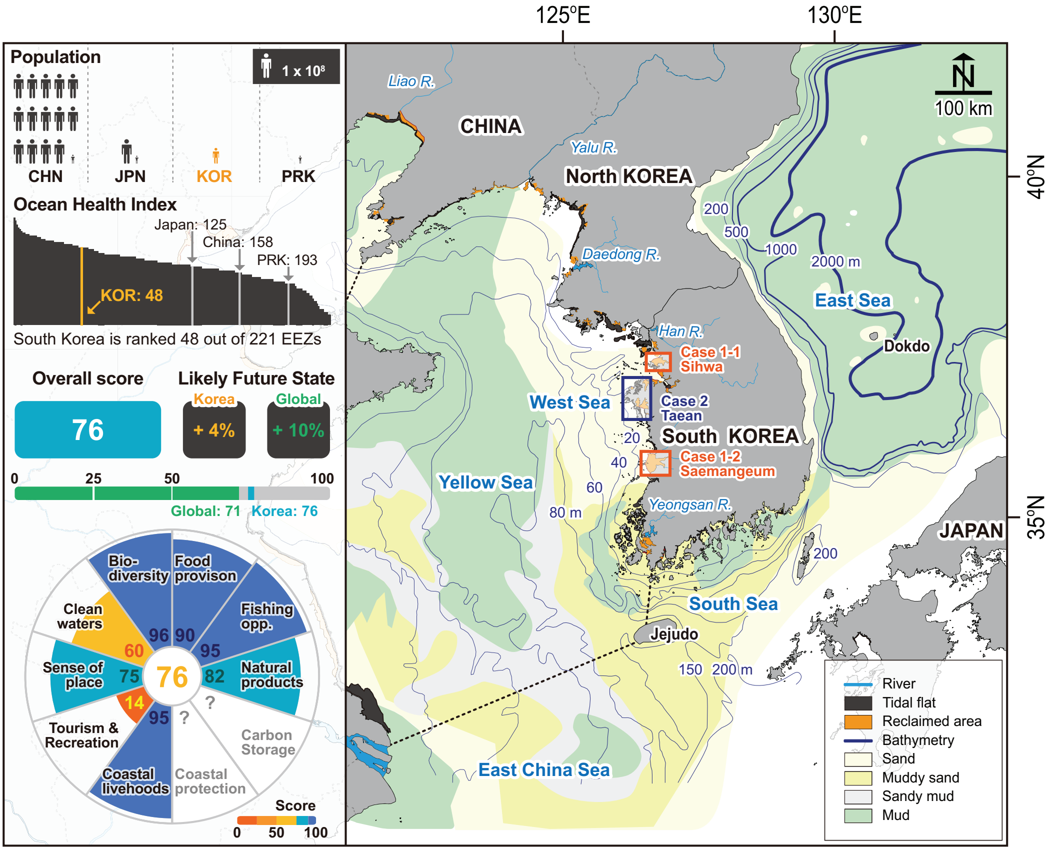


Figure 1 Map showing geographical setting of the Korean peninsula, populations of (South) Korea and its surrounding countries (China, Japan, and North Korea), and Ocean Health Index scores for Korea.

examples of the most destructive activities include large-scale coastal reclamations conducted in Korea over the past 40 years, which have resulted in a 40% loss of natural tidal flats along the West Sea coast (Yim et al. 2018). The loss of microhabitats due to dike construction, which is followed by changes in oceanographic conditions, has had adverse impacts on marine biodiversity. Another issue for biodiversity loss is coastal pollution (Khim et al. 2018), which is caused by eutrophication, land-derived pollutants, oil spills, etc. The event most destructive to the coastal region was the 2007 HSOS, which occurred in the West Sea. Continuing efforts to improve coastal management would benefit from a systematic assessment of the current status of marine biodiversity along the entire coasts of the Korean Peninsula.

In the present review, we first provide a regional overview of the Korean seas to improve understanding of these coastal environments. The basic characteristics of these environments, including seascapes, topography, geography, sedimentology, tides and currents, and water quality are summarized briefly. Then, we focus on the germane marine biodiversity literature and provide an overview of the relevant issues and history. The meta-data analyzed here were constructed from taxonomic and ecological studies of macrozoobenthos performed in Korea from a holistic perspective. The main goal of this review was to provide an up-to-date ecological inventory of Korean macrozoobenthos. In particular, we delineated the assemblages and distributions of macrozoobenthos in the three seas of Korea and describe their regional distributions. As part of this review, we sought to address human impacts on Korea's marine biodiversity, with in-depth analyses of three representative cases.

Two of these cases, namely Lake Sihwa and Saemangeum, were chosen to access the impacts of coastal reclamations. The third, Taean, was chosen to obtain data related to the environment's long-term recovery from the HSOS accident. Finally, we discuss limitations, implications, and future management directions for sustainability of the Korean marine ecosystem and biodiversity.

Oceanographic settings around the Korean Peninsula

The west coast of Korea encompasses well-developed tidal flats (~2500 km^2 in South Korea) and plays an important role in the maintenance of a large marine ecosystem in East Asia. It is characterized by a ria-type coastline with diverse coastal morphology and sea floors of the West Sea slope gently toward the greater Yellow Sea (of which it is a part). The total length of the western coastline in Korea is estimated to be 2450 km (Table 1). The West Sea is a shallow subtidal area within the Korean exclusive economic zone, spanning the area inclusive of longitudes 126–127°E and latitudes 34–37°N (Figure 1). The West Sea has been designated as part of the Yellow Sea Large Marine Ecosystem (YSLME) and is a large semi-closed bay with shallow water depth (~50 m). It has a very large tidal range and extensive tidal flats. The tidal range of the west coast decreases from a maximum of 10 m at its northern end in Incheon City to a minimum of 4 m at its southern end in Mokpo City, located at the south-end of the west coast.

The south coast of Korea lies on a northern boundary line of the East China Sea and is connected geographically to the southeastern Yellow Sea. The south coastal area has a generally flat topography in the west, but deepens southeast of the island of Jejudo. The south coast, the most complicated coastline in Korea geomorphologically, is a submerged coast with an archipelago consisting of over 2200 islands; it has with a total length of 2484 km (Table 1). The South Sea encompasses an area inclusive of longitudes 126–129°E and latitudes 34–35°N. It forms part of the Asian continental shelf and the Korea Strait located between the Korean Peninsula and Japan (Figure 1). The South Sea has a mean water depth of 71 m, and its maximum depth is 198 m near Jejudo. Its mesotidal environment has a depth range of 1.3–4.3 m, and its tidal range decreases eastwards.

Unlike the west and south coasts, the east coast of Korea is characterized by very deep water, a steep sea-floor slope and a very simple coastline. The East Sea is a small marginal sea of the Northwestern Pacific Ocean. It is enclosed by multiple countries, including principally Russia, Korea, and Japan. The East Sea is a shallow area along the east coast of the Korean Peninsula covering an area encompassing longitudes 128–129°E and latitudes 35–38°N. It has a mean depth of 1497 m and a maximal water depth of 2985 m near Ulleungdo (Figure 1). There are 687 km of well-developed sandy beaches along the coastline. However, the local sea bed topographies and microtidal amplitudes below 50 cm prevent the development of tidal flats on the continental shelf (Table 1).

The main currents affecting the Korean Peninsula are the Yellow Sea Warm Current, the East Korean Warm Current, and the Tsushima Warm Current, which are all branches of the Kuroshio Current (Figure 2). The Kuroshio Current, a western boundary current, is the second largest warm current after the Gulf Stream (NGII 2016). It starts from the north equatorial current by turning at the Coriolis reflection and flowing northward along the western boundary of North Pacific Ocean, passing eastern Taiwan, and then, finally, flowing to northern Japan. The Kuroshio Current has a characteristic water mass of high temperatures (20–30°C) and high salinity (34–35 psu) (NGII 2016).

The Tsushima Warm Current branches northwestward from the Kuroshio Current, forming the Yellow Sea Warm Current which passes into the Yellow Sea through the Liaodong Peninsula of China across the Heuksan-do and Baengnyeong-do of Korea, and reaches Bohai Bay (China) when it strengthens in the summer. The Yellow Sea Warm Current weakens as it enters the southern coastal waters of Korea during the fall, with marginal eastward flows along the Jeju Strait. The Tsushima Warm Current branches off the Kuroshio Current into the East China Sea and flows into the East Sea through the Korea Strait and the Tsushima Strait. The East Korean Warm Current branches northward off the Tsushima Warm Current at the east end of the Korea Strait and flows

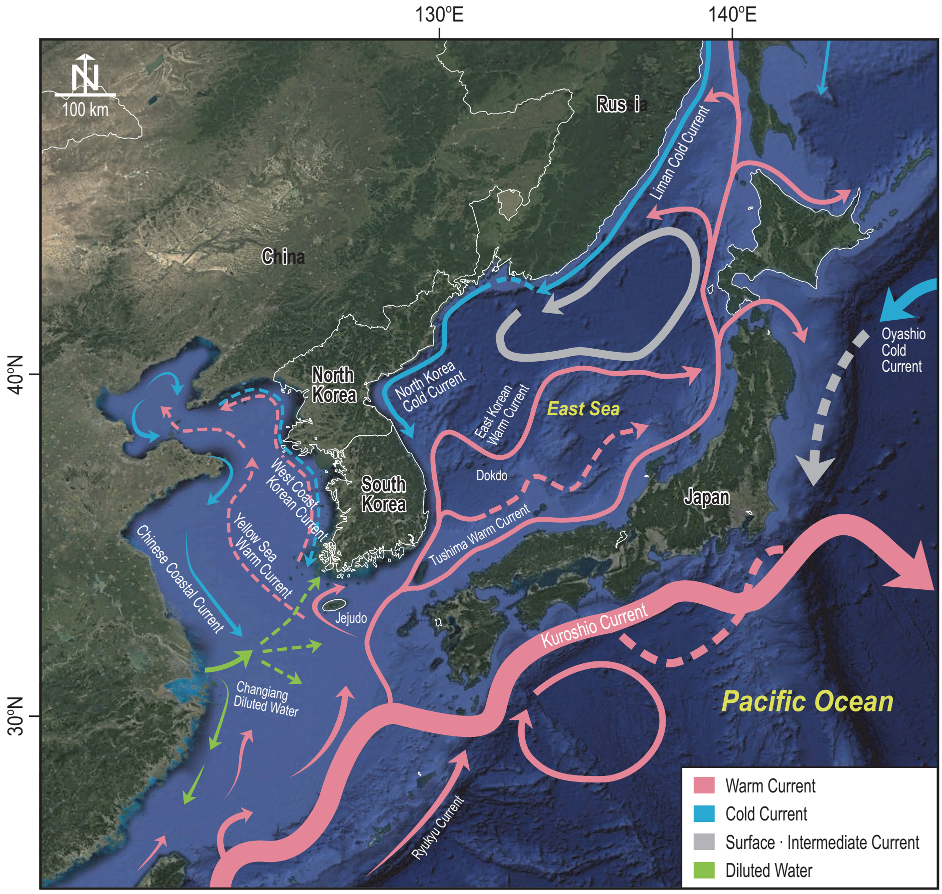


Figure 2 Map showing ocean currents and bathymetric topography around the Korean Peninsula (modified from Hwang et al. 2014 and NGII 2016).

north along the southeast coast of the Korean Peninsula. The East Korean Warm Current makes contacts with the North Korean Cold Current at latitudes in the range of 36–38°N and consequently changes its flow direction such that it flows toward the central East Sea. The boundary between the two currents changes continuously and forms a large eddy in the East Sea. The East Korean Warm Current shifts direction to flow northeast, finally joining the Tsushima Warm Current.

The Liman Cold Current begins in the vicinity of the Russian Tatar Strait and flows southward along the Eurasian Continent to the East Sea. The North Korean Cold Current is an extension of the Liman Cold Current that flows southwest along the east coast of North Korea. During the summer, the Liman Cold Current reaches the Wonsan area of North Korea. The North Korean Cold Current is strengthened during the winter, when it thus has more southward effects as far south of Korea. In the summer, the diluted waters of the Changjiang (Yangtze) River are dispersed eastward or southeastward, reducing seawater salinity along the Jejudo coast and southwestern Korean Peninsula coast; these waters flow south along the east coast of China in the winter (Hwang et al. 2014).

Because of the geomorphology of the Korean Peninsula, most of the major rivers in Korea flow into the West Sea or South Sea. The shoreline of the west coast is very complex with many rivers that flow through highly urbanized coastal cities and thus are exposed to substantial anthropogenic pressures. These rivers deliver large amounts of terrestrial organic matter to the West Sea and South Sea. Our analysis of long-term monitoring data of seawater parameters (20 years, 1997–2019) showed a clear gradient of marine environmental conditions from the west coast to the east coast based on Table 1. Relatively low water column transparency, salinity, and chemical oxygen demand (COD) were observed for the west coast, reflecting a strong influence of (in)organic matter through riverine and estuarine inputs to the West Sea. Consequently, relatively high primary production levels have been evidenced by high concentrations of chlorophyll *a* and a high nutrient potential from re-suspended sediments, which contribute to the maintenance of primary producer abundance available to upper trophic levels in the west coast ecosystem.

Historical overview on the macrozoobenthic studies in East Asia

To provide international research on the ocean environment of East Asia, a mini-review on three major ocean topics, namely seafood, pollution, and biodiversity, was conducted targeting the countries of China, Taiwan, and Japan, in addition to Korea (Figure 3). Of these countries, Japan had the most intensive marine research activities from the 1950s to the 2000s, after which research from China increased drastically (post-2000s). Similarly, there has been a marked increase in relevant publications from Korea since the 2000s, which reflects significant recent advances in ocean science.

Among the three aforementioned targeted topics, seafood science has long been pursued in all four countries. Japan has led in this area of science since the early 1950s. It should be noted that rapid increases in seafood science are evident after the early 2000s across all four countries, particularly for China and Korea in more recent years (Figure 3A). According to global fishery data reported by the FAO (Food and Agricultural Organization of the United Nations), there has been a substantial increase in catch volumes since the mid-1990s following soaring increases in demand for seafood in China (Pauly & Liang 2019).

Following increases in human activities affecting the marine environment, a number of environmental issues arose concurrently, especially in East Asian countries that have undergone dramatic socioeconomic development. Accordingly, research into marine pollution has been on the rise since the 2000s (Figure 3B). In particular, China has seen a noticeable increase in marine pollution research since the 2010s, with a major focus on the tremendous coastal development along the Yellow Sea coastline. Our recent studies on the topic of coastal and marine pollution in the Yellow Sea revealed severe ongoing pollution along the YSLME coast (Tian et al. 2020, Yoon et al. 2020, Shi et al. 2021). Of note, there is a relative lack of marine pollution studies in Taiwan, where there has been a decreasing trend in recent years. Meanwhile, there has been a steady increase of marine pollution studies in Korea from the 1990s to present. Indeed, various environmental issues in the coastal marine ecosystems have become more extensive and intense since the 1990s due to increasing coastal reclamations and land-driven marine pollutions along the Korean coasts (Koh & Khim 2014).

The concept of sustainable marine environment management also began to emerge in the 2010s, concurrent with a surge in publications on the topic of marine biodiversity (Figure 3C). Although the Yellow Sea coast is known as a biodiversity hotspot globally, there have been relatively few studies of this region in Korea, compared to China and Japan. Accordingly, more intensive research efforts on the subjects of marine biodiversity and biogeography in South Korea would be timely and important. The high marine biodiversity of Korea features an especially high species diversity of macrozoobenthos inhabiting diverse coastal habitats. For example, in our previous intensive meta-data analysis focused on the West Sea (Park et al. 2014a), we documented the occurrence of 624 macrozoobenthos. The present review shows that former macrozoobenthos studies were limited by unbalanced study efforts for limited target species, limited surveyed localities, and non-standardized monitoring methodologies.

Further, the Scopus mini-review on macrozoobenthic studies around the Korean Peninsula revealed a large contribution of macrozoobenthos diversity to the marine biodiversity in East Asia (Figures 4A). A substantial portion of the studies reported examined the Chinese and Russian seas nearby the Korean Peninsula. The network analysis bore out this trend, revealing clustering toward

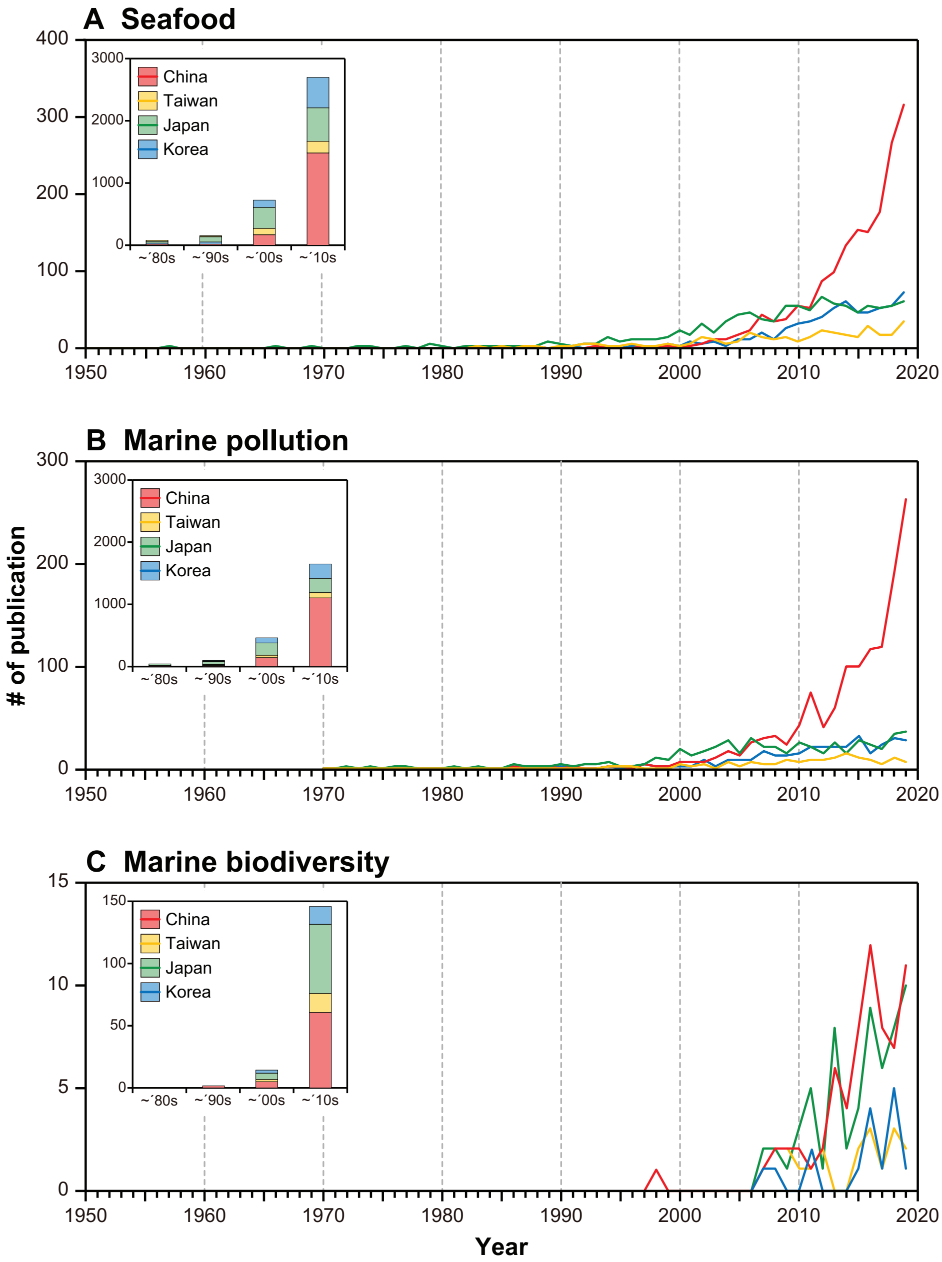


Figure 3 Historical studies on (A) seafood, (B) marine pollution, and (C) marine biodiversity in the East Asian countries of China, Taiwan, Japan, and Korea. The publications include original research articles, reviews, book chapters, books, and letters collected in the Scopus database (title, abstract, keywords) from 1950 to 2019.

two major keywords: the East Sea and the Yellow Sea. More recent ecological studies of macrobenthos have tended to deal with a greater variety of taxa along the Korean coasts (Figure 4B and C). Of note, the South Sea of Korea was not included among the 30 keywords in our analysis, evidencing a lack of study efforts in the region (8 documents of a total of 124). Finally, the results indicated a growing interest in macrozoobenthic research in the Yellow Sea and the East China Sea. Overall,

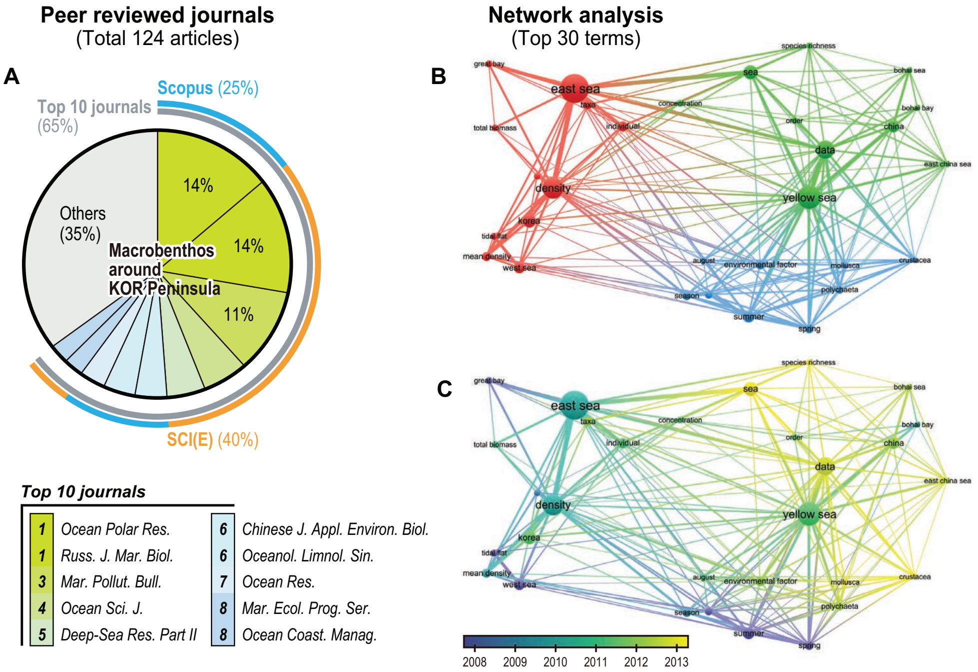


Figure 4 Publications related to the Korean Peninsula macrobenthos from 1970 to 2019. A total of 124 publications in 44 journals, including SCI(E) and Scopus, are included. (A) Top 10 journals accounting for 65% of the collated documents ($n = 80$). To construct and display a terminological map, (B) cluster and (C) chronicle network analyses were carried out based on words in the titles and abstract fields of 124 publications.

holistic study efforts focused on the long-term monitoring of marine biodiversity in the Korean Peninsula are necessary to address the above knowledge gaps.

Methods and materials

Meta-data collection

We provide an up-to-date ecological inventory of macrozoobenthos, practically defined as the invertebrate species of >1 mm mesh size living in or on the sediment and hard substrates, observed along the Korean coasts (Supplementary information of Tables S1 and S2). Faunal species compositions and distribution were analyzed based on meta-data collected from previous studies during the past 50 years. Based on the Scopus and Korean local journal database, we identified a total of 128 peer-reviewed articles relating to macrozoobenthos ecology studies conducted along the Korean coasts. Taxonomic contributions only reporting new species to science or newly recorded species in the Korean waters were excluded because they do not have ecological implications in line with the focus of the current review.

A total of 128 peer-review articles were compiled, including 42 reported in international journals and 86 in Korean domestic journals, related to the community ecology of the Korean macrozoobenthos (Table S3, Figure 5). The first and early benthic ecological studies appeared in the 1970s and the number of studies increased over time. Two pioneering studies dealing with polychaete assemblages were conducted in the early 1970s (Paik 1973, Oh & Kim 1976), representing the emergence of marine ecology of macrozoobenthos in Korea. Many of the early macrozoobenthos studies focused on describing newly recorded taxa or new species in taxonomy; ecological studies joined

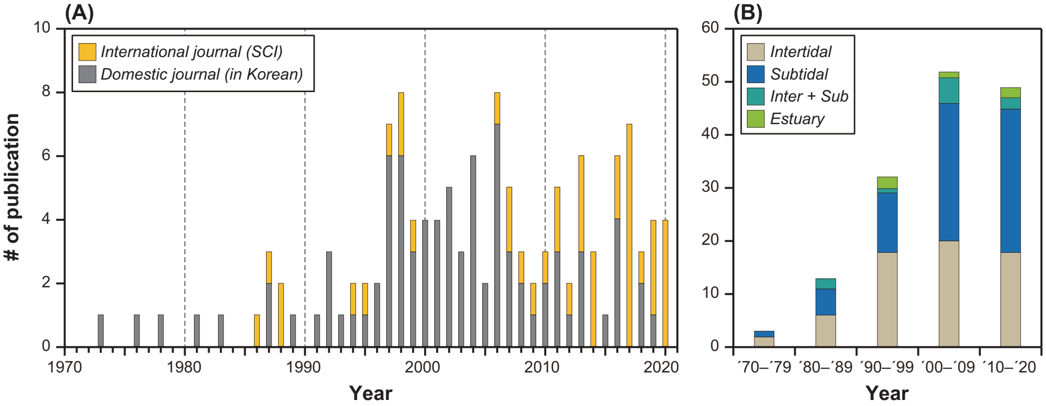


Figure 5 Overview of macrozoobenthos studies conducted in Korea from 1970 to 2020. Only peer-reviewed articles published in international (SCI) and domestic (Korean) journals were considered. (A) Publications each year for the past 50 years. (B) Decadal number of publications on specified benthic habitats (intertidal, subtidal, and estuary).

the literature in the 1980s (Lee et al. 1983, Lee 1987). The early ecological studies reported the distribution patterns of some macrobenthic organisms, with ecological studies increasing rapidly in the 1990s, documenting many aspects of structure and function in marine invertebrates across the diverse Korean habitats (Figure 5). It should be noted that the majority of the ecological studies performed since the 1990s have focused on intertidal and/or subtidal marine macrozoobenthos, while there have been relatively few that have focused on estuaries.

Data analyses

To understand the regional distributions of macrozoobenthos, meta-data were organized based on macrozoobenthos occurrence in a total of 38 subregions along the Korean coasts. The west coast includes 16 subregions (W1–W16), the south coast (including Jejudo) has 10 subregions (S1–S10), and the east coast has 12 subregions (E1–E12) (Figure 6). The subregion boundaries were based on the survey standards provided by Korean National Environment Monitoring (Koh & Khim 2014). The northern limit of the west coast was set as the Han River (W1) because data on the benthic ecosystems in North Korea were not readily available due to the political situation of the Korean Peninsula.

The region of Korea given the most previous research attention (~70%, 88 documents) is the West Sea (especially the tidal flats), followed by the South Sea (27 articles), and East Sea (17 articles). Although this regional inequity might introduce a bias in proportional random sampling, the general features of the macrozoobenthos studies are unlikely to be overly biased considering the substantial amounts of documents available for each region. Also, some documents were reviews, which already encompassed many individual reports and articles. Thus, the presently constructed meta-dataset should be sufficient to address the regional distribution characteristics of the Korean macrozoobenthos within a time frame of 50 years. Under such limitations on meta-data, we tried to evaluate the status of the macrozoobenthic biodiversity across the three seas of Korea, using a number of species and ecological indices of taxonomic distinctness (delta +) (Ryu et al. 2016).

Apart from updating the ecological checklist of Korean macrozoobenthos, the mini-review on the long-term community responses of macrozoobenthos under anthropogenic pressures was given to highlight human impacts on macrozoobenthos. The three representative case areas targeted in the West Sea are relevant for national-level concerns and have associated with them substantial accumulated data in relation to coastal reclamation (Lake Sihwa and the Saemangeum tidal flats) and the HSOS (Taean). There have been a large number of reports documenting environmental

Figure 6 Coastal map of Korea (west, south, and east coasts in the southern parts of the Korean Peninsula), showing total numbers of relevant published articles on the West, South, and East Sea.

and ecological degradation related to these marine pollution issues; debates remain regarding some points. The present review is focused on the deterioration of key environments, such as water and sediment quality, and addresses long-term benthic community changes in macrobenthic faunal structure and its recovery.

Over 60% of the compiled relevant works were published in Korean domestic journals (Figure 5) and international documents increased in more recent years. As part of data quality assurance, we reexamined the macrozoobenthos data published in the domestic Korean journals carefully and validated species identifications using comparisons with the World Register of Marine Species (WoRMS) database and other appropriate taxonomic literature, seeking advice from experts as needed.

The meta-data produced in the present work may provide an overview of scientific efforts and advancement in marine ecology relating to the Korean macrozoobenthos. These efforts provide critically important background information for past and present assessments of the status of benthic community health, and further provide a reference for future monitoring. The present review is the first comprehensive compilation of Korean marine ecology research. It encompasses important aspects of taxonomy and ecology in relation to marine biodiversity. The findings are useful for guiding future research directions in relation to coastal and marine biodiversity monitoring and ecosystem management in the Korean coastal waters from an international perspective.

Biodiversity of macrozoobenthos in Korean coastal water

Overview of faunal assemblages and regional distributions

A faunal inventory of Korean macrozoobenthos, including ecological information, was constructed from the meta-dataset collated for the present review (Table 2). The meta-data analysis revealed that a total of 1915 species or subspecies and 1135 genera belonging to 488 families from 17 phyla occurred in the Korean coastal waters (Table S1). This updated list is comparable to those of previous reports. For example, the recently reported number of macrozoobenthos species from the National Marine Ecosystem Survey conducted in 2015–2019 was 1666 marine invertebrates from coastal locations (Table 2). When counted the species numbers from the tidal flat locations, the NMES number would be around the presently reported species number of 1915 species. Meanwhile, it is noteworthy that the Marine Bio-resource Information System documented a total of 5670 marine invertebrate species as of 2020, supporting the documented high biodiversity of the Korean macrozoobenthos. Regardless, public access to national monitoring data is limited, and taxonomic reconfirmation is required for utilization in a meta-analysis. A species list of all macrozoobenthos constructed, analyzed, and documented in the present review is provided in Table S2 for future public use.

Another mini-review of the global macrozoobenthos inventory indicated that Korea has comparatively high macrozoobenthic diversity (Table 3). The highest macrozoobenthos biodiversity was found in Australia including deep sea (24,854 species), which could be indicative of Australia's exceptionally high marine biodiversity (Costello et al. 2010). Given the lack of global inventory data for specific taxa, efforts to establish a global inventory of coastal marine invertebrates at national or regional sea levels would be beneficial.

With respect to faunal composition, the Korean macrobenthic communities were composed primarily of five dominant taxonomic groups: Mollusca (670 species), Annelida (469 species),

Table 2 Macrozoobenthos species richness in Korean coasts documented over the last two decades and summarized by taxa and/or coastal regions and based on fauna data from National Marine Ecosystem Survey (NMES), Marine Bio-resource Information System (MBRIS), and this study

Program	NMES				MBRIS	This study
Habitat type	Tidal flat			Coast	Marine	Tidal flats and coasts
Year	1999–2005	2008–2012	2015–2018	2015–2019	2019	1973–2020
Macrozoobenthos[b]						
Mollusca	54	185	–	–	1764	670
Annelida	228	213	–	–	361	469
Arthropoda	205	240	–	–	2016	434
Echinodermata	5	30	–	–	213	79
Others	9	49	–	–	1316	263
Total	**501**	**717**	**639**	**1666**	**5670**	**1915**
Coastal region						
West coast	–	–	474	1050	–	829
South coast	–	–	452	1107	–	1103
Jejudo coast	–	–	70	557	–	511
East coast	–	–	55	626	–	621
Total	**501**	**717**	**639**	**1666**	**5670**	**1915**

[a] *MBRIS (2020) data based on the National Marine Biodiversity Research Institute of Korea's species collection list;*
[b] *Total number of species in Korean coasts*

Table 3 Comparison of species richness of macrozoobenthos present in selected global coasts and regional seas; species richness was summarized by macrozoobenthos taxa (references given including this study)

Locality	British Isles	Australia (including deep sea)	Western Turkey	North Pacific (subtidal trawl)	Arctic (subtidal)	Korea (coasts)
Macrozoobenthos						
Mollusca	192	8525	227	255	392	670
Annelida	54	1558	–	–	668	469
Arthropoda	109	6365	116	128	847	434
Cnidaria	93	1754	18	–	–	103
Echinodermata	47	1594	50	85	228	79
Others	35	5058	274	108	501	160
Total	**530**	**24,854**	**685**	**576**	**2636**	**1915**
References	Marine Life Information Network	Butler et al. (2010)	Gönülal and Güreşen (2014)	Volvenko et al. (2018)	Inniss et al. (2016)	This study

Arthropoda (434 species, mostly crustaceans), Cnidaria (103 species), and Echinodermata (79 species) (Table S1). These five faunal groups collectively accounted for >91% of the total macrozoobenthic species (Figure 7A). Annelida was the most dominant taxa, representing ~35% of the total species, followed by Mollusca (30%) and Arthropoda (26%). The relatively diverse polychaete annelids were recorded more frequently along the west coast than along the other two coasts, presumably because of the much extensive shallow mudflat habitats on the west coast (Yim et al. 2018).

Of the three coasts, the south coast had the most faunal species, numbering 1103, and the proportions of the three major taxa differed from those of the west coast. The most diverse taxa were Mollusca (416 species, 38%), followed by Annelida (274 species, 25%) and then Arthropoda (210 species, 19%) (Table S1). The number of molluscan species was the highest in the south coast. Although the east coast showed the lowest total number of species (621 species) among the three Korean seas, the composition of three major phyla did not differ greatly among the three seas, reflecting faunal commonness across the region. Along the east coast, Mollusca were predominant (190 species, 31%), followed by Annelida (149 species, 24%) and Arthropoda (142 species, 23%). Although phylum Cnidaria was ranked as the fourth dominant faunal group (55 species; 9%), the cnidarians were the dominant taxa only within a limited region (Ulleungdo and Dokdo) not diverse in the other regions. Phylum Echinodermata had low species richness (31 species, 5%).

Next, the distribution patterns of macrozoobenthos species richness along different habitat types (intertidal, subtidal, and estuarine) were analyzed (Figure 7B). Not surprisingly, the subtidal environment showed the highest number of macrozoobenthos species (1325 species, >69% of the total). Interestingly, a third of all molluscan species observed (437 species) were found in the subtidal zone, where they account for ~70% of species present. Large portions of the polychaetes species (82%) and arthropod crustacean species (64%) observed in the Korean seas were present in subtidal habitats. Species diversity was relatively moderate in the intertidal area (875 species) and relatively low in estuarine areas (244 species). Of note, about 6% of macrozoobenthic species co-occurred across all three habitats (123 taxa); these organisms are euryhaline or salinity-tolerant species.

Unfortunately, the habitat information for some species was not provided in the original articles. In particular, the habitat information was often lacking for studies conducted along the east coast, especially around Dokdo. Overall, the results indicated a high proportion of habitat overlap in faunal occurrence. Broadly, these co-occurring species across the habitats encompass all observed taxa, including Mollusca (128 species, 20%), Annelida (209 species, 45%), Arthropoda (111 species, 28%), and Cnidaria (17 species, 17%).

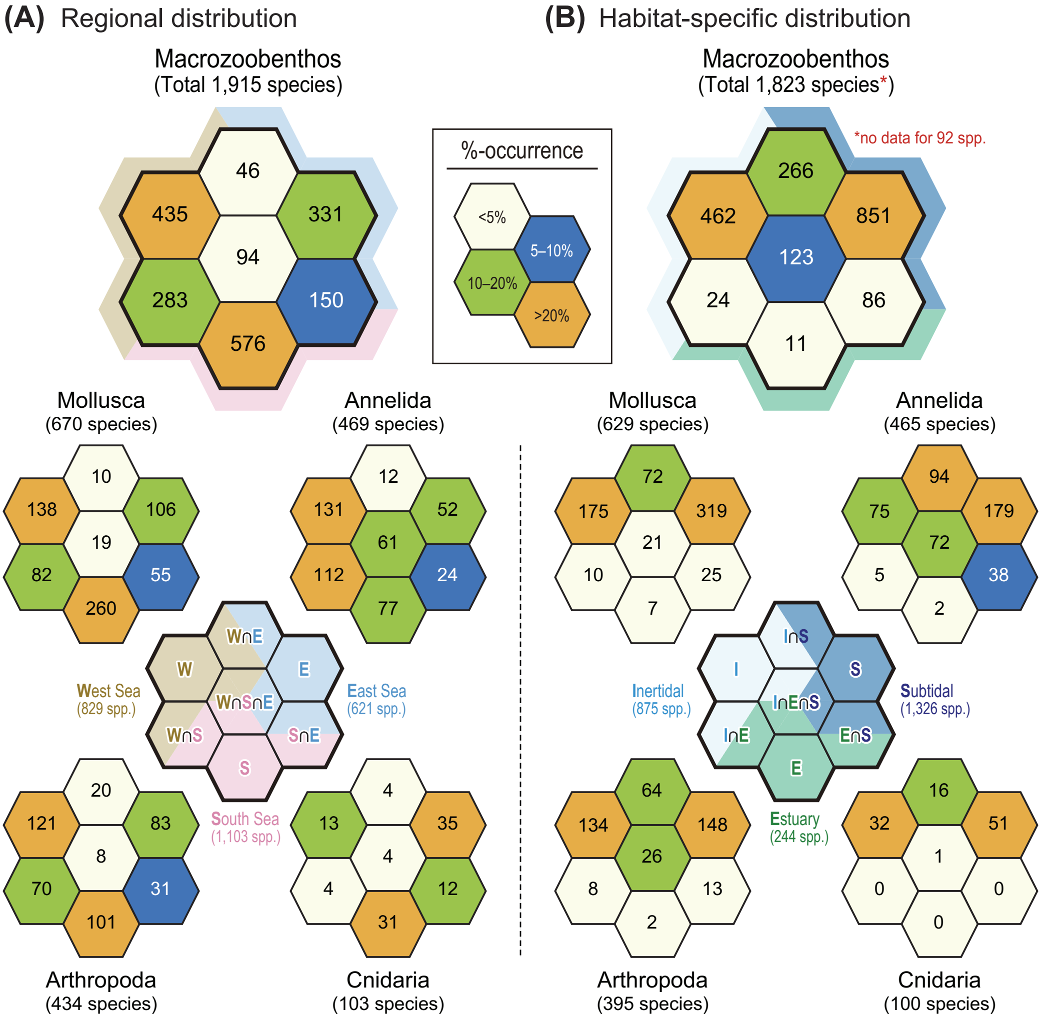


Figure 7 The occurrence of macrozoobenthic species showing intra- and inter-regional and habitat-specific distributions in Korea. (A) Regional patterns for all 1915 species and 4 major taxonomic groups present in the West Sea, South Sea, and East Sea, (B) habitat patterns for 1823 species and 4 major taxonomic groups present in intertidal, subtidal, and estuary areas (92 species were excluded due to there being no habitat information).

The limited information on benthic community structure from the original meta-data made it difficult to address the overall ecological quality at present. Under the limitation, the analysis of taxonomic distinctness indices across the three seas indicated the regional characteristics in benthic ecological quality (Figure 8). In general, the high taxonomic diversity was evident, ranging from delta+values of 65–95, across all the three seas. When depicted the delta+against the number of species, three groups could be featured by representing biodiversity hotspots, estuarine regions, and regions close to the highly populated cities (Figure 8).

Another aspect of regional biodiversity could be explained by variations in delta+and number of species across the subregions in each sea. Considering the significance of both factors to overall biodiversity, the five grades (I–V; from excellent to good, moderate, poor, and bad) across the number of species and delta+are suggested to represent benthic ecological quality (Figure 9). Most of the subregions showed moderate to excellent benthic ecological quality based on the suggested

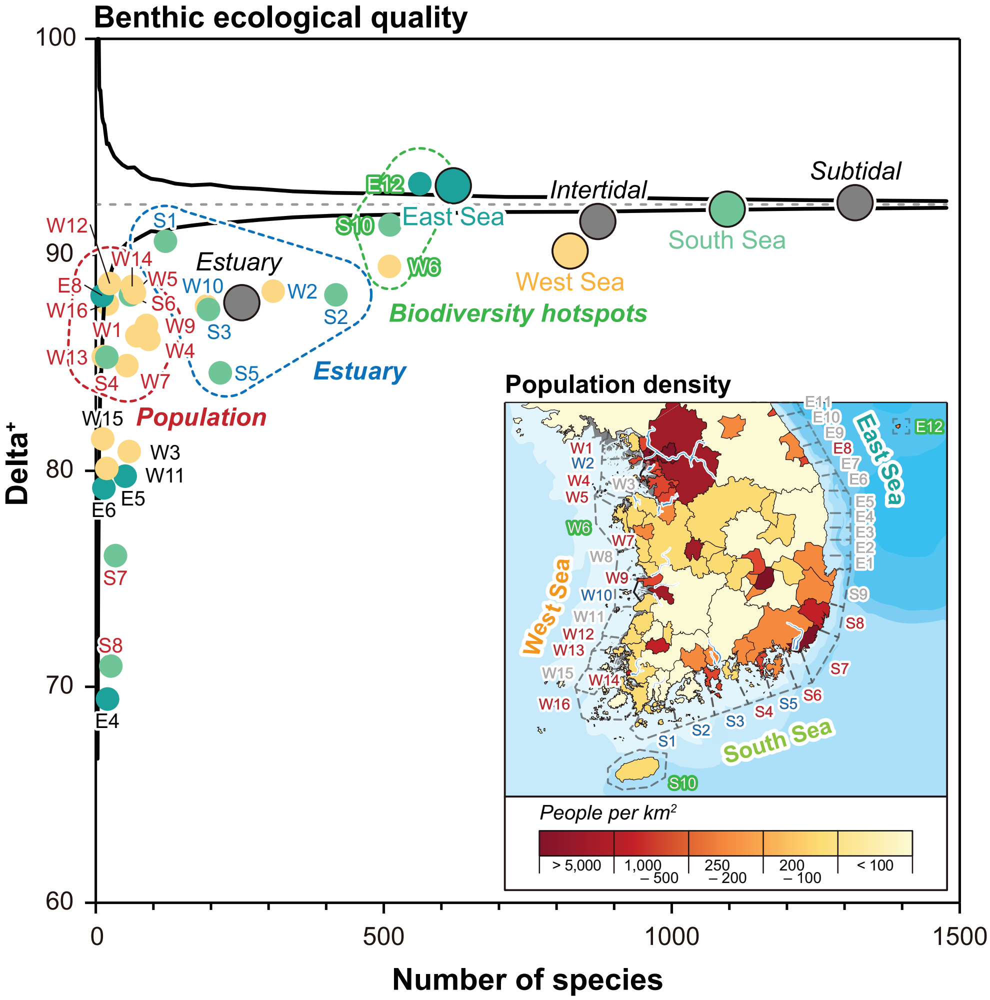


Figure 8 Spatial benthic ecological quality (delta+) results for number of occurred species in 30 coastal areas of Korea (West: 15 regions, South: 9 regions, East: 5 regions; regions in which less than one species appeared were excluded from the analysis). The 95% probability lines represented the delta+values obtained from 1000 independent simulations of the 1915 macrozoobenthic species.

index. It should be noted that subregions with high delta+value may not be always considered as excellent biodiversity if the number of species are relatively low. Overall, the ecological quality analysis reflected general and specific features of macrozoobenthos biodiversity across the three seas and specific habitats and/or conditions.

Faunal composition and distributions in the West Sea

The West Sea was divided into 16 subregions (W1–W16) along the western coast of Korea. The Taean coast (W6) exhibited the most diverse fauna (510 species), with a predominance of polychaetes (192 species), followed by crustaceans (154 species) and molluscans (124 species) (Figure 10 and Table S1), approximately two-thirds of the total number of reported species (829 taxa) from all 16 subregions. The Taean coast was confirmed to be a hotspot of macrozoobenthic biodiversity, which may reflect, at least in part, the intensive sampling efforts that were made following the HSOS in 2007.

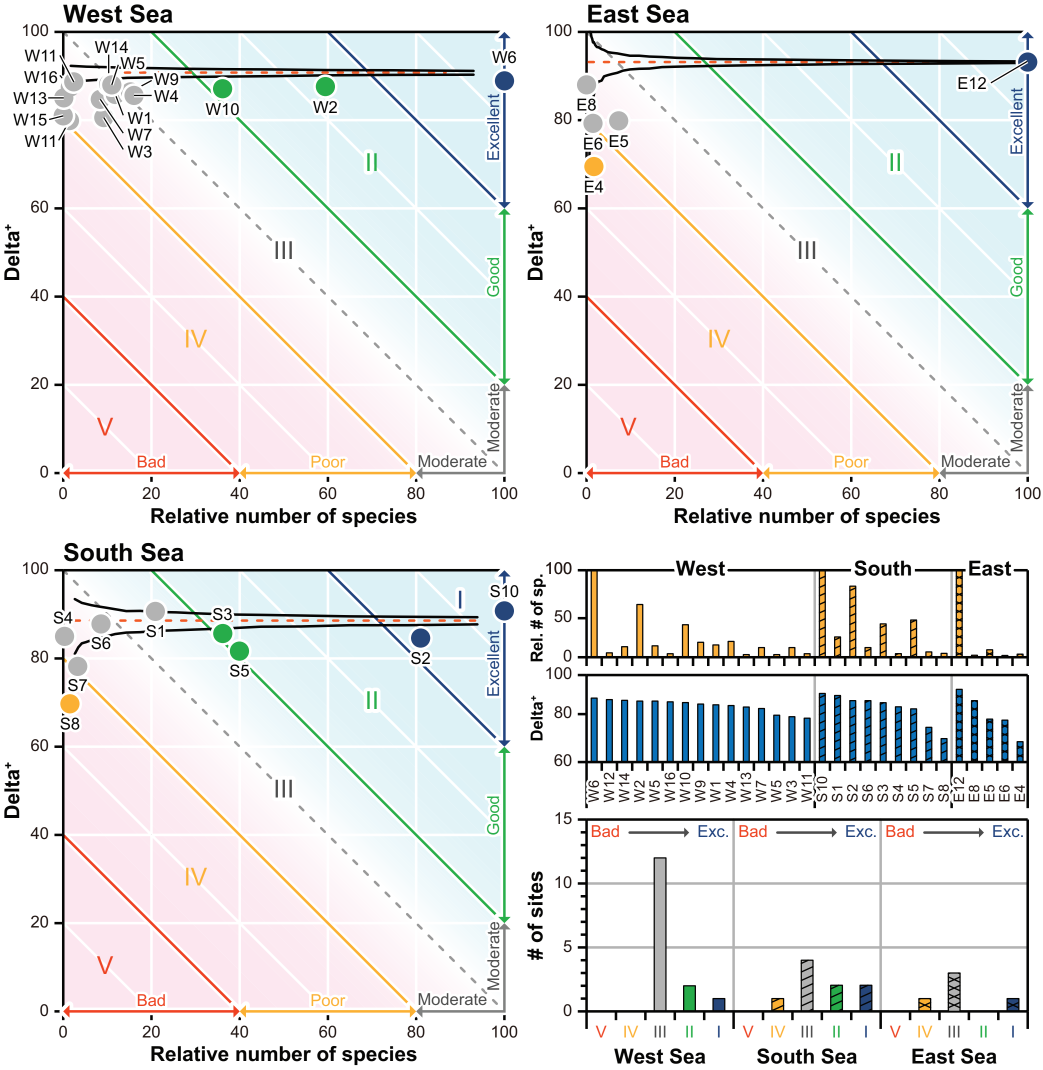


Figure 9 Benthic ecological status of 30 coastal areas in Korea (West: 15 subregions, South: 9 subregions, East: 5 subregions). The criteria used to rate benthic ecological quality included delta + and relative number of species (set 100 for the maximum number of species occurred in each sea). The five grades representing 20% each across two factors (“I: Excellent”, “II: Good”, “III: Moderate”, “IV: Poor”, and “V: Bad”) are suggested as a proxy guideline in overall assessment of benthic ecological quality.

The Incheon coast (W2), which has attracted intense research interest (35 studies), showed high species richness (308 species). It encompasses an extensive harbour near the megapolitan city of Seoul and various industrial complexes, including an electric generation power plant and an international airport. The area includes Lake Sihwa and several representative tidal flats, which have attracted high sampling efforts, and it is considered to have high natural marine diversity.

The Jeonjupo coast (W10) also showed relatively high species abundance with 193 species. Annelid species were the dominant taxa (46%), reflecting the typical mud bottoms around inertial flats. Interestingly, the community structure in the Jeonjupo coast was similar to that found in the Incheon coast, with polychaetes accounting for over half of the total species number. The Jeonjupo coast includes the former Saemangeum tidal flats, where extensive tidal flats (~180 km^2)

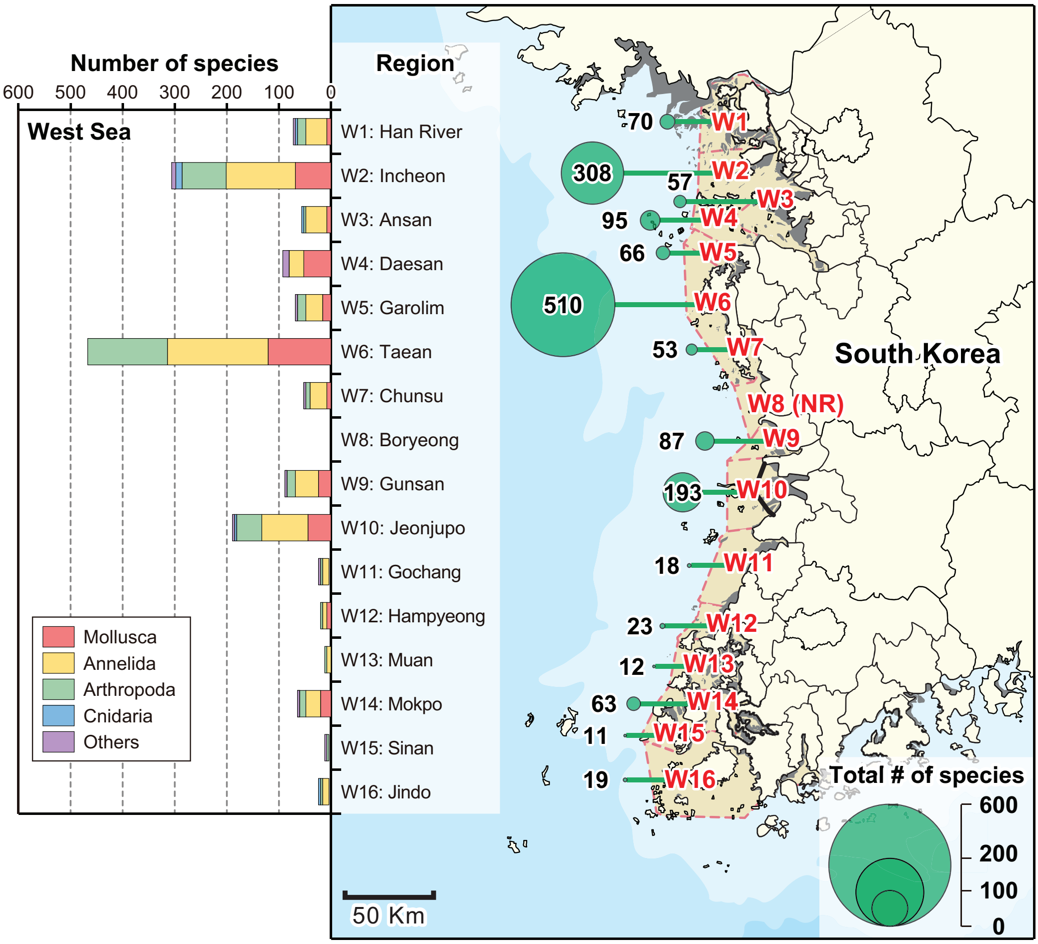


Figure 10 Map of the Korean West Sea showing the total number of recorded species over 16 subregions and the faunal composition of the macrozoobenthos in each region.

had developed before sea-dike construction was undertaken (Ryu et al. 2014). For this reason, many studies have been conducted in the Saemangeum region before and after construction to monitor the marine environment and ecosystem, with a major focus on faunal distributions.

The next most notable ecological hotspots are Daesan (W4) and Gunsan (W9), which had relatively large numbers of recorded species (95 and 87, respectively). The Daesan coast showed a predominance of molluscs (57%), and the Gunsan coast was occupied primarily by annelids (51%). The Gunsan coast contains a major estuary that is fed by the very large Geum River, resulting in an environment distinct from that of the Daesan coast. This distinction seemed to underlie the dissimilarity in faunal composition between these regions.

Examining the regional co-occurrence of macrozoobenthos in the West Sea, it was observed that many macrozoobenthos (>500 species; ~58%) occupied only a single region (Figure 11). There are two possible explanations for this high proportion of uni-regional presence. First, a considerable number of macrozoobenthic species are confined geographically by the dented shoreline and embayment system. Such oceanographic settings on the west coast may thus hinder the coastal migration of macrozoobenthic larvae and favour their site-specific settlement, as described previously by Koh & Khim (2014). Second, it is possible that biased regional sampling could have provided incomplete occupation records.

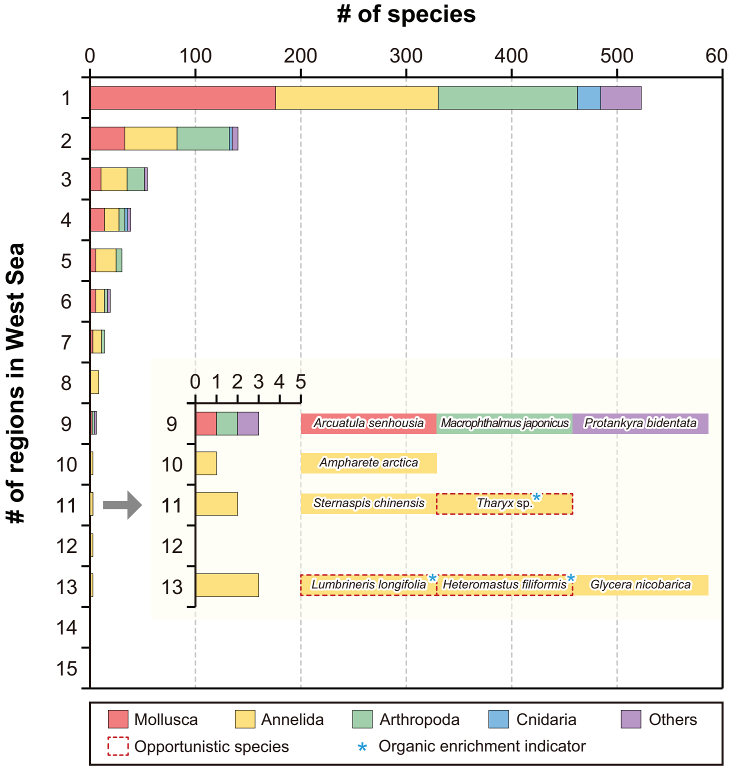


Figure 11 Number of macrozoobenthos species observed in one or more Korean West Sea subregions simultaneously. The inset shows the most common species found in more than 9 subregions. Some opportunistic or organic enrichment indicator species based on their life history traits are denoted.

Among uni-subregional species, molluscs were predominant (178 species, 32%), followed by polychaete annelids (154 species), crustacean arthropods (134 species), and cnidarians (22 species). Macrozoobenthic species observed in two subregions include 147 taxa, consisting mostly of crustacean and annelid species with subequal species numbers (50 and 49 species each), followed by molluscs (34 species). The number of regionally co-occurring species decreased as the number subregions in common increased, as expected. No species were found to be co-occurring in more than 14 subregions. It is notable that of the nine species found to co-occur across at least nine West Sea subregions, three were opportunistic species and organic pollution indicators (*Tharyx* sp., *Heteromastus filiformis*, and *Lumbrineris longifolia*) (Figure 11).

Further analysis of these nine species to characterize each taxon's site specificity (Figure 12) indicated that three polychaete species (*Glycera nicobarica*, *Heteromastus filiformis*, and *Lumbrineris longifolia*) were found in 13 of the 16 regions in the West Sea, affirming their broad spatial distribution across the west coast. Three additional polychaete species were quite broadly distributed: *Glycera chirori* (12 regions), *Sternaspis chinensis* (11 regions), and *Tharyx* sp. (11 regions). Interestingly, but not surprisingly, polychaetes occurred most broadly along the west coast. Three non-polychaete species co-occurred in nine regions, including the bivalve *Arcuatula senhousia*, the crustacean decapod *Macrophthalmus japonicus*, and the holothurian *Protankyra bidentata*. Although there is little information on the distributions of these nine wide-spread macrozoobenthos species, these species seemed to be able to inhabit essentially all coastal areas regardless of habitat preference. Of these species, eight spanned three types of habitat (e.g. intertidal, subtidal, and estuarine area); the exception was a polychaete annelid, *Ampharete arctica*.

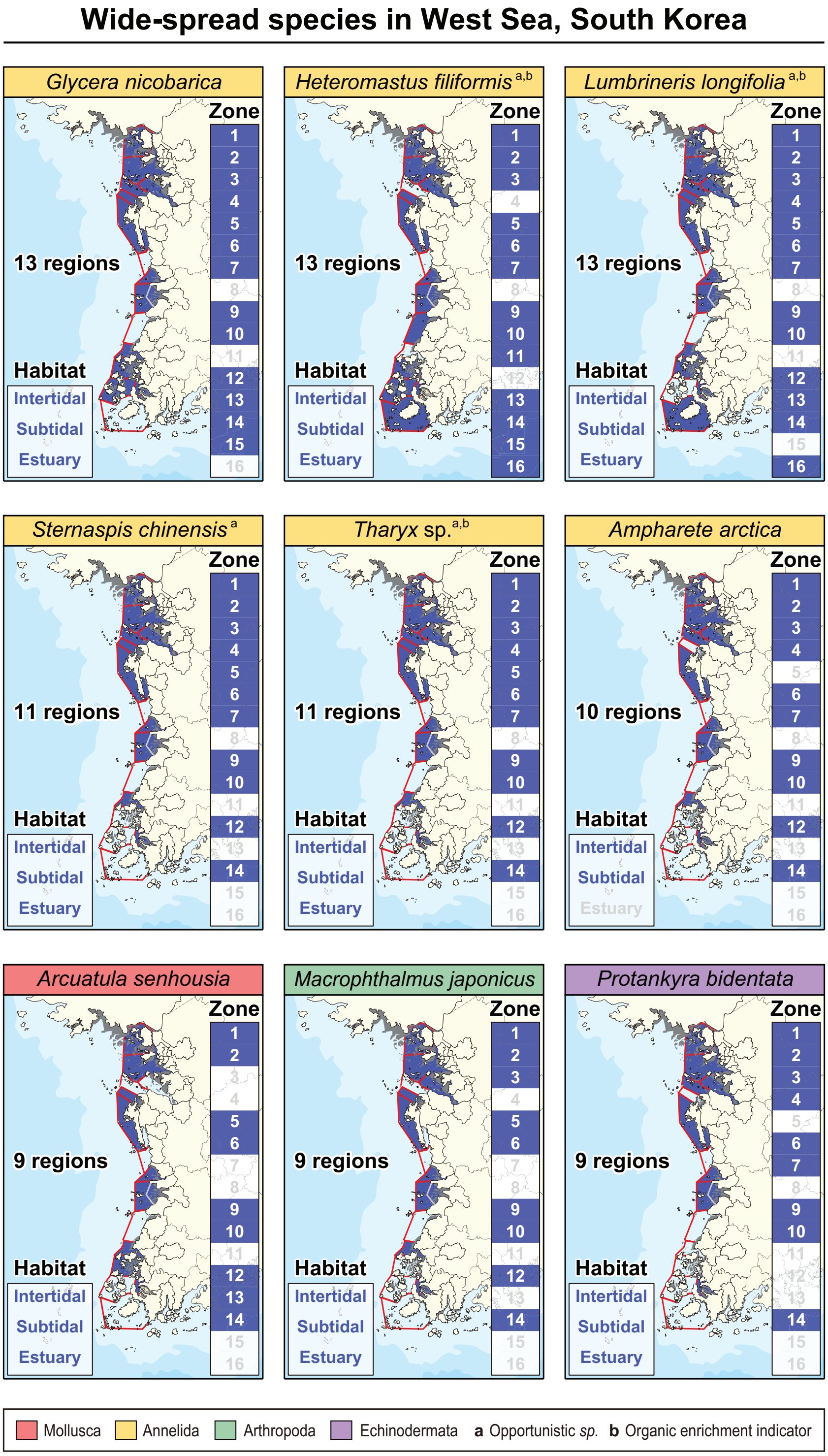


Figure 12 Distribution patterns of nine macrozoobenthic species occurring in more than nine subregions along the West Sea of Korea. Their occurrence regions and habitat types are indicated by blue colour in the map and row of boxes, respectively.

Faunal composition and distributions in the South Sea

The South Sea encompasses 10 subregions including nine (S1–S9) along the southern coast and one subregion around the island of Jejudo (S10). The Jejudo coast showed the most diverse faunal assemblages with 511 species, all of which were recorded by Ko et al. (2016). Molluscan species showed predominance with 254 species (50%), followed by crustaceans and annelids with 70 and 31 species, respectively (Figure 13). This quantity of 511 accounted for about half of the total number of reported species (1103 species) in the South Sea. Notably, the Jejudo coast had an unusual predominance of molluscans, which accounted for over 60% of the total number of mollusc species found in the South Sea. Indeed, the Jejudo coast sustains the most diverse assortment of molluscs among all of the Korean coast regions.

The Goheung coast (S2) was found to be next in species diversity (417 species) despite a low sampling intensity. The taxonomic composition of the Goheung coast differed from that of the Jejudo coast. About half of the total macrozoobenthos, 193 species, were polychaetes, followed by subequal numbers of crustacean arthropods and molluscs (101 and 95 species, respectively). The

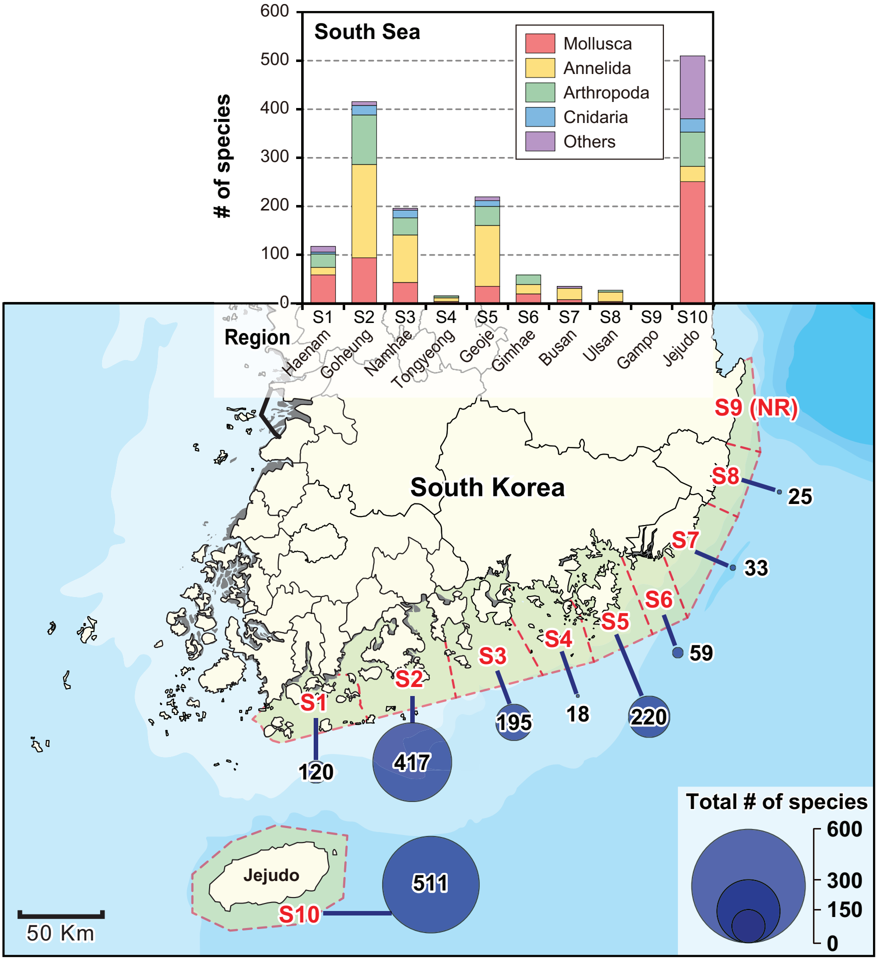


Figure 13 Map of the Korean South Sea showing the total number of recorded species over ten subregions and the faunal composition of the macrozoobenthos in each region. NR: not reported.

Goheung coast exhibited the highest diversity for annelids and crustacean arthropods among all regions of the South Sea.

The next most species-rich hotspot found in the South Sea was the Geoje coast (S5). Among the 10 subregions in the South Sea, S5 had the highest sampling effort, owing to the pursuit of many benthic community studies. The area includes several sediment contamination hotspots, such as Masan Bay and Jinhae Bay, where there has been elevated concern regarding benthic community health in recent decades (Hong 1987, Choi & Seo 2007, Seo et al. 2014a, Bae et al. 2017). Indeed, despite a high sampling intensity and the publication of seven studies focused on the Geoje coast, only 220 species were reported. This relatively low benthic faunal diversity reflects the impacts of sediment pollution (Khim & Hong 2014). Annelid species were the predominant taxa in subtidal bottoms (>58% of total species). There were relatively low numbers of crustacean arthropods (43 species) and molluscs (32 species). All other South Sea subregions had <200 macrozoobenthic species documented, likely reflecting a relative lack of research across the region.

Regional co-occurrence analysis indicated that some 779 macrozoobenthos species in the South Sea (~70%) were found in only a single region (Figure 14). Hence, there were even more uni-subregional species found in the South Sea than were found in the West Sea. These limited ranges may likewise be due to local geographical characteristics and, perhaps in part, sampling bias. Of the species present in only a single subregion of the South Sea, 44% were molluscs (340 species); this quantity of species is nearly double that found in the West Sea (178 species). The next compositional taxa include crustacean arthropods (146 species), polychaete annelids (114 species), and cnidarians (50 species). Only 213 species were found to co-occur in two subregions, including 95 annelid species, followed by 61 mollusc species and 42 crustacean arthropod species. Co-occurrence in more than three subregions much reduced. Of 10 polychaete species found to co-occur across five or more subregions, five were opportunistic, namely *Capitella capitate*, *Tharyx* sp., *Heteromastus filiformis*, *Lumbrineris longifolia*, and *Magelona japonica* (Figure 14). Also, five species were organic pollution indicator species, namely, *Theora lata*, *Capitella capitate*, *Tharyx* sp., *Heteromastus filiformis*, and *Lumbrineris longifolia*.

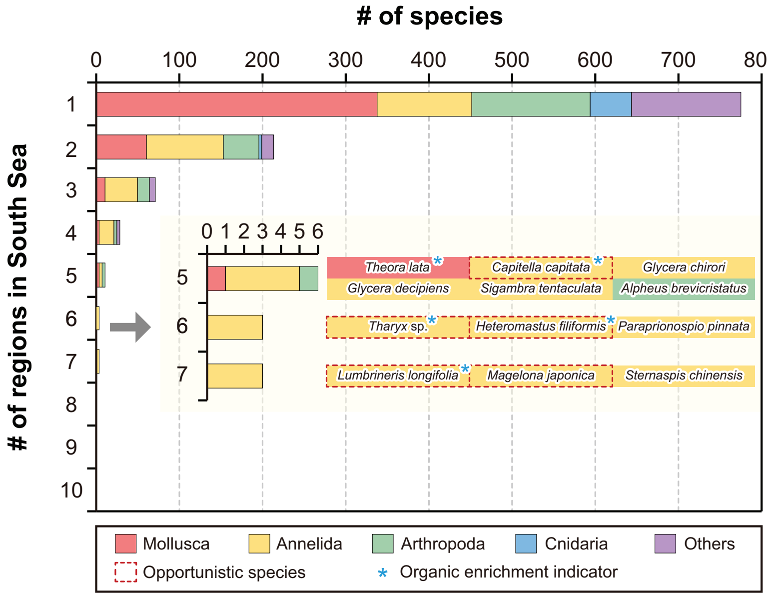


Figure 14 Number of macrozoobenthos species observed in one or more Korean South Sea subregions simultaneously. The inset shows the most common species found in more than 6 subregions. Some opportunistic or organic enrichment indicator species based on their life history traits are denoted.

Next, we described the distribution of selected taxa, seven annelid species and one molluscan species, that co-occurred in more than five subregions to characterize the commonly occurring species along the extent of the South Sea coast (Figure 15). Three polychaete species (*Lumbrineris longifolia*, *Sternaspis chinensis*, and *Magelona japonica*) were found crossing the seven subregions, indicating their wide-spread distribution on the southern coast. Three polychaete species (*Tharyx*

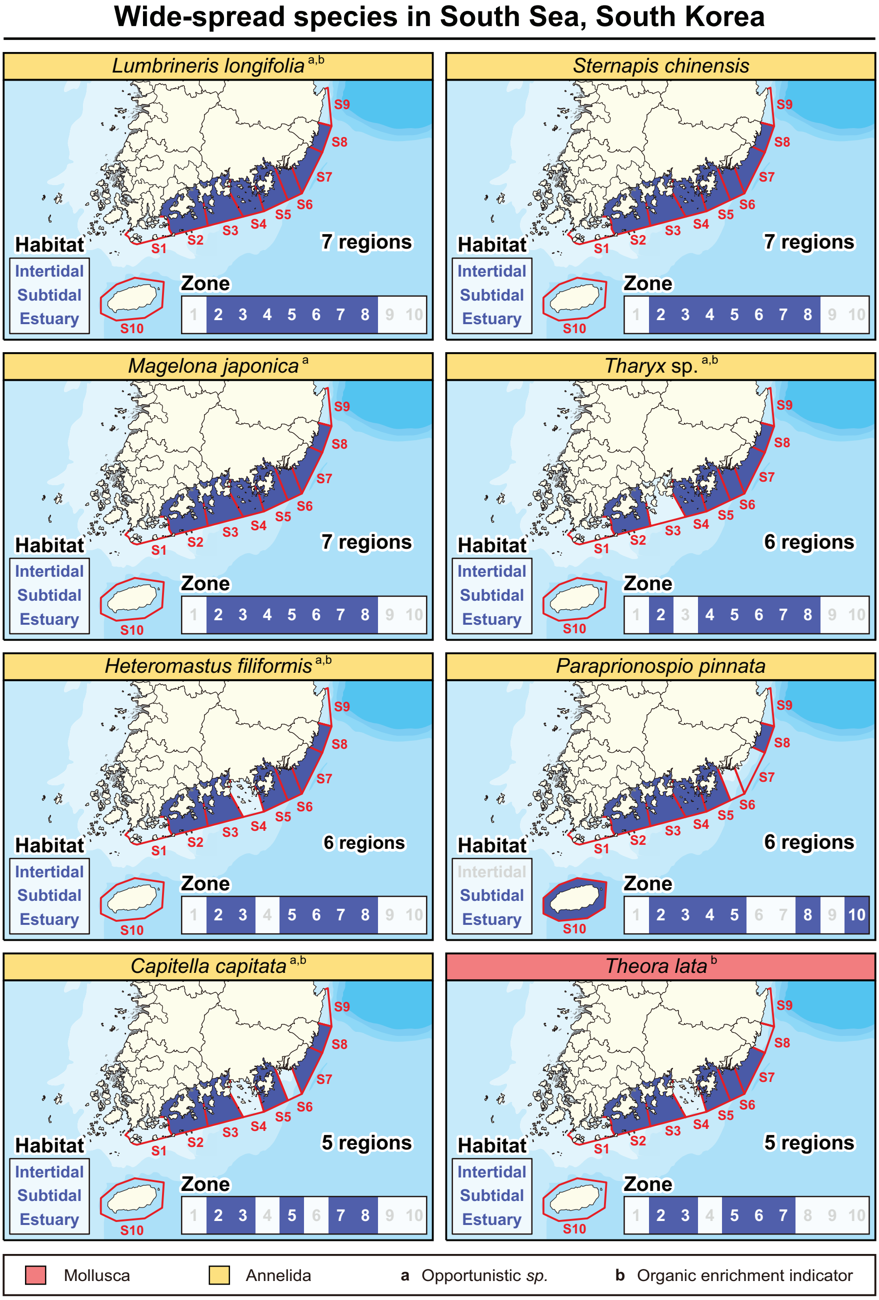


Figure 15 Distribution pattern of eight macrozoobenthos species occurring in more than five subregions along the South Sea of Korea. Their occurrence regions and habitat types are indicated by blue colour in the map and row of boxes, respectively.

sp., *Heteromastus filiformis*, and *Paraprionospio pinnata*) were found to co-occur in six subregions. Five of the aforementioned species showed a widespread presence along the consecutive coastline encompassing S2 to S8 (exceptions: *Tharyx* sp. not at S3 and *Heteromastus filiformis* not at S4). Interestingly, among the cosmopolitan polychaetes, only *Paraprionospio pinnata* showed co-occurrence around the remote island of the Jejudo coast, reflecting an especially wide geographical distribution. In terms of faunal distribution by habitat type, seven of the eight wide-spread cosmopolitan macrozoobenthos species inhabited across all three habitats (intertidal, subtidal, and estuary areas); the exception was *Paraprionospio pinnata*.

Faunal composition and distributions in the East Sea

The East Sea is characterized by its comparatively simple shoreline and a rapidly increasing water depth from the coast toward offshore. Its coastal habitats feature well-developed vast sand beaches and rocky shores. Despite its unique topographical features and varying habitat types, biodiversity research has been concentrated (>75% studies) around the Ulleungdo coast (E12). The few remaining works to date were carried out in the Hupo coast (E4), Jukbyeon coast (E5), and Samcheok coast (E6).

The Ulleungdo coast is a remote volcanic island far from the Korean Peninsula, including the Ulleungdo and Dokdo islands and associated small islets. This subregion was found to exhibit an extraordinarily diverse faunal assemblage with 562 species, a species number close to the total number of species reported for the East Sea (621 species). Our recent review documented a total of 578 macrozoobenthos species from 12 phyla at the Dokdo coast, including the intertidal and subtidal zones (Song et al. 2017). However, we excluded 16 taxa documented from Dokdo in the meta-data of the present review for the following reasons: they were treated as (merged into) one "species" because they were only identified to the genus level; double-counted species were excluded owing to synonyms or typos in the original reports and treated as one taxon according to a taxonomic update in WoRMS.

Among all of the recorded benthic organisms, molluscans were predominant with 183 species (33%), followed by crustaceans and annelids, with 132 and 112 species, respectively (Figure 16). Despite the distance of the island of Dokdo from the mainland and relative inaccessibility, its marine biodiversity was first introduced publicly via reports identifying two new crustacean decapods, *Pagurus similis* and *Pachygrapsus crassipes*, in the early 1960s (Kim 1960). Dokdo's high biodiversity has been recognized internationally by three dedicated works in the last decade (Ryu et al. 2012, Song et al. 2017, Kim et al. 2020). The total number of macrozoobenthic species reported in the Ulleungdo subregion was only 226, based on a recent review (Song et al. 2017).

The other subregion in which studies were conducted, other than the Ulleungdo coast, showed very low species diversity of macrozoobenthos (<100 species), reflecting a lesser variety in habitat diversity. Only 50 species have been documented in the Jukbyeon coast (E5), likely due to low sampling efforts (only three studies). Annelid species were the relatively dominant group in the subtidal area with 35 species, followed by crustacean arthropods and molluscs with eight and five species, respectively. Of note, the Jukbyeon coast, which is well known for public concerns between conservation and development, is home to various marine institutes and eco-tourism but faces potential risk due to the largest nuclear power plants in Korea. Finally, two prior investigations were conducted in the Hupo coast (E4) and Samcheok coast (E6), one study each, yielding the documentation of quite a few marine species (20 and 13 species, respectively).

Regional macrozoobenthos co-occurrence analysis indicated that 598 species have been found only a single region of the East Sea (Figure 17). The results obtained for the East Sea were consistent with those found for the West Sea and South Sea, with biased sampling efforts representing the main reason for there being so few co-occurring species. Among uni-subregional species, molluscs were predominant (189 species, 32%), followed by similar numbers of crustacean and annelid species (139 and 130 species, respectively). Due to the lack of sampling effort in other subregions in the East Sea, these co-occurrence records may not reflect the actual span of the species.

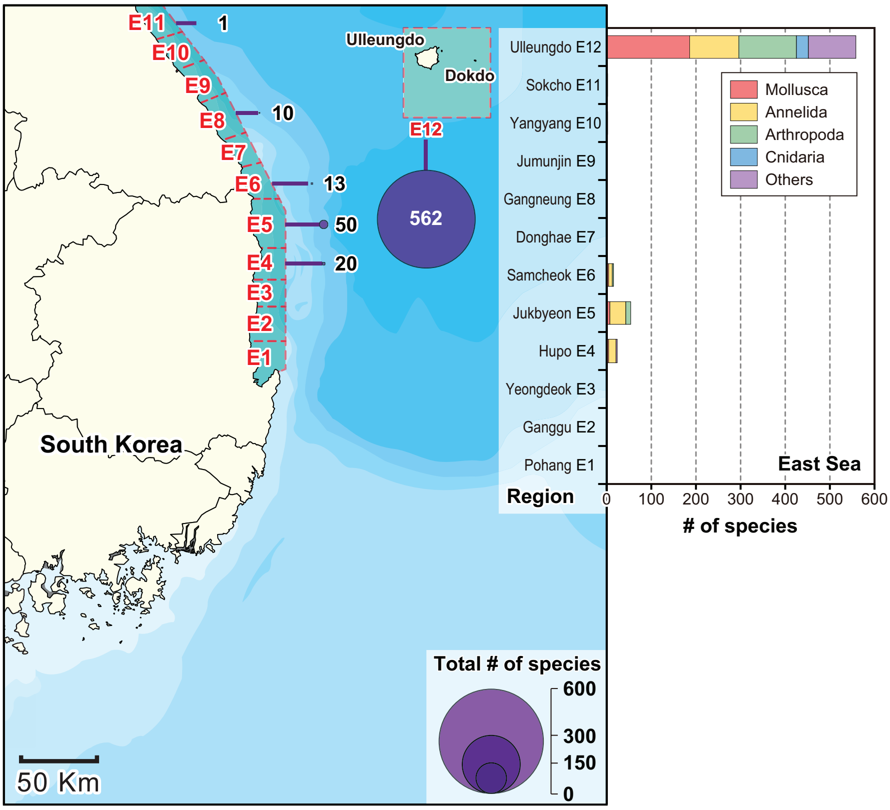


Figure 16 Map of the Korean East Sea showing the total number of recorded species over 12 subregions and the faunal composition of the macrozoobenthos in each region.

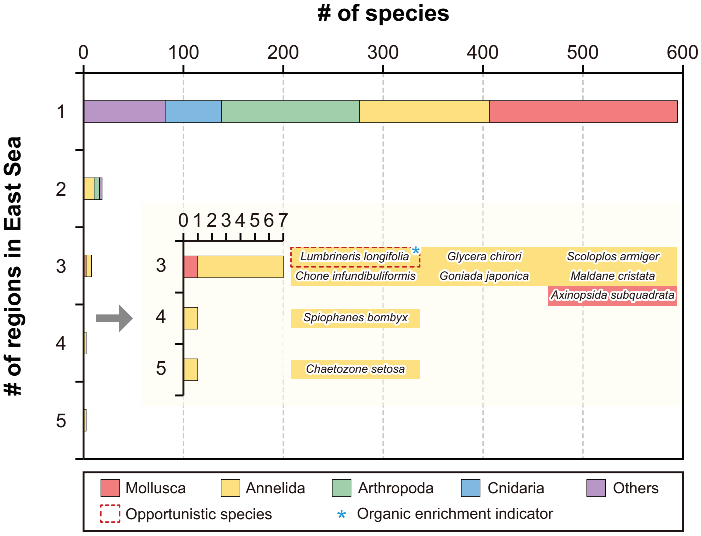


Figure 17 Number of macrozoobenthos species observed in one or more Korean South Sea subregions simultaneously. The inset shows the most common species found in more than 3 subregions. Some opportunistic or organic enrichment indicator species based on their life history traits are denoted.

Notwithstanding, given the presently available data, it was found that a total of 14 macrozoobenthos species co-occurred at two or more subregions, of which most were annelids (11 species). The number of co-occurring species across 3, 4, and 5 subregions were 7, 1 (*Spiophanes bombyx*), and 1 (*Chaetozone setosa*), respectively. Only one of the polychaete species, *Lumbrineris longifolia*, was found to be opportunistic and organic enrichment indicator at this time.

Finally, to characterize the commonly occurring species, we analyzed the distribution patterns for the nine wide-spread species found to occur in three or more subregions of the East Sea (Figure 18). The polychaete species *Chaetozone setosa* spanned five East Sea subregions (E4, E5, E6, E8, and E12), with its widest observable distribution along the eastern coast and Dokdo. The next widely distributed species, *Spiophanes bombyx*, is also a polychaete; it was observed in four subregions. Next, six polychaete annelids (*Lumbrineris longifolia*, *Glycera chirori*, *Scoloplos armiger*, *Chone infundibuliformis*, *Goniada japonica*, and *Maldane cristata*) and one molluscan species (*Axinopsida subquadrata*), co-occurred in three subregions. Most co-occurring species found inhabited three habitat types (intertidal, subtidal, and estuary). The exceptions were *Spiophanes bombyx* (intertidal and subtidal); *Chone infundibuliformis* (subtidal and estuary); and *Maldane cristata* and *Axinopsida subquadrata* (subtidal only).

Long-term human impacts on marine ecosystem: Sihwa reclamation

Backgrounds and overview of Sihwa issue

Coastal habitat destruction (or alteration) is recognized as the main issue relating to marine ecological quality in East Asia, particularly in the Northwest Pacific Action Plan region encompassing Korea, China, Japan, and Russia (Khim et al. 2018). Coastal reclamation has long been an environmental issue, especially in China and South Korea. Its blocking effect on tidal connectivity has contributed to the loss of valuable coastal habitat and loss of marine biodiversity. Lake Sihwa, formerly a natural tidal flat, is a well-known example of ecosystem deterioration due to large-scale coastal reclamation. Lake Sihwa has been isolated from the offshore marine environment by the construction of a 12.7 km sea-dike constructed in 1994. The original purpose of the Sihwa reclamation project was to provide a freshwater supply to nearby industrial and agricultural areas via seawater desalinization (Lee & Khim 2017). After the dike construction, however, the water quality of the lake deteriorated drastically, with a COD approaching 20 mg·L^{-1}, a level far above standard good water quality guidelines (2 mg·L^{-1}) in Korea (Hong et al. 1997, Kim et al. 2002).

The failure of the Sihwa project can be attributed to underestimation of three ecological aspects. First, important ecological functions of the natural environment were not considered prior to sea-dike construction, which resulted in a rapid deterioration of water quality followed by a drastic reduction in benthic faunal diversity. Consequently, a huge budget was consumed to implement an uncertain water quality improvement technique (Lee et al. 2014, Lee & Khim 2017). Second, the volume of annual freshwater flowing into Lake Sihwa was very low, thus necessitating a long time for full desalination, which was not adequately predicted in the initial planning (KWRC 2005). Third, the regional watershed was not adequate to meet increasing volume demands for wastewater and freshwater consequent to rapid expansion of the adjacent industrial and agricultural areas. In response to the unexpected water quality deterioration that occurred within two years of the dike's construction (1996), several short-term temporary measures were applied by the Korean government to address the water quality issue (Table 4), including a simple discharge of wastewater to the outer sea by seawater circulation (Lee et al. 2014). Despite such efforts, good water quality did not recover to the regional ambient level until 2000.

After 2000, the Korean government abandoned its original plan to convert Lake Sihwa into a freshwater reservoir and then constructed a tidal power plant, which allowed seawater circulation

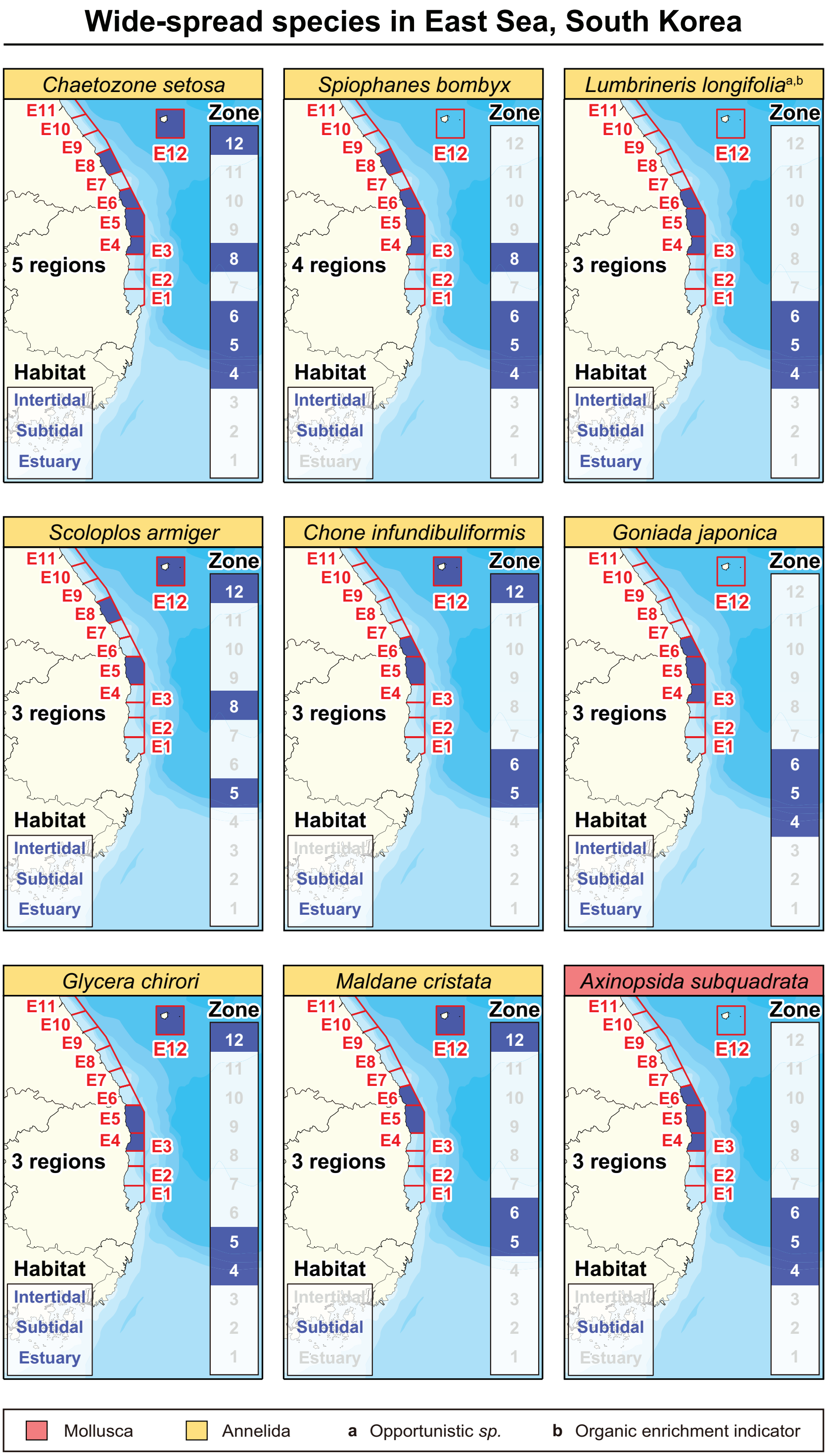


Figure 18 Distribution pattern of nine macrozoobenthos species occurring in more than three subregions along the East Sea of Korea. Their occurrence regions and habitat types are indicated by blue colour in the map and row of boxes, respectively.

Table 4 Summary of progress on political and sociological issues, environmental conditions, and ecological responses to Lake Sihwa reclamation from 1986 to the present

Year	Issues	Major management measures	Environmental conditions	Ecological responses
1986	Developed industrial complexes			
1994–1996	Construction of Sea dike	Establishment of special WQ management measures (96)	Highlighted Lake Sihwa pollution (96)	Brackish water species predominated Opportunistic species dominated
1997–1999	Seawater circulation began	Test sluice operation to increase seawater circulation	Great concentrations of NPs found	Outbreak (>90%) of opportunistic species, *Nitzschia* species dominated
2000	Abandonment of plan to keep Lake Sihwa as a freshwater reservoir	Designation as a SMA (00) Implementation first phase of SCR EMMP (01~06) Construction of wetland to reduce nonpoint pollution (1.04 km^2) (02)	Great concentrations of NPs found Inland sediment highly polluted	Dominant taxa changed and opportunistic fauna decrease
2004	Initiation of TPP	Improvement of sewage treatment plant (03~04)	PFCs originated from surrounding activities	Brackish species and organic indicators still dominant
2007–2010		Second phase of SCR EMMP Stream sediment dredging and marine debris cleanup	Mercury in sediment showed great concentrations; PBDE concentration was the highest in the world	*Acartia* species dominated seasonally, density increased toward the dike
2011	Completion of TPP	Test operation of TPP (32-160 × $10^6 m^3 d^{-1}$)		
2012–2016		Third phase of SCR EMMP Full STPP operation (160 × $10^6 m^3 d^{-1}$) TPLMS implementation (13)		Brackish species and organic indicators still dominant
2019–Present		Fourth phase of SCR EMMP		

Abbreviations: TPP, Tidal Power Plant; WQ, water quality; SCR EMMP, Sihwa Coastal Reservoir Environmental Management Master Plan; TPLMS, Total Pollution Load Management System; NPs, nonylphenols; PEDEs, polybrominated diphenyl ethers.

between the lake and outer sea. Since 2011, the Sihwa Tidal Power Plant (TPP) has been operating with two purposes: electric power generation and water quality improvement via maintenance of water circulation. Although tidal circulation has improved Lake Sihwa's water quality somewhat, various land-based environmental pollutants—such as dioxins/furans, organochlorines, perfluorinated chemicals, and alkylphenols—have long contaminated the lake water and bottom sediments due to the limited artificial seawater circulation (Khim & Hong 2014). More recently, to keep land-based pollutants in Lake Sihwa below set levels, the Korean government launched the Total Pollution Load Management System (TPLMS) policy program. A historical overview of environmental issues and the Korean government's action plans was provided here to highlight efforts to improve the water quality in Lake Sihwa in recent decades.

Long-term changes in the environments of Sihwa

Sea-dike construction at the Sihwa site began in 1987 and ended in 1994. The dike's original purpose was to provide a supply of freshwater from the artificial lake for agricultural and industrial uses. The maximum water capacity of Lake Sihwa was designed to be 330 × $10^6 m^3$, with a storage volume of 180 × $10^6 m^3$. After the dike construction, water quality parameters for lake bottom waters showed rapid deterioration (Figure 19). Notably, COD, which was less than 3.5 ppm in 1992

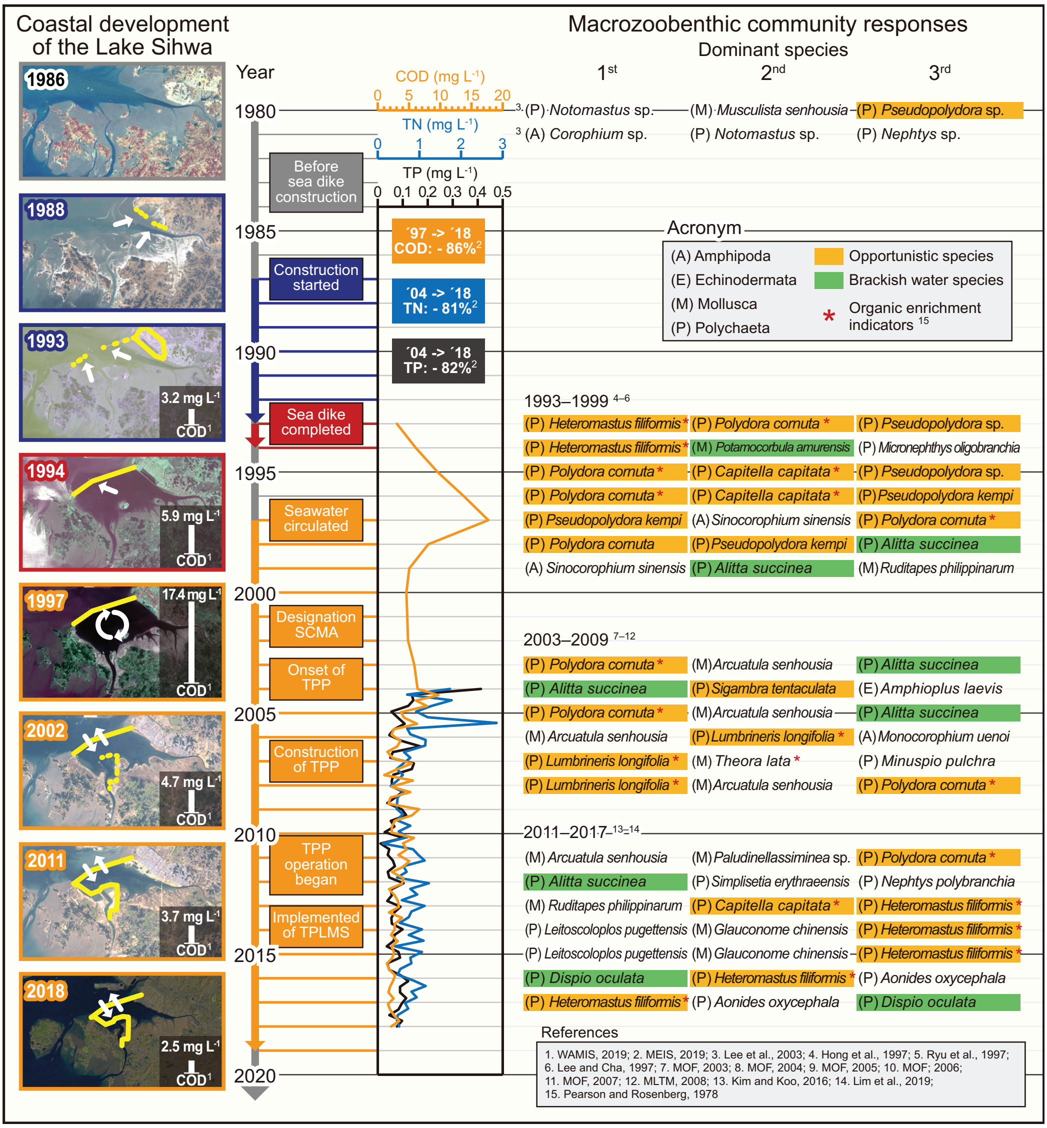


Figure 19 Top three dominant macrozoobenthos found in Lake Sihwa over time. Data are shown over the past 30 years (meta-data extracted from 14 references given), starting from before the Sihwa reclamation project. Species belonging to taxonomic groups with opportunistic species, brackish water species, and organic enrichment indicators that were found to occur in Lake Sihwa are highlighted. A brief summary of the history of the reclamation project, highlighting historical embankment activities with basic water quality data (COD, TN, and TP).

before the dike was functional, increased dramatically from 5.9 mg·L^{-1} in 1994 to 17. 4 mg·L^{-1} in 1997. Although several short-term treatments applied in response to this water quality deterioration did achieve a rapid decline of COD levels in 1997, this course correction began to plateau in 1998. Subsequently, COD levels remained around 5~6 mg·L^{-1} until 2004, after which further significant reductions in COD levels were finally achieved with the use of a sluice.

Opening of the sea-dike sluice gates allowed outside seawater to flow into the lake, thereby mixing the polluted seawater of Lake Sihwa with backfilling seawater. Although this strategy was helpful to some extent, it was not sufficient to fully circulate the lake water with seawater. Thus, construction of the TPP was proposed and implemented by the Korean government in 2004. Because the original sluice gate for Lake Sihwa was situated at the southern corner of the dike, a new gate for the TPP was required to enable the exchange and circulation of seawater and to enable electric power to be generated in a more efficient manner. Accordingly, the TPP was constructed in the middle of the dike, and it became operational finally in 2011 (Figure 19). Thereafter, COD proceeded to decrease to 2.5 mg·L^{-1} by 2015, where it has been roughly maintained until recently. The TPLMS has been exercised to reduce the input of organic materials to the lake by controlling the amounts of COD and total organic carbon levels flowing into the adjacent sea, but efficiency and management system issues have persisted.

Total nitrogen (TN) and total phosphate (TP) concentrations showed temporal patterns similar to that of COD. Although increased seawater circulation seemed to improve water quality in Lake Sihwa, the power of circulation was not enough to improve water quality satisfactorily in the whole lake (Lee et al. 2014). In terms of sedimentary pollution, among coastal Korea areas, Lake Sihwa showed the greatest concentrations of some persistent toxic substances after the completion of dike construction (Lee et al. 2014). In 2006, perfluorinated chemicals (perfluorooctane sulfonate and perfluorooctanoic acid) in the upper stream of Lake Sihwa were present at the highest levels in the world (651 and 62 ng·L^{-1}, respectively) (Rostkowski et al. 2006). Indeed, Lake Sihwa has been suffering from environmental deterioration due to land-based pollution since the early 1990s due to point sources of adjacent industrial complexes and highly populated nearby cities (Khim et al. 1999, Hong et al. 2016). Despite the partial improvement of water quality in Lake Sihwa since the commencement of TPP operation in 2011 (Lee et al. 2014), lake water quality and bottom sediment quality have remained unsatisfactory due to continuing pollution from inland industry sources and densely populated cities (Hong et al. 2016).

Long-term changes in Sihwa benthic communities

The macrozoobenthic community in Lake Sihwa changed in response to habitat condition alterations primarily attributable to the new dike. To determine the ecological responses of the macrozoobenthic community, macrozoobenthos species dominance was analyzed over the past 36 years (Figure 19). The benthic community at Lake Sihwa was significantly affected by hypoxia or anoxic bottom conditions, seemingly due to organic enrichment (Lee et al. 2014, Lee & Khim 2017). There were clear changes in dominant macrozoobenthos species following sea-dike construction. Opportunistic species, such as *Heteromastus filiformis*, *Pseudopolydora kempi*, and *Capitella capitata* were more abundant after construction of the sea dike.

Several previous studies demonstrated clearly that dike construction and sluice closure caused various adverse ecological effects due to limited tidal mixing (decrease in assimilative capacity), water stratification, eutrophication, algal blooming, and increased pollutant load from the watershed (Lee et al. 2014, Lee & Khim 2017). Of note, the COD in Lake Sihwa reached 17.4 mg·L^{-1} in 1997, at which time the direct waste treatment plant's discharge outlet was moved to outside of the lake. Rapid COD increases were associated directly with low tidal mixing after sluice closure. However, after commencing active seawater circulation through the sluice in the late 2000s, COD levels began to decrease rapidly in the 2010s, reaching levels last seen in the early 2000s.

The benthic community of Lake Sihwa would have been directly affected by the sedimentary pollution concomitant with the observed water quality deterioration. Indeed, brackish water species, such as the polychaete *Alitta succinea*, became dominant during the period of limited tidal mixing (Figure 19). The combination of blocked tidal connectivity and continuing freshwater input seemed to alter the composition of the lake's macrofauna. Subsequent long-term changes in dominant species tended to reflect the historical sedimentary pollution (Lee et al. 2014, Lee & Khim 2017).

In terms of species richness and evenness, macrozoobenthos diversity decreased while a small number of opportunistic species exhibited rapid population increases (Lee et al. 2014). Specifically, a prevalence of polychaetes emerged after dike construction, with the numbers of opportunistic polychaetes (e.g. *Pseudopolydora kempi* and *Polydora cornuta*) increasing drastically right after the dike was constructed in 1994 until the COD peak in 1997. The predominance of opportunistic species and organic enrichment indicators seemed to decline after the TPP became operational in 2005. However, they are still present, reflecting long-term polluted bottom conditions. Positive effects of TPP operation have been acknowledged in some aspects of water quality, though the status of benthic community recovery in the lake continues to be debated. Continued monitoring of the benthic community is needed to fully address the long-term effects of the coastal reclamation in Lake Sihwa.

Long-term human impacts on marine ecosystem: Saemangeum reclamation

Backgrounds and overview of Saemangeum issue

Estuaries are ecological hotspots and buffering zones; they support and contribute to various ecological processes across terrestrial, brackish, and marine ecosystems in an integrated manner (Gray 1997). Tidal flats that develop in the critical transition zones constituted by estuaries play an important socioecological role in supporting diverse marine ecosystems (Levin et al. 2001, Wall et al. 2001). However, about half of the Korean estuaries situated along the west and south coasts of Korea have been blocked at the estuarine mouth and/or in the upper rivers by seawalls and/or dams. The worst example of coastal reclamation in Korea is the Saemangeum project, which was designed to achieve a massive inland land-gain of 400 km^2 (about 2/3 the size of Seoul, which is ~600 km^2) for urban development by estuarine filling.

In 2006, two large estuaries at Mangyung River and Dongjin River in the Saemangeum tidal flat area were isolated from ocean waters by the world largest seawall (33.9 km). The Saemangeum seawall was built in four sectors. Sector III (2.7 km, Sinsido to Yamido) was completed in 1994. Sector I (4.7 km, Buan to Garukdo) was completed in 1998. Sector IV (11.4 km, Yamido to Gunsan) was completed in 2003. And finally, Sector II (9.9 km, Garukdo to Sinsido) was completed in 2006 (Figure 20). The former tidal flats that had developed in these estuaries extended seawards some 5~10 km, covering an area of ~180 km^2 and constituting the largest tidal flat area in Korea. The entire marine and estuarine ecosystems of these areas are expected to be destroyed consequent to water quality deterioration and sedimentary pollution due to limited seawater circulation and tidal mixing, as was experienced previously in the Sihwa reclamation case. Rich and productive benthic communities were documented before the dike construction, and observations of benthic community changes, from microphytobenthos to macrozoobenthos, were reported during and after the construction of the dike (Ryu et al. 2014).

The Saemangeum project was launched by a commitment that the president of Korea made in the late 1980s. Work commenced in 1991 with political support. The environmental issues and Korean government's actions at Saemangeum from 1991 to the present are summarized in Table 5. There have long been social conflicts between proponents for and antagonists against such projects involving central and local governments as well as varying stakeholders from local residents to

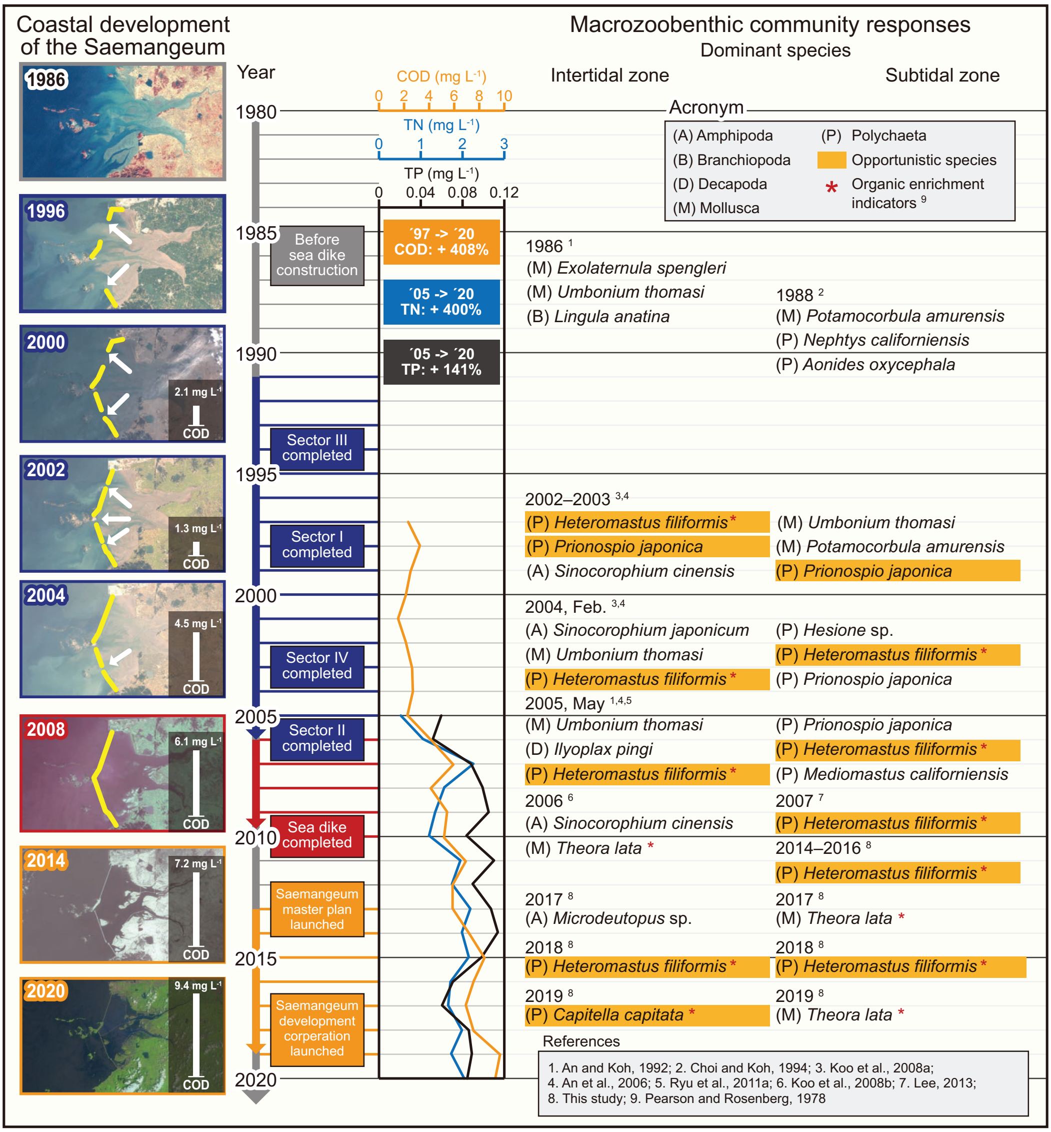


Figure 20 The dominant macrozoobenthos found in the Saemangeum tidal flats since during the Saemangeum reclamation project, over the past 30 years (meta-data extracted from nine references given). Species belonging to five taxonomic groups with opportunistic species, and organic enrichment indicators in the intertidal and subtidal zones of the Saemangeum area are highlighted. A brief summary of the history of the Saemangeum reclamation project is shown, highlighting historical embankment activities with basic water quality data (COD, TN, and TP) in the Saemangeum area.

environmental NGOs. Conflict over the Saemangeum project arose in light of the lessons of Lake Sihwa reclamation case described above. In the middle of project, construction was paused for re-evaluation of the project's feasibility in 1999 and then resumed in 2001 based on a top-down order from the Korean government.

Debates on the Saemangeum project continued, culminating in a remarkable public movement in 2003 led by religious leaders wherein more than 8000 participants chanted *Samboilbae* ("three steps and one bow"). The participants completed a walk of about 300 km from the Buan tidal flat of Saemangeum

Table 5 Summary of progress on political and sociological issues, environmental conditions, and ecological responses to the Saemangeum reclamation project

Year	Progress	Political and sociological issues	Environmental conditions	Ecological responses
1991	Sea-dike construction began			
1994–1995	Sector III completed (2.7 km, 94)	SMG industrial complex plan announced (95)		
1996–1998		Highlighted Lake Sihwa pollution (96); Argued reasonable fishery compensation (97)		Shellfish catch sharply decreased (91–98)
1999	Construction stopped	SERP organized holding for dike construction	>95% reduction in land-based nutrient loading in tidal flats	
2001–2002	Construction resumed (01); environmental monitoring (02–12)	Sustainable, stepwise developmental planning followed by continuing construction (01)		
2003–2005	Sector IV completed (11.4 km, 03)	"Three steps and one bow" campaign against reclamation (03); government lost first trial, but won appeal to SAC (05)	Organochlorine pesticides from two rivers widely distributed in seawater and sediments	Macrofaunal assemblages in intertidal areas were changed and/or altered (Ryu et al. 2011a; 04–05)
2006–2008	Sector II completed (9.9 km, 06) Sea-dike construction completed (06)	Government won at the Supreme Court (06) Established the Special Act for promotion of the SMG Project (07)	Sedimentation increased and strong erosion (06) River inputs induced stratification in waters inside dike	Shorebird composition clearly changed (06) Great decrease of species number and density in tidal flat (Koo et al. 2008b; 08)
2011–2013	SMG Master Plan launched (11) Launched the Korea Agency for SMG Development and Investment (13)			30% reduction in fishing boats (11), and >200 finless porpoises died, due to freezing water surfaces within dike (11)
2016–2018	Operation of SCTP Cogeneration Plant SMG New Port Breakwater Completion	Launch of SMG Development Corporation Amendment to establish SMG Development (18) Corporation with juristic personality (18)		

Abbreviations: SMG, Saemangeum; SERP, Saemangeum Expert Review Panel; SAC, Seoul Administrative Court; SCTP, Saemangeum Cogeneration Thermal Power Plant.

to the Presidential Blue House in Seoul, Korea. This protest caused a great sensation and led to a historic change in the Korean public view, which shifted to favour conservation over development.

The project itself was subjected to legal actions. However, upon winning the final court decision in 2006, the government resumed the project, which led to the loss of the once majestic natural tidal flats of Saemangeum. In 2007, the Special Act on the Promotion of the Saemangeum Project was passed, and the Saemangeum Master Plan was established to further promote the development of the landfilled area in 2011 (Table 5). The Saemangeum area is being developed currently, but the plan continues to be debated.

The Saemangeum case shows a policy failure with respect to protective estuary and coastal management in Korea. The natural value of the flats, ecologically and socioeconomically, was underestimated (Koh et al. 2010). All five major rivers flowing into the sea are now effectively closed estuaries due to seawalls at the river mouth or multiple upstream dams. The mouths of the estuaries of the Han River and Seomjin River are open to the sea, but they have water and sediment quality problems due to upstream dams. Although some development of limited dams is necessary, large-scale coastal reclamations involving seawalls should not be acceptable given their enormous socioeconomic cost and the associated loss of ecosystem services.

Long-term changes in Saemangeum environments

Environmental deterioration consequent to the Saemangeum reclamation has been anticipated since the late 1990s, before the dike was completed, based on several early signs. Water quality and sediment quality deterioration was already evident in 1999–2000. First, water quality parameters (COD, TN, and TP) for bottom waters changed dramatically in the interior of the dike (Figure 20). In particular, COD concentrations increased rapidly after the completion of Sector IV in 2003; these increases can be attributed to water column stratification due to limited tidal mixing (Figure 20). Although there are no COD data available for the pre-dike Saemangeum area, a continuously increasing COD trend has been observed since the completion of the dike in 2006, with data from the most recent year available, 2019, indicating that COD levels in the Saemangeum reached 9.7 $mg{\cdot}L^{-1}$. This level far exceeds the standard water quality guidelines for COD in Korean coastal and marine areas, indicating that the situation is highly concerning.

After Sector II was constructed in 2006, TP concentrations increased sharply and they have remained high for almost 10 years. From 2014 to 2017, TP concentrations fell gradually, perhaps owing to the temporary measures of the water quality improvement project implemented by the local government in Jeollabukdo. By 2017, TP concentrations had decreased to about 52.9% of 2011 levels. However, since 2017, TP concentrations in the Saemangeum have again been increasing due to increased nutrient input and particulate organic matter from river inflows. Lower density freshwater and summer heating favour the formation of a thermocline and vertical stratification in the water column interior to the dike. TN levels have remained relatively constant since their peak in 2007, not yet reflecting water quality improvement.

The direct effects of the Saemangeum dike seem to be to reduced volume, velocity, and duration of tidal inflows, effects that would be expected to alter benthic geochemical conditions (Park et al. 2014b). Furthermore, the dike and the altered tidal currents associated with its presence stimulate surface sediment erosion (Lie et al. 2008). These physical regime shifts can alter natural biogeochemical cycles, including those related to benthic community structure and function. In particular, the concentrations and fluxes of particulate organic matter in coastal areas within and outside the Saemangeum dike have changed dramatically in recent years (personal observation by the first author in 2020).

Long-term changes in benthic communities of Saemangeum

The benthic community structure was altered during the dike construction (2002–2006), due to bottom layer hypoxia associated with water column stratification as well as changes in sediment faces owing to altered sedimentary dynamics (Ryu et al. 2014). In addition, many fishermen have reported fishery reductions in harvestable shellfishes and fishes in tidal flats and coastal areas since completion of the dike. For example, increased deposition of fine sediments on tidal flats near Sector IV resulted in decreased macrozoobenthic diversity and increased opportunistic species in

2002–2003 (Koo et al. 2008a). Numerous adverse ecological effects of the Saemangeum dike construction have been documented for numerous marine organisms, including microbiota (Choi & Noh 2008), zooplankton (Lee et al. 2009), and waterfowl (Jin et al. 2010, Kang et al. 2011).

In the present review, we collected long-term macrozoobenthos data from the Saemangeum area and then analyzed benthic community changes longitudinally in response to environmental changes (Figure 20). Fortunately, before the Saemangeum project began, studies on macrozoobenthos (An & Koh 1992) and microphytobenthos (Oh & Koh 1995) had been conducted, establishing the natural baseline benthic community conditions for the area. In general, the macrobenthic faunal composition showed two clear temporal trends. First, increases in proportions of polychaetes, particularly in the subtidal zone, occurred after the dike was constructed. Second, increased proportions of opportunistic species and/or indicator species for organic pollution/enriched sediments were evidenced during and after dike construction, in particular the predominance of two opportunistic polychaete species, *Heteromastu filiformis* and *Prionospio japonica*. *H. filiformis* was a widespread polychaete species in the West Sea (Figure 20), whilst *Prionospio japonica* could be an opportunistic local species associated with the Saemangeum reclamation event.

After dike construction in the Saemangeum, the population density of previously dominant species in the intertidal zone, including a molluscan species, *Exolaternula spengler*, and a brachiopod species, *Lingula anatina*, decreased dramatically (Ryu et al. 2011a,b). Dominant species in the subtidal zone also showed a pronounced temporal change in the faunal composition of macrozoobenthos, and such temporal change might reflect more dynamic environmental changes that are directly linked to long-term benthic community alterations.

Macrozoobenthic community data for the Saemangeum tidal flats evidenced long-term and ongoing alterations in macrozoobenthic community responses to environmental deterioration. There remains a knowledge gap regarding long-term benthic community changes to fauna and flora. Likewise, there are limited data available from before the dike was constructed. We realize, and would like to emphasize, the critical importance of baseline and monitoring data to address long-term ecological changes, particularly in the Saemangeum case (Reise 2012). Without such basic long-term data, it would be difficult to address the status and trends of marine biodiversity in the Saemangeum region, and elsewhere, adequately. Considering the ongoing events affecting the Saemangeum flats, further accumulation of benthic community data is needed.

Long-term human impacts on a marine ecosystem: Taean oil spill

Backgrounds and overview of the Taean case

The HSOS occurred on the 7 December 2007, less than 10 km offshore of Taean County on the west coast of Korea. Approximately 13 million liters of crude oils, including three types of oils (Iranian Heavy, United Arab Emirates Upper Zakum, and Kuwait Export), spilled into ecologically sensitive areas of the coastline near Taean (Hong et al. 2014, Yim et al. 2017). The spilled crude oil reached the nearby shore within 14 h of the spill; the oil slick was 33 km long, 10 m wide, and 10 cm thick after two days (Sim et al. 2010), and it was distributed in intertidal areas, covering pacific oyster farms and natural beaches (Kim et al. 2017). Historically, the HSOS was the largest oil spill in the Korean waters and remains one of the largest recent oil spills in the world, second only to the Deepwater Horizon oil spill in the Gulf of Mexico in April 2010.

The Korean Government and local authorities responded to the HSOS immediately by placing tremendous efforts on implementing a comprehensive cleanup over several months (Table 6) (MLTM 2009, Hong et al. 2014). There was an intensive human endeavor (>2.1 million people) that included some 1.2 million volunteers and 0.9 million residents, military personnel, and others, during the cleanup period (Hong et al. 2014). Cleanup activities at sea and in the onshore areas of

Table 6 Summary of the Hebei Spirit Oil Spill (HSOS) accident and HSOS cleanup activities in marine and coastal area

HSOS occurrence	Location	~10 km off Taean County	
	Month/Day/Year	December/07/2007	
	Amount of spilled oil	12,547 kL	
	Type of spilled oils	Kuwait Export Crude Iranian Heavy Crude UAE Upper Zakum	
	Polluted areas	375 km of Korean west coast (total 1300 km^2)	
Cleanup activities	Ships	KCG	6630
		KOEM	889
		Navy	723
		Others	11,968
		Total, units	20,210
	Heavy machinery	Truck	9991
		Excavator	5559
		Tractor	1304
		Others	12,119
		Total, units	28,973
	Personnel	Volunteers	1,226,730
		Residents	566,343
		Military personals	152,695
		Public officers	76,684
		Others	249,884
		Total no. of individuals	2,122,296
	Cleanup materials	Oil boom, km	47
		Oil absorbent, kg	493,127
		Dispersant, kL	298
	Cleanup cost	USD	~330 M
Oil collection	Liquid oil	At sea	2360
		On shore	1815
		Total (kL)	4175
	Oil wastes	At sea	1034
		On shore	31,040
		Total (Tons)	32,074
Research	Fund and duration	US ($)	~23 M, 10 years

Source: Modified from KCG (2008) and Hong et al. (2014).

Abbreviations: KCG, Korean Coast Guard; KOEM, Korea Environment Management Corporation; M, million.

Taean were officially terminated in October 2008. However, oil persisted in the deeper subsurface sediments (>20 cm below the surface) and in the most heavily affected intertidal areas of Taean for at least 24 months after the spill (Hong et al. 2014).

Oil spills can cause a wide range of adverse ecotoxicological effects by way of physico-chemical pollution of diver marine environments with effects across habitat areas (intertidal and subtidal) and sediment types (muddy, sandy, and rocky shore), thereby affecting resident organisms. The short-term environmental impacts of an oil spill can be severe, including the infliction of serious physiological distress and mortality upon individual marine organisms. Indeed, the intertidal and nearby shallow subtidal ecosystems of Taean are healthy and productive encompassing diverse habitats such as rocky shores and sand beaches, but most oil-sensitive marine organisms were eradicated immediately by the spill (Yu et al. 2013, Seo et al. 2014b). Fortunately, due to the open coastal regime with high tidal energy together with extensive initial cleanup activities after the spill, the coastal ecosystem recovered faster than ecosystems impacted by other oil spills, such as the EXXON VALDEZ case (Yim et al. 2020). Notwithstanding, contamination hotspots are still found in intertidal areas, where residual oils still remain in subsurface layers until present day, underscoring the need for continued monitoring (Yim et al. 2012).

The present macrozoobenthos meta-dataset was collected from long-term ecological monitoring data for the HSOS and some independent ecological studies of the HSOS effects. In the present review, we delineated the recovery timeline of macrozoobenthos in four typical coastal areas of Taean, encompassing intertidal sandflats, intertidal mudflats, intertidal rocky shores, and the subtidal zone over a period of about seven years.

Long-term changes in Taean coast environments

Crude oil is composed mainly of hydrocarbons, including aromatic hydrocarbons, such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). Aromatic hydrocarbons accounted for approximately 30% of the spilled oils from the HSOS (Ha et al. 2012). All of the VOCs evaporated within a few days after the accident as follows: benzene – 10 hours; toluene, ethylbenzene, and xylene – 48 hours; and other VOCs – ≤4 days (Kim et al. 2012). Several carcinogenic compounds, including PAHs, remained for weeks to months; PAHs can be highly persistent in environmental media and thus can bioaccumulate over time (Lee et al. 2013).

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). Other factors affecting degradation include microbial community and activity (Lee et al. 2019), natural energy (e.g. tidal flushing) (Hong et al. 2012), and even degree of initial cleanup activity (NOAA 2013). Residual oils are more persistent in sediments than in seawater, especially in low-energy regions (Hong et al. 2012, Yim et al. 2012, Kim et al. 2017). In addition, the adverse effects of residual oils on marine organisms depend on initial oil concentrations and the degree of oil weathering, which is further dependent on site-specific tide-associated exposure conditions (Hong et al. 2012). Indeed, in the Taean environment, oil weathering seemed to have a strong influence on the persistence of residuals and potential toxicities, particularly in intertidal benthic hotspots. Residual oil trapped in the bedrock along the rocky shores accumulated over long periods in the bottom layer, due to the lack of natural weathering.

Immediately after the HSOS, very high maximum concentrations of total petroleum hydrocarbons (1630 $\mu g \cdot g^{-1}$), PAHs (3350 $ng \cdot g^{-1}$) and alkylated PAHs (66,430 $ng \cdot g^{-1}$) were recorded (Figure 21). These peak concentrations would be expected to have direct adverse effects on intertidal organisms. The spatial distributions of PAHs in sediments varied widely, both regionally on the west coast and within Taean County, primarily due to the patchy distribution of spilled oil and non-uniform sediment characteristics (Hong et al. 2012). In general, PAH concentrations in intertidal sediments decreased over time—except for in hotspot areas, particularly in the intertidal zone—with relatively high concentrations being recorded in the subsurface layer (Hong et al. 2012; Hong et al. 2014) (Figure 21). For example, in March 2014, the concentrations of 16 PAHs and alkylated PAHs in sediments ranged from 0.42 to 74.8 $ng \cdot g^{-1}$ and from 0.56 to 50.9 $ng \cdot g^{-1}$, respectively. However, at the Sinduri and Sogeunri mudflats, high concentrations of alkylated PAHs were observed, remaining as oil contamination hotspots. Analyses of the compositions of alkylated chrysenes and dibenzothiophene homologues in mudflats with elevated PAHs showed that mudflats continued to be impacted by spilled oil residues. Six years after the HSOS, concentrations of PAHs and other chemicals settled into normal environmental levels in Taean and along the nearby coast, with the exception of the Sinduri hotspot.

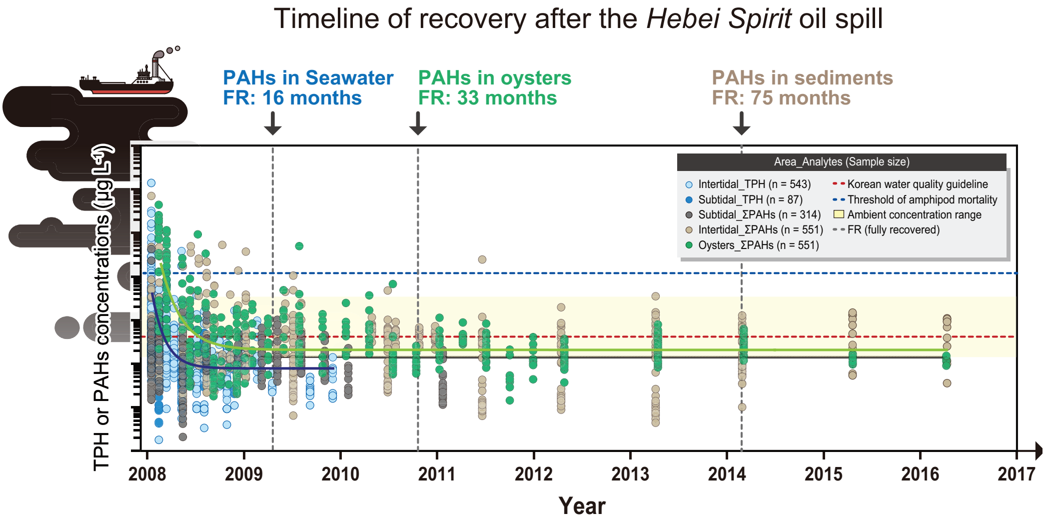


Figure 21 Temporal variations in residual oil concentrations in multiple environmental samples from different sources in the Taean coast, Korea. Concentrations of total petroleum hydrocarbon (TPH) and PAHs in seawater were checked after 16 months; those in sediment collected from intertidal and subtidal areas were measured after 75 months. Temporal variation in PAHs (including alkyl-PAHs) in oysters collected from intertidal areas in the Taean subregion was monitored. Fitted curves were obtained based on residual oil concentrations and the number of months after the oil spill using an exponential decay model. Yellow-shaded sections represent the ambient PAH concentration ranges in sediments on the west coast of Korea. The two dotted lines represent the Korean water quality guideline (red) and the threshold value of amphipod mortality (blue).

Long-term changes in benthic communities of the Taean coast

A dynamic marine environment shows substantial fluctuations in abundance and diversity as a feature of their normal functioning. These fluctuations evidence the strong capacity of marine environments for natural recovery from severe perturbations caused by natural phenomena as well as anthropogenic pressures, such as an oil spill. The HSOS impact has been evaluated extensively with respect to marine organism responses and recovery status. For example, a recent review indicated that the recovery period for macrozoobenthos varied across taxa and habitat, but generally spanned five to six years for the HSOS. The relative abundance of opportunistic bivalve species *Felaniella sowerbyi* had increased within eight months of the catastrophic mortality of the previous community (Figure 22). After other benthic species, such as polychaetes, expanded, the relative abundance of initial colonizers began to decline during the partly recovered stage. Over time, the initial community was seemingly eliminated through competition with species from higher trophic levels via complex biological interactions.

Four categories of habitat, namely intertidal sandflat, intertidal mudflat, intertidal rocky shore, and subtidal zone, were examined for macrozoobenthos community recovery at a population level (Figures 22–25). The number of macrozoobenthic species in the intertidal sandflat ranged from 94 to 114 during the sampling period, with a mean density of 1688 individuals (ind.)·m^{-2}. One year after the spill, the number of species and biodiversity of macrozoobenthos in the oil-impacted area continued to increase, but remained low compared to that of lesser oil impacted areas. After 2014, the density of macrozoobenthos increased in lesser impacted areas, but decreased in the oil impacted area. The most dominant species, *Felaniella sowerbyi*, which decreased at Sinduri and Mallipo in 2011 and 2012, respectively, increased in the oil impacted area after 2014. Two species that were dominant before the oil spill, *Umbonium thomasi* and *Scopimera globosa*, had low densities in the oil impacted area until 2014. Since 2010, the number of species has increased gradually, with current species diversity similar to non-polluted west coast areas.

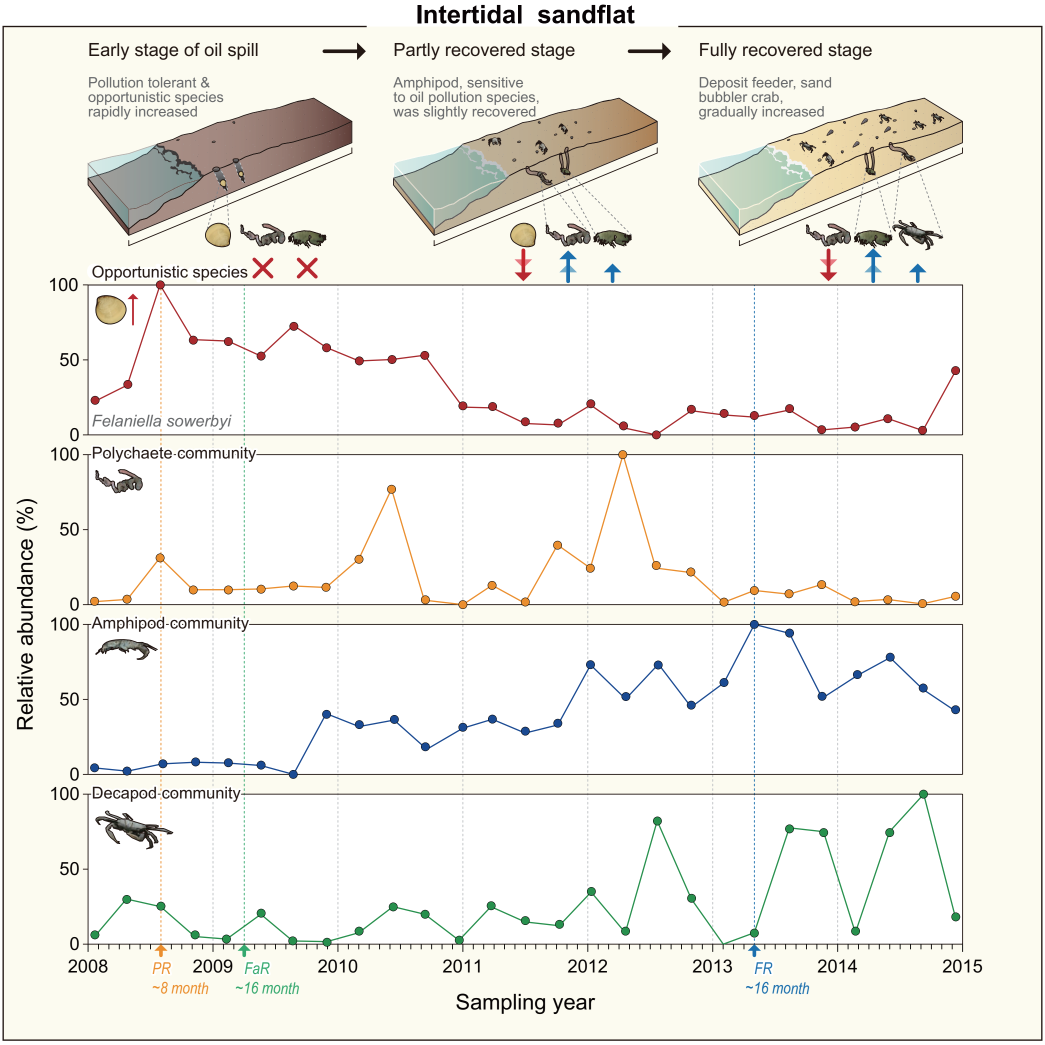


Figure 22 Schematic diagrams showing macrozoobenthic community recovery and colonization in oil spill-affected intertidal sand flats. Red/blue arrows indicate decreasing/increasing trends in relative abundance of benthic communities in the oil-contaminated environment.

Next, the impact of the oil spill on the macrozoobenthic community was assessed in the intertidal mudflat of Sogeunri (Figure 23). It was analyzed relative to the control area of Keunsoman. We found that the number of species, density, and diversity of macrozoobenthos at Sogeunri continued to increase after 2011, with signs of a strong recovery. The number of species and density differed between the two areas in 2014. Of note, the recovery at both areas showed some varied features depending on tidal conditions, such that differences in number of species or faunal density were observed only between upper to lower zones at Keunsoman. Although opportunistic species did not occur in the low tidal zone at Keunsoman, abundant *Ruditapes philippinarum* individuals were observed. Meanwhile, the nereid polychaete species, *Perinereis aibuhitensis*, was detected only at Sogeunri.

The intertidal rocky shore showed another feature in macrozoobenthos recovery. Macrobenthos on rocky shores in the mid-shore areas of polluted sites at Padori were analyzed (Figure 24). At the polluted sites, the ecological index increased gradually after 2009, with minimal fluctuations since

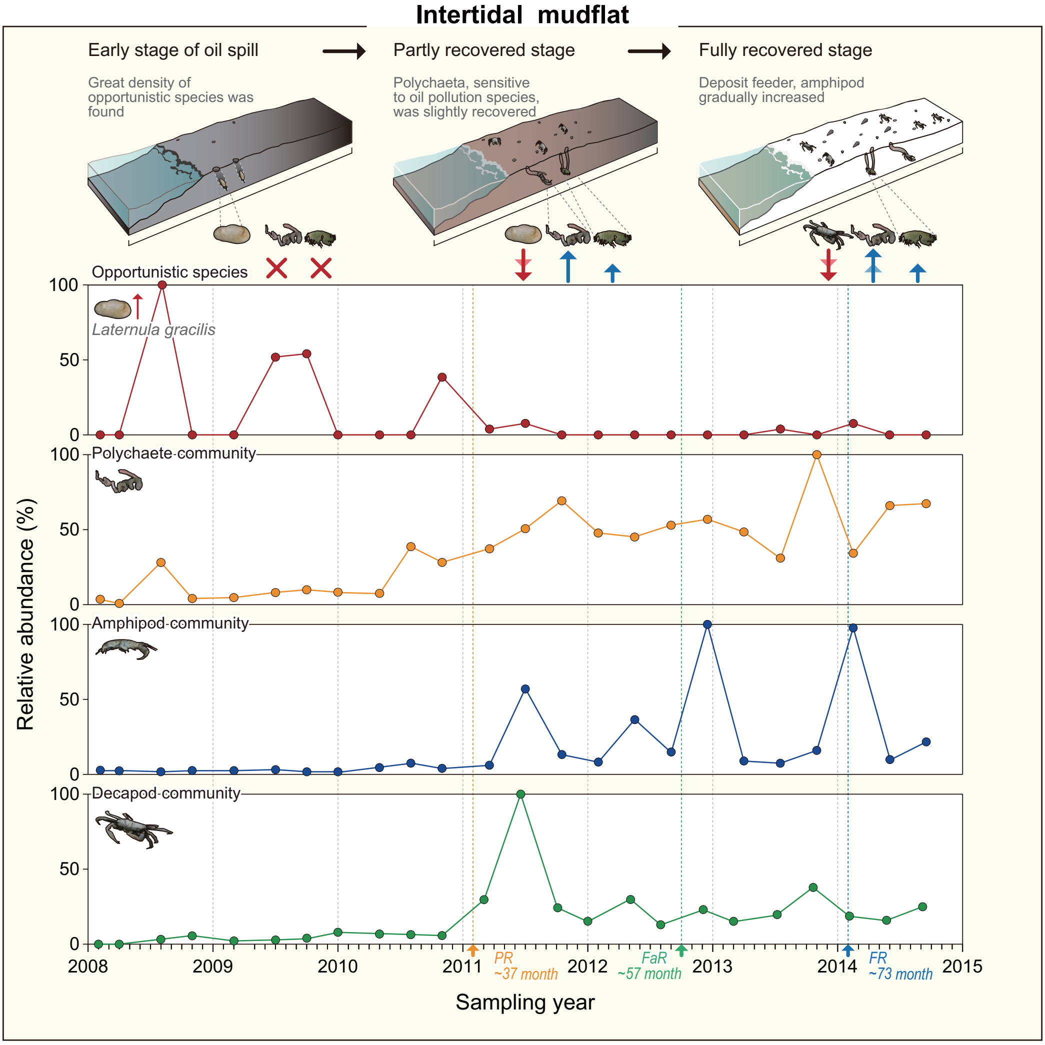


Figure 23 Schematic diagrams showing macrozoobenthic community recovery and colonization in oil spill-affected intertidal mudflat. Red/blue arrows indicate decreasing/increasing trends in relative abundance of benthic communities in the oil-contaminated environment.

2012, indicating a rapid recovery of diversity. However, the mean density remained below 50% of that at the control site, indicating partial recovery at the oil impacted rocky shore. By 2014, both diversity and density at the polluted sites were similar to (or higher than) those at the control site at Yeonpo, reflecting a full recovery. Correlational analyses of dominant species indicated that the recovery of *Crassostrea gigas*, a habitat forming bivalve, had an important influence on the overall recovery of macrozoobenthos on rocky shores. The proliferation of *Crassostrea gigas* in the oil spilled site can be regarded as one indicator of general ecosystem which is recovering in similar environments as it provides habitat for a diversity of other organisms.

Finally, the macrozoobenthos communities inhabiting soft subtidal bottoms were assessed to observe the impacts of the oil spill in the deep-water zone (Figure 25). We found that species richness decreased continuously from spring to summer of 2008, indicating adverse acute impacts of submerged oils on macrozoobenthic community health. However, the number of macrozoobenthic species and their density increased after the summer of 2009 at almost all locations. By July 2012,

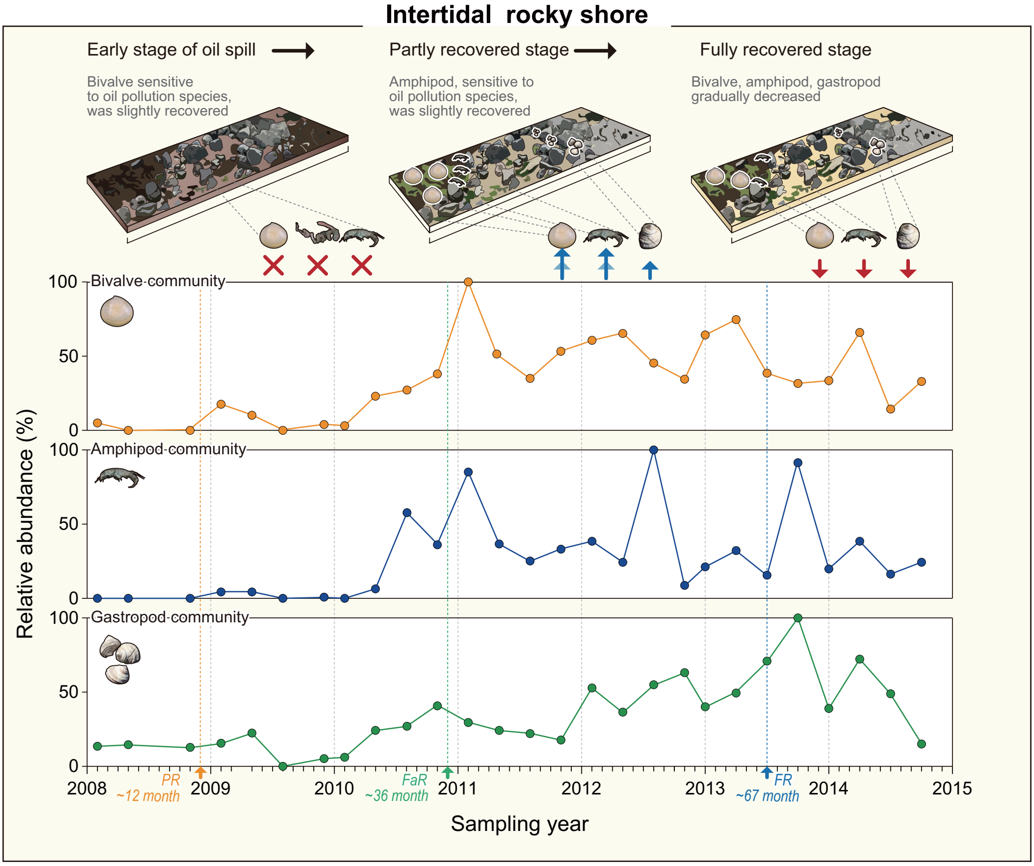


Figure 24 Schematic diagrams showing macrozoobenthic community recovery and colonization in oil spill-affected intertidal rocky shore. Red/blue arrows indicate decreasing/increasing trends in relative abundance of benthic communities in the oil-contaminated environment.

over 40 macrozoobenthic species occurred in the subtidal zone, with a density of 1769 ind.·m^{-2}, reflecting a more rapid recovery than in the intertidal mudflats. These numbers declined again after 2013, which might reflect a natural fluctuation rather than effects from residual oils.

Management of the Korean coasts and marine biodiversity

The legal framework of coastal management

The current conservation strategy for coastal areas in Korea was implemented primarily through the establishment of the Conservation and Management of Marine Ecosystem Act, Marine Environmental Management Act, and Wetlands Conservation Act. These three documents establish fundamental principles of ocean conservation policy at a national level. The shared purposes of these acts are (1) to protect marine ecosystems from artificial damage and to conserve or manage marine ecosystems in a comprehensive and systematic manner; and (2) to provide the resources necessary for marine pollution prevention, improvement, response, and recovery.

The aforementioned acts establish marine protected areas (MPAs), of which there are eight types, each of which serves a specific purpose. Currently in Korea, there are five Specially Managed Sea Areas (SMSAs), four Environmental Preservation Sea Area (EPSAs), eight Fishery

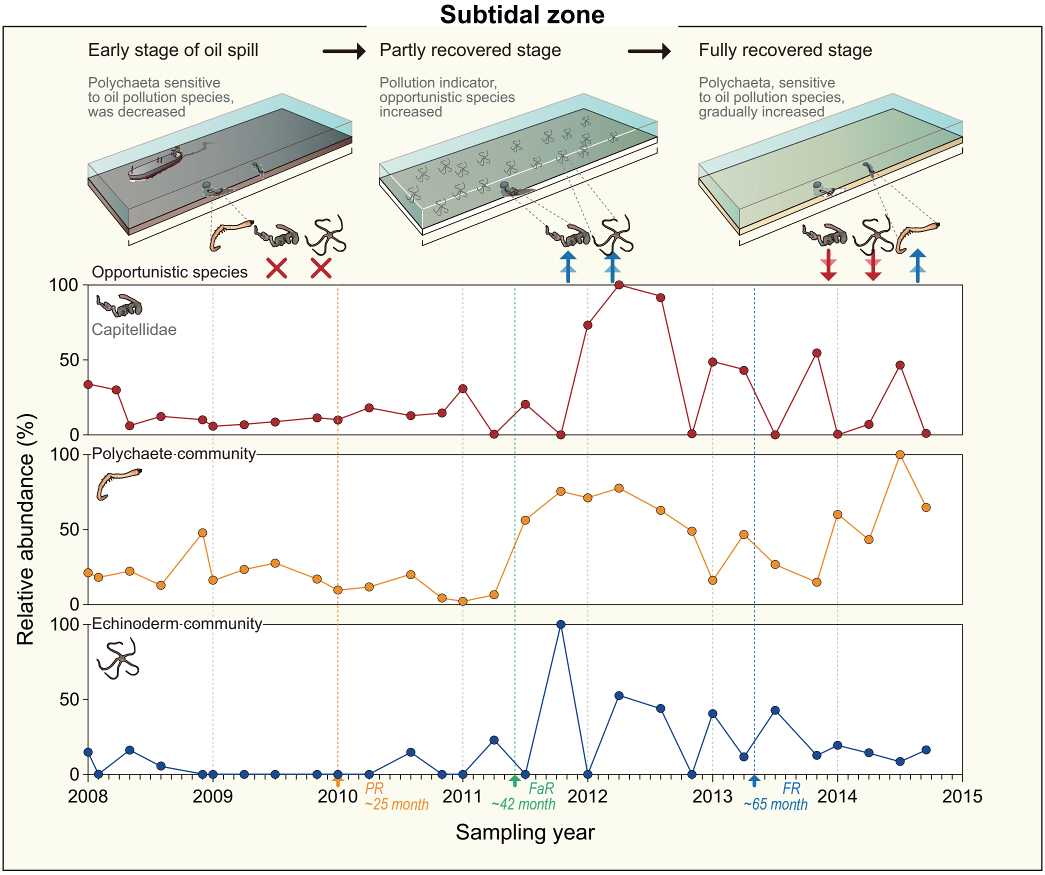
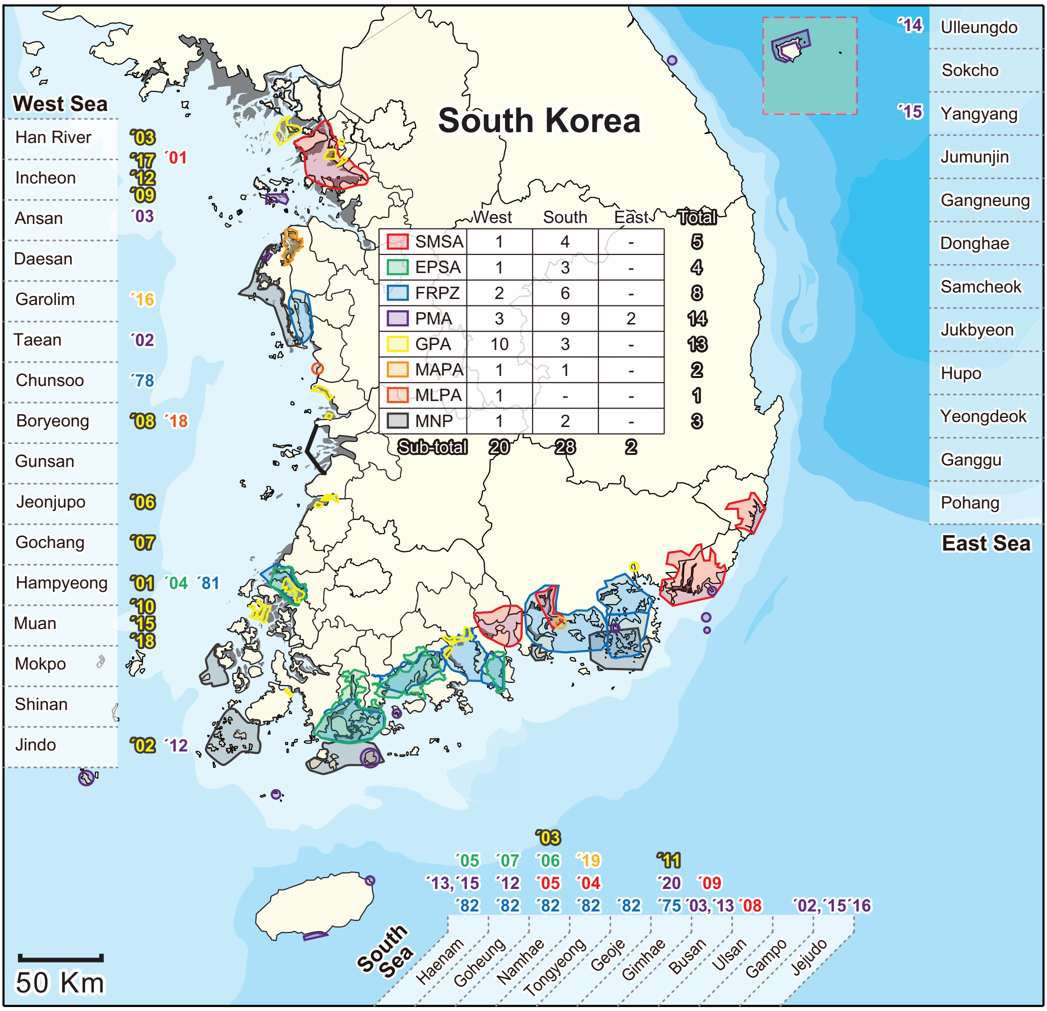


Figure 25 Schematic diagrams showing macrozoobenthic community recovery and colonization in oil spill-affected subtidal zone. Red/blue arrows indicate decreasing/increasing trends in relative abundance of benthic communities in the oil-contaminated environment.

Resources Protected Zone (FRPZs), fourteen Protected Marine Area (PMAs), thirteen Getbol (mudflat) Protected Areas (GPAs), two Marine Animal Protected Area (MAPAs), one Marine Landscape Protected Area (MLPA), and three Marine National Parks (MNPs). The locations and aerial coverage of these MPAs along the Korean coasts are shown in Figure 26.

A total of 50 MPAs (localities) have been designated along the coasts of Korea in the West Sea (20 areas), South Sea (28 areas), and East Sea (2 areas). The only two designated MPAs along the coast of the East Sea are Ulleungdo and Dokdo which were identified for protection first because they have high marine biodiversity and they provide valuable marine ecosystem services that need to be protected and managed for sustainability and second because they are in need of immediate attention due to past or ongoing ecological deterioration.

The six categories of MPAs (FRPZ, GPA, PMA, MAPA, MLPA, and MNP) address the first reason for protection mentioned above. That is, it is hoped that the marine biodiversity, ecosystems, and ecosystem services (e.g. fisheries and coastal seascape) of these areas can be sustained long term. Within the MPA strategy, GPAs have the longest history. A total of 13 tidal flat sites have been designated as GPAs since 2001: Muan (2001), Jindo (2002), Suncheon (2003), Boseong and Beolgyo (2003), Ungjin and Jangbong (2003), Buan and Julpo (2006), Gochang (2007), Seocheon (2008), Songdo (2009), Sinan (2010, 2015, 2018), Masan Bongam (2011), Siheung (2012), and Daebu (2017). These designations represent a fragmented approach to protecting and managing tidal flats in that



	West	South	East	Total
🟥 SMSA	1	4	-	5
🟩 EPSA	1	3	-	4
🟦 FRPZ	2	6	-	8
🟪 PMA	3	9	2	14
🟨 GPA	10	3	-	13
🟧 MAPA	1	1	-	2
🟥 MLPA	1	-	-	1
⬜ MNP	1	2	-	3
Sub-total	20	28	2	

Figure 26 Map showing the location and aerial coverage of eight types of protected areas on the coast of Korea. Each number represents the year when the protection area was designated.

selected localities are designated despite the tidal flats being extensively and continuously developed along the west and south coasts of Korea. This fragmentation reflects the independent management systems across local governments and perhaps weak policy management power. In terms of protection effectiveness and management philosophy, the Trilateral Cooperation on the Protection of the Wadden Sea—which involves Denmark, the Netherlands, and Germany—provides a model of integrated policy for the management of tidal flats.

Regarding the aforementioned need for immediate attention, two cases of coastal and marine pollution should be considered. First, an SMSA was designated to manage inland and adjacent coastal areas to control land-driven coastal pollution. Within this area, the land and coastal areas should be managed as one unit in an integrated manner. Five areas have been designated as SMSAs for this purpose: Sihwa (2001); Incheon (2001); Masan (2004); Gwangyang (2005); Ulsan (2008); and Busan (2009). These areas have long experienced severe land-driven pollution due to elevated industrial and urban activities in recent decades that have resulted in severe coastal and marine pollution (Khim & Hong 2014). EPSAs are designated in sea areas with direct susceptibility to marine pollution from lands to protect and manage coastal and marine resources, such as fisheries. The four bay regions have been designated as SMSAs: Wando and Doam Bay (2005), Gamak Bay (2006), Dukryang Bay (2007), and Hampyeong Bay (2009).

Management of marine biodiversity in Korea

Apart from spatial management, the Korean government seeks to protect ecologically important marine and wildlife species in marine ecosystems. These activities are conducted by the Ministry of Oceans and Fisheries (MOF), the Ministry of Environment (MOE), and the Cultural Heritage Administration (CHA) (Table 7). These agencies are charged with the protection or management of five categories of marine organisms: (1) marine organisms under protection; (2) harmful marine organisms; (3) organisms disturbing marine ecosystems; (4) endangered wild marine fauna species; and (5) cultural heritage species.

The term “marine organisms under protection” was established by the MOF in 2006 on the basis of the Conservation and Management of Marine Ecosystems Act (Article 2, Subparagraph 11). The MOF interprets this term as being inclusive of organisms in the following categories: (1) endemic species inhabiting Korean waters; (2) species with a marked decrease in their population size or density; (3) species with high academic or economic value; and (4) species with high international protection value. The MOF designated 46 protected species in 2007, and the number of protected species is presently 80. They include 16 mammals, 7 algae/sea grasses, 4 reptiles, 5 fishes, 14 birds, and 34 marine invertebrates (21 cnidarians, 3 molluscans, 1 polychaete annelid, 7 crustacean arthropods, and 2 echinoderms) (invertebrates presented in Table 7). Interestingly, one brackish water molluscan species, *Clithon retropictum*, is included in the species list of marine organisms under protection.

Korea’s national action plans related to harmful marine organisms were established by the MOF in 2016 on the basis of the Conservation and Management of Marine Ecosystems Act (Article 2, Subparagraph 13). The MOF considers harmful marine organisms to be any organisms that are harmful to life in nature or the property of human beings. Thus far, the government has designated 17 marine species as harmful marine organisms, including the following five macrozoobenthos: two echinoderms, *Asterina pectinifera* and *Asterias amurensis*, and three bryozoans, *Membranipora tuberculata*, *Tricellaria occidentalis*, and *Watersipora subovoidea* (Table 7).

The term “organisms disturbing marine ecosystems” was defined by the MOF in 2020 on the basis of the Conservation and Management of Marine Ecosystems Act (Article 2, Subparagraph 12). According to the ordinance, any marine organism can be designated as such when it meets either of the following criteria: (1) having been introduced from abroad intentionally or naturally, and causing (or being likely to cause) a disturbance to the balance of marine ecosystems; (2) causing (or being likely to cause) a disturbance to the balance of marine ecosystems due to being a genetically modified organism without natural control organisms. The government assigned a tunicate species, *Ciona intestinalis*, to this category based on its rapid population growth (Table 7). The animal was introduced from the Mediterranean and then became widely distributed throughout the coasts of Korea, including Jejudo. It is a sessile suspension feeder and a biofouling organism that inhabits mainly hard substrates, such as aquaculture farm facilities, ships, and bridge abutments, thereby causing damage to farms and boating equipment.

The Wildlife Protections and Management Act, established in 2012, allows for the designation of “endangered wild fauna and flora” based on the Protections and Management Act (Article 2, Paragraph 2) of the MOE. The government divided this category into Grade I and II, which currently include 50 and 171 species, respectively. The Grade I species include 12 mammals, 14 birds, 2 amphibians/reptiles, 11 fishes, 6 insects, 4 invertebrates, and 11 plants. Among the invertebrates, there are two marine species, including one molluscan (*Charonia lampas*) and one crustacean crab (*Pseudohelice subquadrata*) (Table 7). The Grade II species include 8 mammals, 49 birds, 6 amphibians/reptiles, 16 fish, 20 insects, 28 invertebrates, 77 plants, 2 algae, and 1 fungus

Table 7 Species list of marine invertebrates under legislative management by Korean governmental organizations, including the Ministry of Oceans and Fisheries (MOF), Ministry of Environment (ME), and Cultural Heritage Administration (CHA)

Authority		MOF ('19)			ME ('18)	CHA ('05)
Target species		Marine species			Wildlife species	
Category (purpose)		MOP[a]	HMO[b]	NIS[c]	EW[d]	NM[e]
# of targets		80	17	1	267	461
# of marine invertebrate species		34	5	1	23	2
Phylum	Scientific name					
Cnidaria	*Antipathes densa*	y				
	Antipathes dubia	y				
	Antipathes lata					y
	Cirrhipathes anguina	y				
	Dendronephthya alba	y			y	
	Dendronephthya castanea	y			y	
	Dendronephthya mollis	y			y	
	Dendronephthya putteri	y			y	
	Dendronephthya suensoni	y			y	
	Dendrophyllia cribrosa	y			y	
	Dendrophyllia ijimai	y			y	
	Dichopsammia granulosa	y				
	Echinogorgia complexa	y			y	
	Echinogorgia reticulata	y			y	
	Ellisella ceratophyta	y				
	Euplexaura crassa	y			y	
	Myriopathes japonica	y			y	y
	Myriopathes lata	y				
	Plumarella adhaerans	y			y	
	Plumarella spinosa	y			y	
	Synandwakia multitentaculata	y				
	Tubastraea coccinea	y			y	
	Verrucella stellata				y	
Arthropoda	*Chasmagnathus convexus*	y			y	
	Ocypode stimpsoni	y				
	Parasesarma bidens	y				
	Pseudohelice subquadrata	y			y*	
	Scopimera bitympana	y				
	Sesarmops intermedius	y			y	
	Uca lacteal	y			y	
Echinodermata	*Asterias amurensis*		y			
	Asterina pectinifera		y			
	Nacospatangus alta	y			y	
	Ophiacantha linea	y			y	
Bryozoa	*Membranipora tuberculata*		y			

(*Continued*)

Table 7 (*Continued*) Species list of marine invertebrates under legislative management by Korean governmental organizations, including the Ministry of Ocean and Fisheries (MOF), Ministry of Environment (ME), and Cultural Heritage Administration (CHA)

Authority		MOF ('19)			ME ('18)	CHA ('05)
Target species		Marine species			Wildlife species	
Category (purpose)		MOP[a]	HMO[b]	NIS[c]	EW[d]	NM[e]
# of targets		80	17	1	267	461
# of marine invertebrate species		34	5	1	23	2
	Tricellaria occidentalis		y			
	Watersipora subovoidea		y			
Mollusca	*Charonia lampas*	y			y*	
	Clithon retropictum	y			y	
	Ellobium chinense	y				
Annelida	*Paraleonnates uschakovi*	y				
Chordata	*Ciona intestinalis*			y		

[a] Marine organisms under protection

[b] Harmful marine organisms

[c] Non-indigenous invasive species

[d] Endangered wildlife species (Grade I* and II)

[e] Natural monument including animals, plants, minerals, caves, geological features, biological products and special natural phenomena, carrying great historic, cultural, scientific, aesthetic or academic values, through which the history of a nation or the secrets to the creation of the earth can be identified or revealed

(a mushroom). There are 21 Grade II marine invertebrates, including 1 molluscan, 15 cnidarians, 3 crustacean arthropods, and 2 echinoderms (Table 7).

Finally, the Cultural Heritage Protection Act, established in 1962 by the CHA, has thus far designated 70 organisms, as natural monuments for preservation and management; 12 mammals, 47 birds, 1 reptile, 4 fishes, and 2 marine invertebrates, 3 insects, and 1 plant. Two marine invertebrates are anthozoans, both designated in 2005: *Myriopathes japonica* (No. 160) and *Antipathes lata* (No. 457).

Conclusions

The present review confirms the high marine biodiversity of marine macrozoobenthos in Korea and provides an updated ecological checklist for macrozoobenthos in Korean coastal waters. Although overall species diversity remains high, site-specific distributions were highly variable across the regional seas (West Sea, South Sea, and East Sea) and across subregions along each coast. Both widely present species and site-dependent species were observed, reflecting the heterogeneous oceanographic setting along the coasts of Korea.

By region, the South Sea had the most diverse taxa, indicating its favourable coastal environments for marine organisms. This diversity might be explained by the convergence of West Sea and East Sea waters in the south. By habitat, subtidal areas were found to have the highest diversity of macrozoobenthos, which was principally attributable to large numbers of molluscs in the submerged zone. There was notable species co-occurrence across intertidal and subtidal habitats, indicating that there are extensive habitats under the dynamic macrotidal environment in the Korean coastal waters, particularly in the West Sea. By taxa, molluscs, polychaete annelids, and arthropods were predominant, followed by cnidarians. Their regional distributions varied across the three seas and three habitats greatly varied, reflecting their favoured habitats. It should be noted that regional diversity biases and unbalanced regional distributions of macrozoobenthos reflect sampling limitations, which should be addressed in future research efforts and activities.

Long-term benthic ecological studies in the Korean waters have been limited by a lack of trained professionals and the relatively short history of marine ecological science in Korea. Some long-term studies were conducted in response to the development of environmental issues, such as those described above at Lake Sihwa, Saemangeum, and Taean. Long-term studies of the benthos have also been conducted at Gwangyang Bay and Masan Bay, known pollution hotspots in Korea. The long-term macrobenthic community data that are available provide clear documentation of ecosystem deterioration in response to environmental changes and events, such as reclamations and oil spills. In each case, we observed diversity loss accompanied by a rise in the abundance of opportunistic species and/or organic enrichment indicator species. These effects were related to overall deterioration of water/sediment quality.

In conclusion, the macrozoobenthos in the Korean coastal waters support, contribute to, and play an important role in maintaining nearby communities. Benthic food webs and material flows are important ways in which macrozoobenthos contribute to the overall ecosystem functions. The benefits of local ecosystem health on human populations should be further examined. Continuing efforts in diverse scientific fields, including taxonomy, marine ecology, fisheries biology, pollution biology, environmental science, mathematical modeling, bioinformatics, and oceanography, are needed to elucidate, maintain, and protect the diversity and ecosystem services of the macrozoobenthos in coastal and marine environments. A holistic, integrated approach from multiple related fields, with balanced efforts and international perspectives, would support the development of sound marine science and biologically informed marine policies in Korea and elsewhere.

Acknowledgements

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