Long-term changes of marine subtidal benthic communities in North East Asia (Yellow and Japan seas) in a global change context: A review

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Abstract
1 A review of the long-term changes and variations in benthic communities and the current status of the marine invasive species (MIS) in shallow waters of the Yellow Sea (Chinese sector) and the Sea of Japan (Russian and partly Korean sectors) is presented. This paper reflects on the progress and lessons learned, recommending actions for the future about the conservation of biodiversity.
2 In the Bohai Sea, the benthic ecosystem has been degenerating due to anthropogenic activities such as overfishing and pollution since the 1950s. The dominant position of K-strategy species is gradually being lost and replaced by R-strategy species. In the Yellow Sea, the macrobenthic community is different from other areas due to the Yellow Sea Cold Water Mass. Many economic species have been destroyed, and the biotic structure has changed significantly due to overfishing and climate change.
3 In the Russian sector of the Sea of Japan, the macrobenthic communities in the shallow-water soft bottom have generally been in a stable condition for the last decades, except for some heavily polluted or disturbed areas due to dredging operations. The abundance of select large invertebrate species has changed considerably due to commercial fishing and poaching. Variations in macro and meiofaunal communities under aquaculture conditions have occurred on a local scale during the last five decades.
4 MIS show obvious differences between China and Russia in the following aspects: introduction pathways of MIS, composition and number of non-native species, threats and impacts of MIS to native communities and ecosystems, and economic and public health impacts.
5 Long-term monitoring programmes should be developed to reveal future biotic changes and to separate the effects of cyclic variations of benthic communities from the impacts of pollution and eutrophication. Standardization of sampling procedures is required to compare changes/alternations in benthos across various regions worldwide.
**KEYWORDS**
abundance, benthic communities, benthos, biomass, invasive species, long-term changes, Sea of Japan, shallow waters, Yellow Sea

1 | INTRODUCTION

The problem of long-term changes in marine ecosystems and related biotic communities due to anthropogenic influences during the last decades has become one of the key issues in marine ecology. Increasing anthropogenic pressure on marine environments leads to significant and drastic alternation of subtidal benthic communities and their biodiversity on a large scale both for oceanic seas and very sensitive shallow-water areas (Bulling et al., 2010; Crossland et al., 2005; Gallmetzer, Haselmair, Tomašovič, Stachowitsch, & Zuschin, 2017; Heath et al., 2012; Zhang, Zhang, Zhang, Du, & Xu, 2016). These changes can provide essential information for explaining the function of an ecosystem and its response to factors such as global climate change (Davoult, Dewarumez, & Migne, 1998) and interpreting the ecological consequences of disturbances as well as the environmental changes (Underwood, 1996). Additionally, the direct and potential influences from these community changes also exert serious impacts on marine ecosystems by altering the trophic structure, food web, habitat, and even the energy and material flow (Bilyard, 1987). Normally, these kinds of temporal and spatial changes in invertebrate community structure, including the faunal composition and distribution, are inherently unpredictable in direction (Currie & Parry, 1999). Long-term monitoring programmes are essential for defining the extent of change and identifying the cause (Currie & Small, 2005).

Macrobenthos are key components of benthic marine ecosystems, playing important roles in trophodynamics and food webs (Herman, Middelburg, Van de Koppel, & Heip, 1999). They are widely used as a sort of biotic indicator to evaluate the seabed health conditions due to their sensitivity to environmental change (Bilyard, 1987; Borja, Franco, & Pérez, 2000; Pinto et al., 2009).

The situation in North-East Asia (along Russia, Japan, Korea and China) differs between various geographical regions, due to their particular species richness and biological diversity (Figure 1). Asian seas are considered as one of the hotspot regions for marine biodiversity research. This region has also experienced large-scale changes in the coastal environment due to the human population explosion and rapid economic development in the past decades, which will inevitably impact long-term changes in the macrobenthic community. Furthermore, the conservation and sustainable use of marine biological diversity beyond areas of national jurisdiction has become a crucial issue discussed by the United Nations Convention on the Law of the Sea (UNCLOS) (Scovazzi, 2016). This review compares benthic changes during the last decades in the most studied areas of two Asian marginal seas—that is, the Sea of Japan (western part, Russian and Korean sectors) and the Yellow Sea (Chinese sector)—with the aim of identifying the general pattern of benthic community change, providing some theoretical support in the conservation of marine biological diversity for the UNCLOS.
The Bohai Sea, located between 37°07′–41°00′N and 117°35′–121°10′E in the North-West Pacific, is a shallow semi-enclosed marginal inland sea in China, with an area of approximately 77 × 10³ km², an average depth of 18 m, and a coastline length of nearly 3,800 km. The Bohai Sea is enclosed by the Liaodong and Shandong Peninsulas and connected with the north Yellow Sea through the Bohai Strait. This sea consists of four parts: Bohai Bay, Liaodong Bay, Laizhou Bay, and Bohai Strait. More than 100 rivers flow into the seawater, of which nearly half of the runoff is contributed by the Yellow River (Huanghe), the second largest river in China. The Yellow River plays a fundamental role in controlling the local ecosystem dynamics and function. Depending on river runoff with high nutrient input, a high plankton biomass, and its shallow depth, the Bohai Sea was a vital spawning, nursery, and feeding ground for many migratory species from the Yellow Sea and East China Sea (Zhou, Zhang, Liu, Tu, & Yu, 2007).

Over the past 50 years, the Bohai Sea ecosystem has deteriorated due to climate changes and various anthropogenic activities, such as overfishing and pollution (Jin & Tang, 1998; Zhang, Zhu, Wang, & Wang, 2006). Each year, approximately 50% of China’s total maritime pollutant discharge is carried by river runoff into the Bohai Sea (Zhang et al., 2006). In recent years, this sea has also been subjected to intensive offshore exploration for natural gas and petroleum reserves (Fan & Zhang, 1988).

The Bohai Sea has undergone great changes in environmental conditions over the past 60 years. The bottom water temperature has seen an average increase of 0.013 °C per year in the southern Bohai Sea (Ning et al., 2010). The bottom salinity was stable at 28.7 PSU between the 1950s and 1980s and then increased to 30 PSU in the 2000s with an increasing rate of 0.105 PSU per year (Comprehensive Sea Survey Department in State Scientific and Technological Commission, 1961; Ning et al., 2010; Zhou, Zhang, Liu, & Hua, 2012). Both the meiofaunal and macrofaunal abundances were two to five times greater in the 1990s than in the 1980s and the 2000s (Zhou et al., 2012). The sediment grain size generally tended to become coarser in Laizhou Bay (Zhou et al., 2012). The biogenic elements in the southern Bohai Sea also changed noticeably (Ning et al., 2010); for example, a significant decrease in dissolved oxygen (DO) concentration was observed in the southern Bohai Sea during the period 1978–1991; both bottom phosphorus (P) and silicon (Si) concentrations exhibited decreasing trends from 1978 to 1996; the concentration of dissolved inorganic nitrogen (DIN) increased from 2.9 μmol L⁻¹ in 1985 to 8.7 μmol L⁻¹ in 1996, which led to the increase of nitrogen (N):P and N:Si ratios, thus affecting the phytoplankton community. The sediment chlorophyll a and phaeopigment concentrations were seven to ninefold lower in the 2000s than in the 1980s and 1990s (Zhou et al., 2012). However, the organic content in the sediment also increased by three to fourfold in the 1990s and markedly decreased in the following 10 years (Ning et al., 2010; Zhou et al., 2012).

The dominant position of K-strategy species (i.e. with long life spans and high competitiveness) is gradually being lost and replaced by R-strategy species (i.e. with short life spans, high adaptability, and high reproduction ability; Chen, Wang, Li, Zhou, & Li, 2016). Three different temporal stages could be divided based on the changing species composition, biomass, and abundance; for example, the first stage before the 1960s, in which the community was characterized by a low number of species and high biomass and abundance, and with commercial molluscs and crustaceans as the dominant groups; the second stage from the 1980s to 2006, in which the assemblage was changed with an increased number of species and decreased biomass and abundance, with the dominant groups being small molluscs and echinoderm; and the third stage after 2006, in which the community recovered with an increased biomass and dominance of both molluscs and crustaceans (Figure 2 and Figure 3). Previous investigations also found that the macrobenthic community in the Bohai Sea had similar changes in state (Zhou et al., 2007; Zhou et al., 2012).

The Yellow Sea is a semi-enclosed marginal sea in the north-western Pacific, with an average depth of approximately 50 m (Lin, Ning, Su, Lin, & Xu, 2005). This sea connects with the Bohai Sea in the north and with the East China Sea in the south. In the western region, the depth of the China Continent Coastal Water is less than 20 m, where there are many bays along the coast of the Shandong Peninsula, such as Jiaozhou Bay, Sangou Bay, Swan Lake, Sishili Bay, and Taozi Bay. In its central region, there is the Yellow Sea Cold Water, with a low temperature. In its eastern region, the Yellow Sea Warm Current has a characteristic warm and saline flow from south-east to north-west (Su, 1998). The primary production is high due to high nutrient concentrations, which results from the confluence of warm and cold waters. The fishery resources in the Yellow Sea are the most abundant in China (Lin et al., 2005; Figure 4).

The environmental features of the Yellow Sea suffered significant changes from 1976 to 2000. Time series of temperature T, salinity S, DIN, including nitrate-N, nitrite-N, and ammonium-N, and N:P ratios exhibited positive trends, whereas those of DO, P, and Si showed negative trends. From 1976 to 2000, the annual means of T and DIN in the Yellow Sea increased by 1.7 °C and 2.95 μmol L⁻¹ respectively, whereas those of DO, P, and Si decreased by 59.1 μmol L⁻¹, 0.1 μmol L⁻¹, and 3.93 μmol L⁻¹ respectively (Lin et al., 2005). Since the 1980s, the Yellow Sea ecosystems have probably been experiencing limitations of P and sometimes Si, resulting in a change in the dominant species of phytoplankton communities from diatoms to dinoflagellates (Dong et al., 2002) in the north Yellow Sea. The species diversity and richness of fish communities declined in 2000 compared with those in 1985 in the central Yellow Sea. These changes were the
result not only from climate changes but also anthropogenic impacts (Lin et al., 2005).

Several previous studies on macrobenthos have been carried out in this region. The macrobenthic community in the north Yellow Sea is different from other areas due to the Yellow Sea Cold Water Mass (YSCWM). Typically, the abundance and biomass of macrobenthos are higher, and the biodiversity is relatively lower than other areas. The dominant species is the bivalve *Thyasira tokunagai* (a typical cold-water species) (Sun, 2014). Li (2011) concluded that the total average abundance and biomass of macrobenthos were 2,017.4 ind. m$^{-2}$ and 99.66 g m$^{-2}$ respectively, to which Echinodermata contributed the most.

Liu, Cui, Xu, and Tang (1986) noted the differences between cold-water (boreal) communities in the north and south Yellow Sea. The dominant species were *Ophiura sarsii vadicola*–*T. tokunagai* and *T. tokunagai*–*Onuphis geophiliformis*–*O. sarsii vadicola* respectively. Zhang et al. (2016) found two sea anemones, *Metridium senile fimbriatum* and *Metridium farcimen*, were primarily distributed in the north Yellow Sea, whereas the bivalves *Portlandia japonica*, *Keenaea samarangae*, and *Pandora otukai* were primarily distributed in the south Yellow Sea. These communities remained stable because of the sustained low-temperature environment of the YSCWM.

Zhang et al. (2016) surveyed the macrobenthic biodiversity in the Yellow Sea based on 58 grab samples and found that the average abundance was 350.43 ind. m$^{-2}$ in 2007. No significant differences were found for the abundance, biomass, and number of species in 2007 between the south and north Yellow Sea. The Shannon–Wiener $H'(\log_{2})$ and Pielou’s evenness $J'$ indices were not significantly different between the south and north Yellow Sea.

Macrobenthic community structures were analysed based on the data obtained in the spring of 2007. Qu, Yu, Liu, Su, and Zhang (2009) divided the communities into three groups. Group I was the eurythermal and low-salinity species group dominated by *Lumbrineis cruzensis* and *Sternaspis scutata*, which was located in the offshore areas of the Shandong and Liaodong Peninsulas. Group II consisted of cold-water species dominated by *T. tokunagai* and *O. sarsii*, which was located in the Cold Water Mass area. Group III was a species assemblage preferring sand substrate dominated by *Spiophanes bombyx* and *Echinocardium cordatum*, which was located in the eastern part of the north Yellow Sea (Qu et al., 2009).

Shou et al. (2018) described the benthic communities in the Yellow Sea and East China Sea based on a survey from 2011 to 2012. The dominant species were bivalve molluscs in the Yellow Sea and small-sized polychaetes in the East China Sea (Figure 5). There are notable regional and seasonal differences in the two seas. The density, biomass, and number of species in the East China Sea are larger than those in the Yellow Sea. The average biomass and density of macrobenthos from 2011 to 2012 were greater than historical data in the spring and autumn. The average biomass and density of macrobenthos from 2011 to 2012 were larger than 2000–2001 but less than 1998–2000 in the East China Sea. Although there are some fluctuations in abundance and biomass within a certain range during various periods in the two seas, it is difficult to explore long-term changes in macrobenthic communities due to the large difference between surveys (Shou et al., 2018).

### 2.1.3 The south Yellow Sea

The south Yellow Sea is located between the mainland of China and the Korean Peninsula. The coverage area is approximately $3.0 \times 10^{5}$ km$^{2}$, and the average depth is 44 m. The northern boundary is the connecting line between the eastern corner of Shandong Peninsula and Bailing Island, and the southern boundary is the Qidong
area of the Changjiang Estuary (Yuan, Song, Li, Li, & Duan, 2012; Figure 6). The main hydrological features of the south Yellow Sea are: (i) the Huang Hai Cold Water Mass in the central part; (ii) the Northern Jiangsu Coastal Current in the west; (iii) the Huang Hai Warm Current in the central and eastern part; and (iv) the Yangtze River flushing fresh water in the south-west (Xu et al., 2017). The sediment grain sizes are mainly fine sand and silt in the coastal areas, and mud in the central areas (Liu et al., 1986; Zhang, Xu, & Liu, 2012). Owing to its special geographical location and hydrological characteristics, the south Yellow Sea is an important spawning and nursery area for many economic species. In the past few decades, many economic species in the south Yellow Sea have been destroyed, and the biotic structure has changed significantly due to overfishing and climate change (Xu, Sui, & Li, 2016).

The research on macrobenthic assemblages began with the National Marine Census in the late 1950s in the South Yellow Sea, with gradually increasing survey effort until the 2000s. A survey carried out by Yang (2014) revealed the general condition of macrobenthic assemblages in the south Yellow Sea. A total of 343 macrobenthic species were identified in the south Yellow Sea: 165 Polychaeta species, 42 Mollusca species, 98 Crustacea species, 15 Echinodermata species, and 23 species from other groups (belonging to Coelenterata, Nemertini, Oligochaeta, Brachiopoda, and Chordata). The total average abundance in the survey area was 903.8 ind. m$^{-2}$, of which Polychaeta was 606.2 ind. m$^{-2}$, Mollusca 76.9 ind. m$^{-2}$, Crustacea 158.5 ind. m$^{-2}$, Echinodermata 22.3 ind. m$^{-2}$, and other taxonomic groups 39.8 ind. m$^{-2}$. The total average biomass in the survey area was 15.93 g m$^{-2}$, of which Polychaeta contributed...
5.10 g m$^{-2}$, Mollusca 1.83 g m$^{-2}$, Crustacea 1.33 g m$^{-2}$, Echinodermata 4.32 g m$^{-2}$, and other taxonomical groups 3.34 g m$^{-2}$.

To understand the macrobenthic structure and evaluate the benthic health conditions, it is necessary to divide communities into different functional groups. Liu et al. (1986) first used the Petersen–Thorson system to discriminate the macrobenthic communities in the south Yellow Sea when each community was named after the dominant species in quantity or biomass. Zhang et al. (2012) used the CLUSTER method in dividing the macrobenthos into (i) a cold-water mixed group and (ii) a near-shore eurythermal group. Jia et al. (2010) recognized seven communities in the Yellow Sea based on the cooperative research by Korea and China in 2008. The results show that the community structure of the southern Yellow Sea is relatively stable compared with historical data, with Polychaeta and Mollusca as the dominant species. The abundance, biomass, and species number were higher in nearshore stations than offshore ones. According to Xu, Sui, and Li (2016), the macrofauna in the southern Yellow Sea had changed drastically for over half a century. The macrobenthos was classified into three communities: the YSCWM community, the mixed community, and the eurythermal community. The echinoderm O. sarsii vadicola replaced Mollusca and Crustacea as the dominant species in the YSCWM community. Polychaeta replaced Echinodermata and Mollusca as the dominant species in the mixed community and the eurythermal community. The polychaetes increased and the echinoderms decreased in the western waters, whereas the opposite occurred in the eastern waters.

In general, the macrobenthic community structure and species composition in the south Yellow Sea experienced evident succession from 1958 to 2014 (Xu, Sui, & Li, 2016). In the late 1950s, there were two main functional groups in this area, the Anadara kagoshimensis–Nassarius sp. group and the Temnopleurus hardwickii–Amphioplus japonicus group. In the 2010s, the dominant groups of eurythermal communities also showed a unipolar trend towards polychaetes, which is similar to the aforementioned trend of mixed communities. Polychaetes with a short life span can adapt to unstable living conditions, thus replacing those with a long life span as the dominant groups. Multiple factors are attributed to this variation, including (i) abiotic factors, such as depth, temperature, and salinity, and (ii) anthropogenic factors, such as demersal fishing, intensive aquaculture activities, and wastewater discharge. This long-term succession also coincides with the variations in macroalgal and jellyfish blooms in the ecosystems of the south Yellow Sea (Xu, Sui, & Li, 2016; Figure 7).

2.1.4 Coastal waters off Subei Shoal

Subei Shoal is one of the largest intertidal mudflats in Asia, with an area of approximately 22,740 km$^2$ (Yi & Liu, 2007). It stretches from the Sheyang River estuary in the north to the Changjiang River estuary in the south. The average width from the shoreline to open sea is 90 km (Fan et al., 2010). The hydrological features are mainly dominated by (i) the Yellow Sea coastal waters; (ii) the Yangtze River fresh waters; and (iii) the YSCWM (Xu, Li, Wang, & Zhang, 2016). Owing to strong economic development and increasing anthropogenic activities, the nutrient content from the major rivers flowing into Subei Shoal has increased significantly (Song et al., 2015). Studies have shown that Subei Shoal is the original source of jelly blooms and Ulva prolifera blooms (green tides) that have occurred in the Yellow Sea every summer since 2007 (Song et al., 2015; Wei et al., 2015).

Macrobenthos is a key component of tidal flat ecosystems. As previously mentioned, they are vulnerable to short-term or long-term environmental changes due to specialized life histories. Thus, macrobenthos can also be used to indicate the health conditions of
intertidal ecosystems, such as Subei Shoal (Xu, Li, et al., 2016). However, few studies into species composition and functional groups have been carried out on macrobenthos in this area and adjacent waters.

Fan et al. (2010) investigated the species distribution and composition of macrobenthos around Subei Shoal waters. The results identified 120 species, among which polychaetes are dominant in both abundance and species number. The average abundance is 273.57 ind. m$^{-2}$ and average biomass is 44.50 g m$^{-2}$, both showing a decreasing trend from the open sea to coastal waters. The macrobenthic community is closely related with the sediment grain size, which could be categorized into three groups based on Bray–Curtis similarity: (i) Amphiura vadica group; (ii) S. scutata–Terebellides stroemii group; and (iii) Prionospio sp.–Notomastus latericeus–Tellinidae–Nassariidae group. Another study by Que, Kang, Xu, Chen, and Zhou (2012) focused on the spatial–temporal distribution of Hoplocarida and Decapoda shrimps. Eighteen Decapoda and two Hoplocarida species were identified, among which Palaemon gravieri was the dominant species in spring and Parapenaeopsis hardwickii in autumn. The shrimp species compositions showed seasonal alternation between spring and autumn, and the alternation rate was 55%.

A more thorough study was carried out by five survey cruises from May to June covering 24 stations belonging to four groups...
(5–10 m, 10–20 m, 20–30 m, and 30–35 m; Xu, Sui, & Li, 2016). The results were similar to those investigated in 2007 (Fan et al., 2010), in which 163 species were identified and Polychaeta was the dominant species in both species number and abundance (Figure 8). Significant differences in community structure were observed between inshore (5–10 m) and offshore stations. However, the exact species composition differed greatly from 2007 to 2013. Polychaeta increased from 42.8% to 71.7%, whereas Crustacea and Echinodermata decreased from 25.1% to 8.0% and from 14.9% to 7.7% respectively. The main causes were: (i) nutrient contamination induced by anthropogenic activities; (ii) rapid increase of suspended particles in a short time; and (iii) seasonal variation of adjacent water masses, such as the YSCWM and Yangtze River fresh water (Fan et al., 2010; Que et al., 2012; Xu, Li, et al., 2016). The community succession of macrobenthos at Subei Shoal needs further investigation in terms of environmental factors and long-term monitoring.

2.1.5 Port areas in the Yellow Sea

A number of ports are located along the Chinese coastline in the Yellow Sea, such as Dalian Port, Yantai Port, Weihai Port, Qingdao Port, Lianyungang Port, Nantong Port, and so on (Figure 9). However, few studies have focused on the macrobenthic communities in these ports. Research was focused on the two important ports (Qingdao and Lianyungang Ports) to understand the status of macrobenthic communities.

Lianyungang Port is located in north-eastern Jiangsu Province, which is the transportation hub for Jiangsu Province and China. As the eastern starting point of the New Asian–European Continent Corridor, harbour construction and reclamation were conducted to meet the demands of the economy and population development. The macrobenthos suffered from compounded anthropogenic activities, such as dredging, dumping, and burial effects due to the port construction and reclamation and the ballast water discharged from ships.

![FIGURE 8](image1.png)  
**FIGURE 8** (a) Abundance (ind. m$^{-2}$; mean ± SE) and (b) biomass (g m$^{-2}$; mean ± SE) of macrobenthos in four depth groups in Subei Shoal based on the pooled data across cruises. (After Xu, Sui, & Li, 2016, text-figure 2)

![FIGURE 9](image2.png)  
**FIGURE 9** A map of main ports in the Yellow Sea.
Li, Zhu, and Sun (2010) reported that urban built-up land increased sharply along with a decrease in large-scale salt wetlands degradation since 2005. A survey on the status of benthic communities in autumn 2005 showed that the biomass was heterogeneous in the Lianyungang Port areas. The biomass was lower in stations that were close to the port area. Only slight disturbance was found, so the health status of benthic communities was not yet considered poor (He, Chen, & Wang, 2009). The macrobenthic community evidently changed in a temporal pattern due to the construction of a nuclear power station in Lianyungang. The dominant species changed from Mollusca and Echinodermata species with larger bodies in 1998 to smaller polychaete species in 2005. The abundance of macrobenthos increased due to nutrient enrichment coming from wastewater, whereas the macrobenthic biomass decreased due to the disturbance during construction of the Lianyungang nuclear power station (Chen, Fang, Zhang, & He, 2007). Chen et al. (2007) also compared the status of macrobenthic communities in three main areas (an alkaline factory, a port region, and a nuclear power station) that suffered from serious human disturbance in Lianyungang; Polychaeta and Mollusca were the dominant groups in all three areas. The alkaline factory area possibly suffered more disturbance because the status of one station in the alkaline factory was worse and the overall biodiversity was lower in the alkaline factory area than the other two areas (Chen et al., 2007).

Qingdao Port is located in Jiaozhou Bay. It is one of the 10 busiest ports in the world. In Jiaozhou Bay, a 10-year survey from 2000 to 2009 found that Polychaeta was the dominant taxa group (Wang, 2011). The species composition was not significantly different between surveys, whereas the dominant species varied markedly among years in Jiaozhou Bay. The average abundance of macrobenthos decreased gradually from 381.73 ind. m\(^{-2}\) in 1998–1999, 304.6 ind. m\(^{-2}\) in 2000–2004, to 280.88 ind. m\(^{-2}\) in 2005–2009 (excluding the local cultured species Ruditapes philippinarum). The average biomass fluctuated from 22.22 g m\(^{-2}\) in 1998–1999, to 16.30 g m\(^{-2}\) in 2000–2004, and to 27.6 g m\(^{-2}\) in 2005–2009. The biomass maintained the increasing trend, which was most possibly due to implementing a policy forbidding bottom trawls since 1998 and a fishing off season since 2011 (Wang, 2011).

### 2.2 | Typical areas in the Russian sector

#### 2.2.1 | Russian sector of the Sea of Japan

The Russian sector of the Sea of Japan extends from the mouth of Tumen River (Tumangan) at the Russian–North Korean border to the northermost Tatarksky Strait (a strait between Sakhalin Island and the continent) (Figure 1). The most populated area along the coastline is Peter the Great Bay, in the southern sector, with a series of secondary, ria-type bays (Nakhodka, Vostok, Ussuriisky, Amursky, and Possjett bays) and two cities and related industry and ports as a major source of pollution: Vladivostok (with a population over 600,000, the largest city in the Russian Far East) and Nakhodka. Vladivostok city is located on the coasts of Amursky and Ussuriisky bays, and much data on the benthic communities and environmental states of these bays have been published during last five decades.

Sewage containing multicomponent mixtures of polluting agents of both mineral and organic origin (oil hydrocarbons, polychlorinated hydrocarbons, surfactants, heavy metals, and radionuclides) are discharged into the coastal waters of Peter the Great Bay, Zolotoy Rog Bay (in downtown Vladivostok), Bosphor Vostochny Strait, Nakhdoka Bay (especially its innermost portion, around Nakhdoka Port), and Amursky Bay, which are the most polluted areas (Ogorodnikova, 2001; Vashchenko, 2000; Vashchenko, Zhadan, Almyashova, Kovalyova, & Slinko, 2010). Pollution is one of the most important problems for environmental and biological safety in the Russian Far Eastern seas, along with bioinvasions, ballast water transfer, and overfishing (Adrianov, 2014).

Coastal environments of the Sea of Japan in regions north of Peter the Great Bay (between Cape Pavorotny and Tatarksky Strait) are mostly undisturbed; rare localized pollution occurs, and there is no large-scale fishing in shallow waters, although there are some quite large aquaculture installations (e.g. scallop, Mizuhopecten yessoensis, farms in Vladimir Bay). These conditions result in the presence of stable and healthy marine ecosystems in this region (Galyshева, 2009). However, little is known about benthic communities and the possible changes that have occurred in some ports of Primorye and Khabarosky Krai (e.g. Vanino and Sovetskaya Gavan).

#### 2.2.2 | Peter the Great Bay

The most detailed comparative analysis of the long-term dynamics of structure, biomass, and abundance of benthic species in Peter the Great Bay (Figure 10) was conducted for the first time by Klimova (1971). Then Klimova compared the results of benthic surveys from 1970 to 1972 at depths of more than 15–20 m with the pioneer studies by Derjugin (1939) and Derjugin and Somova (1941) (Klimova, 1971, 1974, 1975, 1976); in which, 31 benthic communities were described and a significant change in bottom biota was concluded at a depth of 100 m due to siltation. The most important reasons for siltation were regarded as bottom trawling and soil erosion. The Maldane sarsi–Scoloplos armiger communities and the Obelia longissima–M. sarsi–O. sarsi vadicola community, widely distributed in the 1930s, were replaced in the 1970s by the O. sarsi vadicola community at depths down to 40 m, the Liocyma fluctuosum community was replaced by Echiurus echius and Macoma calcarea communities at a depth of 50–80 m, and the Solariaella community by M. calcarea, Cucumaria calcigera, Nicomache lumbricoides, and O. sarsi communities at a depth of 80–200 m. Changes in benthic composition appeared to be very significant and led to a complete alternation of the trophic structure of bottom communities: in the upper subtidal zone, the zone of detritiphages consuming detritus changed to a zone of ‘gathering’ detritiphages, whereas at the depths of 50–80 m, the zone of seston-feeders changed to a zone of gathering detritiphages. Additionally, the benthos stock decreased by 40% and mean biomass from 168 g m\(^{-2}\) to
113 g m$^{-2}$. Klimova (1975) also suggested a decline of population density of the abundant infaunal boreal-arctic bivalve _L. fluctuosum_ and even its complete disappearance at depths down to 70 m. In a detailed analysis of benthic communities of the Sea of Japan, Shuntov (2001) stated that the bottom trawling influence on seabed biota in Peter the Great Bay is largely exaggerated.

A more recent study (Nadtochy, Budnikova, & Bezrukov, 2005) on the distribution of macrobenthos in Peter the Great Bay was more large scale than previous research: 450 quantitative and 200 qualitative samples were collected with bottom samplers and Sigsby trawls over a depth range of 7–280 m. In that study, the total benthic biomass varied from 15 to 3,154 g m$^{-2}$ in 2003, with an average of 265.4 ± 25.1 g m$^{-2}$, which is twice that in the 1970s. The maximum biomass (3,154 g m$^{-2}$) was recorded in the eastern part of Amursky Bay, where the major animal groups were cirripedes (1,696 g m$^{-2}$; Figure 11) and bivalve molluscs (1,037 g m$^{-2}$). Another benthic-rich area was the inner part of Ussuriysky Bay (maximum biomass 1,571 g m$^{-2}$), dominated by phoronids (552 g m$^{-2}$) and bivalve molluscs (848 g m$^{-2}$). The minimum biomass was detected in the inner part of Amursky Bay (15 g m$^{-2}$) and was associated with small-sized polychaetes and cumaceans. In general, bivalve molluscs, sea cucumbers, cirripedes, and echinoderms were most dominant in terms of biomass in Peter the Great Bay in 2003 and together made up more than 80% of the total benthic biomass (Nadtochy et al., 2005).

An interesting conclusion drawn from the same study contradicts previous observations by Klimova (see earlier): according to the 2003 data, variations of benthic density and biomass depended largely on the number of sampled stations (survey grid) and sampling methods, and substantial reorganization or changes in benthic communities were not detected (Nadtochy et al., 2005). Moreover, the macrobenthic biomass in Amursky Bay was almost four times higher as compared to the 1970s (on average, 433 g m$^{-2}$ in 2003 vs. 118 g m$^{-2}$ in the 1970s) and twice as much in the central and eastern parts of Ussuriysky Bay. A similar viewpoint regarding the shortcomings of benthic sampling methods used in the 1970s and associated errors in estimates of benthic composition, abundance and distribution was argued by Shuntov (2001).

The most recent comprehensive study on benthos in Peter the Great Bay (Nadtochy & Kolpakov, 2017) showed that the average total biomass of the macrobenthos in 2011 was 241.8 ± 21.1 g m$^{-2}$, which is almost the same as in 2003 (265.4 ± 25.1 g m$^{-2}$; Figure 12). The major taxonomic groups of macrobenthos were bivalves (34.0%), polychaetes (23.0%), phoronids (7.1%), and barnacles (7.1%); these...
four groups made up 71.1% of the total biomass, and with another 11 common groups (sea anemones, nemerteans, echiurans, amphipods, gastropods, sea stars, brittle stars, sea urchins, sea cucumbers, ascidians, and algae) made up 96.6% of the total biomass. Compared with 2003, the shares of polychaetes and phoronids became larger (15.8% and 4.33% respectively in 2003), and the shares of sea cucumbers and echiurans became smaller (12.1% and 7.3% respectively in 2003). A decrease in the biomass of bivalve molluscs (Figure 13) and an increase in that of polychaetes were observed in all areas of Peter the Great Bay. In Amursky Bay, the mean total biomass and proportions of dominant groups did not change, with the exception of some decreases in bivalves and increases in polychaetes. In Ussuriysky Bay, the mean total biomass and composition of the dominant groups did not change either, but the proportions of sea cucumbers and echiurans decreased significantly and the share of phoronids increased more than threefold by biomass. In the western area, the position of echiurans, almost undetected in 2011, was replaced by sea urchins and ascidians; the biomass of brittlestars decreased 1.5 times, but amphipods became more abundant in the central area; the biomass of sea cucumbers decreased eightfold, which caused a 1.7-fold decrease in the mean total macrobenthic biomass. In the eastern area, the most significant changes were a decrease in sponge biomass and an almost twofold increase in polychaete biomass. However, the dominant taxonomic macrobenthic groups in Peter the Great Bay have always been bivalves and polychaetes (and additionally barnacles in Amursky Bay), and changes in taxonomic structure or replacement of taxa in benthic communities by abundance were related to subdominant or minor taxa (Nadtochy & Kolpakov, 2017).

Belan (2003, 2013) found that large numbers of pollution-tolerant species of polychaetes occurred from 1975 to 1980 in the coastal zones of Amursky Bay: *Tharyx pacifica*, *Darvillea japonica*, *Dipolydora cardalia*, and the phoronid *Phoronopsis harmeri* were living in areas where severe pollution was detected. At the beginning of the 1980s, new positive species indicators did not occur, and dominant and subdominant sets of species did not change. Belan and Belan (2006) observed that the total benthic biomass in Amursky Bay significantly increased in 2001, although the species richness declined in comparison with the period of 1986–1989. In 2001, as well as in the 1970s and 1980s, the benthic trophic structure was characterized by the prevalence of deposit feeders, and the entire benthic structure was evaluated as a eutrophic one. Between the periods from 1931 to 1933 and from 1973 to 1975, the abundances of *M. sarsi*, *S. armiger*, *O. longissimi*, and, probably, the stomatopod *Squilla oratoria* in the central and southern areas of the northern part of Amursky Bay declined appreciably (Moshchenko & Belan, 2008). Maximal changes in the composition and structure of the Amursky Bay bottom fauna occurred within the period from the 1970s to the 1980s (Belan, 2003; Tkalin, Belan, & Shapovalov, 1993). In this period, pollution and eutrophication-tolerant *T. pacifica* and *P. harmeri* (observed only occasionally earlier) became common species, whereas *Luidia quinaria bispinosa* and *O. sarsi vadicola* communities disappeared, being replaced by *M. sarsi* and *T. pacifica* communities respectively.
granulometric analysis. (Moshchenko & Belan, 2008), but this conclusion was based purely on community, might be a result of siltation from the 1970s to 1980s. M. sarsi towards shallow waters, replacing the structure of benthic communities: ‘expansion’ of mud-inhabiting M. sarsi might be a result of siltation from the 1970s to 1980s (Moshchenko & Belan, 2008), but this conclusion was based purely on comparison of simple descriptive bottom maps rather than granulometric analysis.

According to Moshchenko and Belan (2008, p. 86), “… in the end of the 1980s the northern part of the Amursky Bay was on the verge of ecocatastrophe, which was confirmed at least by depression of bivalves fauna …”. However, this concept is in absolute contradiction to the faunal analysis of bivalves in Amursky Bay (Lutaenko, 2003) and the quantitative data of Galysheva and Nadtochy (2008): bivalves were most dominant by biomass in the inner part of Amursky Bay, contributing 74% of the total biomass; the composition of dominant species in the latter work was very different from those in the Belan and Moshchenko studies (noted earlier) and included many large species; the inner part of the bay supported 36 species of bivalves (out of 119 known from the entire bay), and no signs of their degradation were detected (Lutaenko, 2003). Oleinik, Moshchenko, and Lishavskaya (2004) enumerated different dominant bivalve species in the 1930s (based on data from a few stations) and from the 1970s to 1980s (18 stations only) in Peter the Great Bay, but they were mostly small bivalves, whereas larger species were simply not caught by bottom samplers (Van Veen grab with a 0.11 m² capture area), although these authors did not find changes in bivalve abundance due to pollution.

In the Far Eastern Marine Biosphere Reserve (south-western Peter the Great Bay), the abundance of many species of bivalve molluscs from 2005 to 2007 compared with the 1980s is believed to have changed: the abundance of the relatively warm-water species Macrta chinensis, Cadella lubrica, and Actila insignis decreased by 1.5–6 times, and the abundance of the subtropical species Alvenius ojanus decreased by 20 times and biomass by 57 times; the abundance of boreal-arctic Axinopsida subquadralta and L. fluctuosum increased three to four times, and the biomass of the latter species increased by 14 times (Lebedev, 2010). If these changes are connected with climatic fluctuations, this conclusion contradicts data on the warming of coastal waters of Peter the Great Bay during the last decades (Gayko, 2005). Obviously, different collecting methods and efforts (number of stations) prevent comparison of various data sets and lead to unreliable conclusions.

At the same time, the abundance and distribution of large commercial species of bivalves in Peter the Great Bay have significantly decreased since the 1930s due to overfishing; for example, in Ussuriysky Bay, the population density of the blood cockle Anadara broughtoni reached 13 ind. m⁻² in the 1930s but decreased to 4.7 ind. m⁻² in the 1990s; in some areas, the mean abundance of the giant mussel Crenomytilus grayanus decreased from 27.4 ind. m⁻² (1959) to 3.4 ind. m⁻² (1970)—see the review by Lutaenko (2006). Active Japanese scallop fishing (M. yessoensis) in Peter the Great Bay was carried out from the 1920s to 1930s, and from 1933 to 1937 its catch reached 900 tons, and the average density was 0.3 ind. m⁻² and up to ≥7 ind. m⁻² in some areas; the total stock was estimated at approximately 10,000 tons (Sedova, Sokolenko, Borisovets, Afeichuk, & Bratishchev, 2007). Due to overfishing, the scallop fishery has been banned since the 1950s. In the 1970s, the Japanese scallop density ranged from 0.2 to 2.4 ind. m⁻², and the total stock was approximately 1,700 tons; from 2000 to 2005, the abundance varied between 0.010 and 0.466 ind. m⁻², and in some areas its stock decreased by 35 times due to poaching (Sedova et al., 2007). There are documented population changes for a number of commercial benthic species in Russian waters of the Sea of Japan: abundance and biomass decreased for the infalunal clam Spisula sachalinensis (Sokolenko & Sedova, 2008), a large shallow-water gastropod, the rapa whelk Rapana venosa (Rakov, 1998), deep-water buccinid dogwhelks (Repina, 2006), the sea cucumber Apostichopus japonicus, sea urchins Stronglylocentrotus nudus and Stronglylocentrotus intermedius, and decapod crustaceans (especially the king crab Paralithodes camcchaticus) due to overfishing and poaching. Inevitably, benthic communities where these species were previously dominant or subdominant have also been modified.

Notable improvement of the marine environment in relation to chemical pollution in some areas of the inner part of Amursky Bay due to reduced industrial activity has been observed since 1995 (Luysanov, Chershkin, & Simohon, 2012; Moshchenko, Chernova, & Lishavskaya, 2008). This decline is reflected in both meio and macrozoobenthic changes. Substantial differences have been found in the qualitative and quantitative characteristics (taxonomic composition and population densities) of foraminiferal faunas near the mouth of the Razdolnaya River (northern part of Amursky Bay), studied in 1985 and 2005 (Tarasova, 2008). In 1985, all characteristics were distributed in Amursky Bay along with the aforementioned agglutinated species (Tarasova, 2008).

According to Gabaev, Taupek, and Kolotukhina (2005), the consequences of anthropogenic impacts on the waters of Amursky Bay include eutrophication of coastal waters and littering with various objects used as artificial substrates, which protect sedimentary animals from predators and contribute to the survival of their larvae, and these authors suggest that eutrophication would lead to changes in the structure of marine communities. The diatom Skeletonema costatum, an indicator of eutrophication, accounts for 81–96% of the total abundance of phytoplankton and is consumed mainly by barnacles and the Pacific oyster Crassostrea gigas. Thus, oysters and
barnacles gain an advantage in the colonization of artificial substrates. This conclusion is not obvious, as natural hard bottoms are widely developed in the bay (e.g. oyster reefs and grounds, gravel bottoms, and rocky intertidal zones), and sessile organisms already have enough space for settlement. Moreover, oyster settlements in the form of banks, reefs, and fields are widely distributed in Amursky Bay, occupying 30% of the total distribution area of oyster settlements in Peter the Great Bay and being a thriving community (Rakov, 2008).

In general, qualitative and quantitative characteristics of the benthic communities of Amursky Bay in the 2000s differed from those of the 1930s, 1950s, 1970s, and 1980s: changes were observed in species composition, dominant and subdominant species, abundance, diversity indices, eutrophication, and chemical contamination of the bay, which are the most important factors responsible for possible transformation of benthic communities (Lutaenko & Vaschenko, 2008). However, methodological differences of various research approaches in benthic studies do not allow for affirmation of this conclusion. Based on the results of a comprehensive survey of benthos in Amursky Bay and in other areas of Peter the Great Bay, Nadtochy and Galysheva (2012) reported that the average total benthic biomass was two times higher at the time of study than that estimated in the 1920s–1930s, and sufficient changes in structure and composition of benthic communities have not been observed.

In examining the effects of pollutants on marine benthic communities, one must be aware of natural long-term fluctuations, which might wrongly be attributed to the effects of pollutants (Gray & Christie, 1983). Analysis of long-term hydrographic data for the North Atlantic Ocean shows evidence of cycles with periods of 3–4, 6–7, 10–11, 18–20, and 100 years, and benthic data suggest 6–7 and 10–11-year cycles are present, and evidence exists for a secular cycle (Gray & Christie, 1983). Thus, the cause of at least some of the long-term and interannual fluctuations in benthic biomass abundance in Amursky Bay may be partly (or largely) related to natural events, such as hypoxia. The main causes of hypoxia in Amursky Bay during the summer are a synergism between the monsoon climate of the southern Russian Far East and eutrophication of the coastal area; unpredictable nutrient fluxes caused by heavy precipitation provide ‘excess’ phytoplankton (Tishchenko, Lobanov, Sergeev, Semkin, & Zvalinsky, 2016). During autumn and winter, natural drivers (such as upwelling, decreased river runoff, and winter convection) alleviate hypoxia. At the same time, the available published historical data clearly demonstrate that the lowest values of DO obtained in the summer in the bottom waters of Amursky Bay have been systematically decreasing with time over the last 80 years, and there is a period between the 1960s and 1980s when Amursky Bay became hypoxic during the summer, most likely starting in the 1970s (Tishchenko et al., 2016). A direct biological consequence of hypoxia is the documented mortality of small fish (e.g. in autumn 2008). In coastal waters of South Korea, disturbances due to low DO and organic enrichment altered benthic community dynamics and resulted in defaunation during summer hypoxia with delayed recolonization occurring in winter; as DO decreased, the number of taxa, their abundance, and macrofauna biomass dropped significantly at inner bay stations affected by hypoxia; with the return of normoxic conditions in Chinhae Bay, recolonization was initiated by opportunistic species, with a 1–4 month lag (Lim, Diaz, Hong, & Schaffner, 2006). Such intra-annual benthic dynamics have never been studied in Peter the Great Bay in detail, although this may lead to reconcluding the causes of possible long-term changes in bottom communities. Only recently, Moshchenko, Belan, Borisov, and Lishavskaya (2017) stated that the deterioration of the ecological state of benthos in Zolotoy Rog, Dionid, and eastern Amursky bays was due not only to the high level of chemical contamination but also to oxygen deficiency and the complex factors involved. Thus, ‘changes’ in benthic communities may be rather described as ‘variations’ caused by both natural and anthropogenic factors. Climatic changes have not been considered in the regional literature as an impact factor of macrozoobenthic variations, although there is clear evidence of coastal warming in the northwestern Sea of Japan during the last decades: according to Gayko (2005), sea surface temperatures in Peter the Great Bay for the last 50 years have increased by 0.6 °C on average. Fish fauna in Peter the Great Bay significantly changed during the 20th century, indicating that two warming periods, in the first half of the century and in the 1990s, resulted in an influx of warm-water species (up to 55 and up to 53 species respectively) (Sokolovsky & Sokolovskaya, 2007).

Environmental and biotic long-term changes in scallop aquaculture areas are of special interest. In Minonomosok Bay (Possjet Bay, south-western part of Peter the Great Bay), the oldest scallop (Japanese scallop M. yesoensis, a large scallop cultured mostly in cages) aquaculture farm has existed since 1971. The total annual yield of Japanese scallop spat varied from 6 million to 10 million individuals for the last 30 years; two-thirds of this amount were placed in cages for further rearing, and the rest were seeded on the bottom or passed to other enterprises; from 1986 up to 2002, the total yield of scallops was 950 t, or 6.3 million individuals (including those that were reared to commercial size on the bottom and in suspended cages; Vyshkvartsev, Regulev, Reguleva, Grigorjev, & Lebedev, 2005).

Benthic communities here were described in detail by Lebedev, Levenets, and Vyshkvartsev (2004) for 1997 and then by Levenets and Lebedev (2015) for 2012. In total, 140 taxa of benthic organisms were found in the 1990s, with molluscs and algae dominating by species number, abundance, and biomass; their total biomass was high, up to 29 kg m⁻². All these parameters were lower in 2012, based on underwater photographic surveys. The mono-dominant benthic communities changed mainly to polydominant ones; mainly, plant communities changed to animal-dominated ones; macroalgae changed biotopes: they were not attached to the bottom, because of increasing siltation, but mostly to aggregations of large mussels; and the trophic structure changed: primary producers were replaced by sestonophages, detritophages, and predators (Levenets & Lebedev, 2015). The high population density of nematodes in meiofaunal communities in central Minonomosok Bay was, probably, related to the increased organic matter content in the bottom sediments (Pavluk, Trebukhova, & Chernova, 2005), which is in accord with macrobenthic studies. Ninety-three species of benthic foraminifera were found in Minonomosok Bay in 1998 and 83 species in 2000. In
1998, the calcareous species *Cribroelphidium frigidum* was the most abundant; in 2000, calcareous *P. asterotuberculatum* and arenaceous species *T. inflata* and *E. advena* were dominant (Tarasova & Preobrazhenskaya, 2007). The effect of scallop cultivation on the distribution of benthic foraminifera was local, and the species composition and population density under scallop cages were decreased compared with areas of the bay where there were no aquaculture operations (Tarasova & Preobrazhenskaya, 2007).

A 1985 study of the meiobiotnic structure under the conditions of Japanese scallop aquaculture, which was carried out in Alekseev Bay (Popov Island, Peter the Great Bay), demonstrated that, in the central part of the bay with scallop cages, the bottom sediment comprised thin black mud with an admixture of shell debris, and intense sediment silation (64%) was also observed in the remaining bay area; the average organic matter content was 4–5% in the bottom sediments (Galtsova & Pavlyuk, 1987). The density of the meiobenthic organisms was very high in the bottom deposits under the cages, varying from $1.4 \times 10^{5}$ to $2.5 \times 10^{5}$ ind. m$^{-2}$. A depletion of the taxonomic structure of meiobenthos and an abnormal increase in population density of nematodes, ranging from $1.2 \times 10^{6}$ to $1.6 \times 10^{6}$ ind. m$^{-2}$, were recorded, whereas in cage-free sites, on the bottom, the population densities of the meiobenthos and nematodes were much lower, these being $1.9 \times 10^{5}$–$3.2 \times 10^{5}$ ind. m$^{-2}$ and $5.0 \times 10^{2}$–$2.6 \times 10^{5}$ ind. m$^{-2}$ respectively (Galtsova & Pavlyuk, 1987). In 1998, the aquaculture farm was removed from Alekseeva Bay, silting decreased, and the number of taxonomic meiobenthic groups increased; nematodes that previously dominated meiobenthos were later exceeded by foraminifers and their species diversity increased (Pavlyuk, Preobrazhenskaya, & Tarasova, 2001). Changes were revealed in the composition of the dominant species of these groups; the population density of meiobenthic animals decreased from $2.5 \times 10^{6}$ to $6.0 \times 10^{6}$ ind. m$^{-2}$ in the former aquaculture operation area and increased from $2.5 \times 10^{5}$ to $4.2 \times 10^{5}$ ind. m$^{-2}$ in the remaining area of the bay (Pavlyuk et al., 2001).

Variations of macro and meiobenthic communities under aquaculture conditions have occurred on a local scale during the last five decades in various regions of Peter the Great Bay, but the environment and benthos are generally restored after removal of aquaculture farms. In other cases, where aquaculture operations are still ongoing, degradation of benthic communities is observed at a higher degree.

Studies on the long-term changes in benthic communities mostly deal with soft-bottom communities, but there are some data on hard-bottom biotic variations. The giant or Gray’s mussel (*C. grayanus*) is very characteristic of subtidal hard bottoms in Peter the Great Bay, where it forms massive aggregations inhabited by numerous organisms that have both trophic and topical relationships with *C. grayanus* and among themselves (Golikov & Scarlato, 1967). The composition and structure of the giant mussel community in Vostok Bay were studied from 2000 to 2004 (12–22 m deep) in comparison with 1976 data (Galysheva, 2008). A total of 165 macrobenthic species were identified, and the community species composition had changed little since the 1970s; however, the total biomass had decreased, and the size–age composition of the *C. grayanus* population had changed; the trophic structure of the community had also changed, with the Shannon indices of species diversity and equitability becoming lower due to the intensive organic pollution of Vostok Bay resulting from increased recreational activities and sewage discharge (Galysheva, 2008). The average biomass of plants in the community from 2000 to 2004 was 251 g m$^{-2}$, and that of animals was 1,420 g m$^{-2}$, including 975.1 g m$^{-2}$ accounted for by the giant mussel; the total animal density averaged 563.7 ind. m$^{-2}$. A comparison with the data obtained in the 1970s shows that the average biomasses of animals and plants in the community had decreased by 47.4% and 37.3% respectively (Figure 14). The main cause for the biomass decrease was poaching: unselective mussel harvesting led to destruction of aggregation structures, decreases in their biomass, and consequent changes in quantitative characteristics of the accompanying species. On the whole, the biomass of *C. grayanus* in Vostok Bay had decreased by 57.6% over 30 years (Galysheva, 2008).

Soft-bottom communities in Vostok Bay have also been significantly transformed during the last decades. According to Galysheva (2004), this transformation can be attributed to both natural processes and different sampling techniques; however, obvious changes have occurred in the most polluted areas of the bay—in its innermost part and in Gaydamak Inlet—where water and bottom sediment are polluted with domestic sewage and petroleum hydrocarbons. In a previous study conducted in the 1970s (Tarasov, 1978), the *M. yessoensis–Mercenaria stimpsoni* community was recorded in Gaydamak Inlet, whereas from 2000 to 2002 these species, though still occurring, were no longer dominant, being superseded by the *Modiolus kuriensis* community dominating by biomass. The *O. sarsi–M. sarsi* community has persisted and is distributed fairly widely on soft bottoms but is not found in Gaydamak Inlet; the polychaete *M. sarsi* inhabits mainly clean areas and is an indicator of unpolluted environments; thus, the disappearance of the previously dominant *M. sarsi* can be explained by impairment of the environment because of the accumulation of organic matter and pollutants in sediments (Galysheva, 2004). Analysis of the macrophyte species composition

![Figure 14](image_url) Changes in mean values of macrobenthos biomass in the giant mussel (*Crenomytilus grayanus*) community in Vostok Bay since the 1970s. (After Galysheva, 2008)
and the value of the floristic coefficient suggested a moderate anthropogenic impact on Vostok Bay (Galysheva, 2004).

2.2.3 Port areas

A number of small ports and two large ports are located in Peter the Great Bay. Vladivostok is the largest Russian Pacific port, occupying the entire area of Bosphor Vostochny Strait and Zolotoy Rog (Golden Horn), Diomid, and Uliss bays and some other adjacent areas. The coastline of the port area is heavily modified with various port facilities, wharfs, docks, and piers; additionally, a fishing port and a shipyard are included. Over the past 40 years, the water temperature in Zolotoy Rog Bay has been anthropogenically influenced by the effects of effluents from the Thermal Electric Station No. 2, as this station uses seawater for cooling produced steam, and heated seawater is discharged into the bay, causing thermal pollution (Belan, Belan, & Berezov, 2009). Zolotoy Rog Bay is the most polluted by urban and industrial wastewaters, with the highest volume of discharged untreated wastewater (Davydkova, Fadeva, Kovekovdova, & Fadeev, 2005; Tkalin, 1996; Tkalin et al., 1993; Vashchenko, 2000).

Analysis of polychaete populations in Zolotoy Rog Bay from 1979 to 1981 showed that 15 species inhabited this area (Bagaveeva, 1992). Among them, three species were found almost constantly and formed dense settlements: Capitella capiata (with a maximum density of 920 ind. m\(^{-2}\)), Schistomeringos japonica (1,770 ind. m\(^{-2}\)), and Cirratulus cirratus (1,080 ind. m\(^{-2}\)). In the inner part of the bay, only C. capiata was found. Observations at the same stations from 1986 to 1988 indicated that live macrozoobenthic organisms were absent in the inner part of the bay, whereas a small number of benthic species, represented mainly by polychaetes, were found in the central part, where the biomass and density were on average 2 g m\(^{-2}\) and 96 ind. m\(^{-2}\) respectively (Belan et al., 2009). In the outer part of the bay, the species richness and number of faunal groups increased, as well as the population density and the benthic biomass. However, in many cases, the high biomass in polluted areas was related to settlements of fouling organisms on piers, docks, and so on (e.g. Balanus crenatus, Eudistylia polymorpha, and Mytilus trossulus), constituting up to 62% of the total biomass, whereas the biomass of infaunal, soft-bottom organisms was only 28.7 g m\(^{-2}\).

Dominant species in Zolotoy Rog Bay varied from year to year, but the most abundant were the polychaetes Nereis vexillosa, C. capiata, and S. japonica (Belan et al., 2009). From the 1980s to 2001, benthic species compositions in Zolotoy Rog and Diomid bays did not change; macrozoobenthos in the most polluted area of the port was characterized by low biomass and species diversity but high population density. In 2001, bottom communities in these bays were in a state of degradation and were characterized by low diversity and biomass, as well as an exceptional predominance of opportunistic species. The average values of biomass, number of species, and ecological indices in these bays were the lowest in comparison with other areas of Peter the Great Bay (Belan et al., 2009). These biotic and environmental changes likely began to occur in the first half of the 1970s, when urbanization and industrialization were most intense in the USSR era. The rising level of marine pollution led to major changes in benthic community structure: benthic pollution-sensitive species with long life cycles were replaced by cyclic tolerant organisms, and taxonomic diversity dramatically decreased and a ‘dead zone’ lacking live benthic organisms was present in the inner part of Zolotoy Rog Bay (Belan et al., 2009; Figure 15). A recent benthic study in 2016 in the same port area of Vladivostok revealed that only 10 macrozoobenthic species were observed in Zolotoy Rog Bay: the polychaete species C. capiata occurred in the innermost part of the bay, five species were found in the middle part, and six species in the outer part (Moshchenko et al., 2017). The polychaetes C. capiata, Aphelochaeta pacifica, and S. japonica showed the highest frequency in Zolotoy Rog benthos, whereas only four polychaete species were collected in Diomid Bay with dominance of A. pacifica (540 ind. m\(^{-2}\)). The benthic composition was richer in outer Uliss Bay, with 16 species belonging to eight faunal taxonomic groups; the bivalve Macoma scarlatoi, the brittlestar O. sarsii vadicola, and the polychaete A. pacifica had the highest values of numerical parameters: the first one dominated by biomass (475.9 g m\(^{-2}\) on average), the second species by density (480 ind. m\(^{-2}\)), and the third one by density (420 ind. m\(^{-2}\)). In general, the lowest biomasses of macrozoobenthos were detected in the innermost parts of Zolotoy Rog Bay (<0.1 g m\(^{-2}\)) and Diomid Bay.
(6.0 g m$^{-2}$). Schornikov and Zenina (2014) found that ostracods, a group of meiofaunal organisms very sensitive to pollution, completely died out in the most polluted inner zone of Zolotoy Rog Bay, and only three of 73 species collected as empty shells in bottom deposits were found alive, indicating a later stage of degradation of the ostracod fauna.

Another study of the benthic environment of Zolotoy Rog Bay was based on samples from two sites with different concentrations of heavy metals—iron, zinc (Zn), copper (Cu), lead (Pb), manganese (Mn), chromium, nickel, cadmium (Cd), and cobalt (Co)—and petroleum hydrocarbons and included counts of culturable bacteria, complemented with microscopic diversity assessments of benthic communities (Fadeeva, Bezzverbnaja, Tazaki, Watanabe, & Fadeev, 2003). The specific communities had a limited number of species, tolerant to abnormally high levels of toxic compounds, and dominant species were several short-lived small polychaetes (C. capitata) and nematodes (Onchohaimium ramosum); the highest population density was recorded in microbenthos, diatoms, and various physiological groups of bacteria participating in biomineralization: marine heterotrophic bacteria oxidizing oil and black oil in addition to groups resistant to heavy metals. Thus, Zolotoy Rog Bay has experienced a catastrophic degree of defaunation and environmental degradation, being the most polluted and ecologically unhealthy area of Peter the Great Bay.

Port Vostochny (Vrangel Bay) is located in the easternmost secondary bay within Peter the Great Bay, Nakhodka Bay, and has operated since 1973. Port Vostochny is an intermodal container port at the eastern end of the Trans-Siberian Railway and the largest port in the Russian Far East. Long-term ecosystem studies and biota monitoring, including plankton and fishes in this area, show that most drastic changes happened in benthic communities due to dredging operations to deepen the port resulting in impoverishment of species composition, decreased biomass and species abundance, especially of long-lived fauna, and decreased bioproductivity (Rakov, Selivanova, Shevchenko, Zaivertanova, & Slobodskova, 2007). For example, at one station in 2005 (after dredging operations), the total benthic biomass was 0.63 g m$^{-2}$, whereas at the same station in 2004 it was 176.2 g m$^{-2}$ (Rakov et al., 2007). The same conclusion was drawn in an earlier study at Port Vostochny: benthic surveys carried out in 1989, 1995, and 2001 revealed changes in the structure of soft-bottom communities, but port operation had not caused significant environmental pollution by heavy metals, hydrocarbons, and other pollutants, whereas bottom dredging and the siltation induced by it drastically lowered the benthic biomass (Figure 16) and altered the trophic structure; nearly all sestonophages had disappeared and been replaced by detritivores, and the ecological state of the benthos was characterized as unstable (Gulbin, Arzamastsev, & Shulkin, 2003). Later, the state of benthic communities in Port Vostochny became more deteriorated: unlike benthic surveys from 2010 to 2011, in April 2012, the common green algae Ulva fenestrata and Enteromorpha linza and the red algae Pseudopolydora sp., Lumbrineris longifolia, Maldane cristata, and Polydora sp. were the major species that contributed to the abundance of the polychaete assemblages, and C. capitata, a well-known organic pollution indicator, occurred in the harbour region and the estuarine region of the bay (Shin, Choi, & Koh, 1992). The distribution pattern of polychaete assemblages seems to be influenced by the sedimentary facies and organic loads from Pohang city and seaport (Shin et al., 1992).

**FIGURE 16** Long-term dynamics of biomass of the total benthos and contributing taxonomic groups in Vrangel Bay (Nakhodka Bay). Bi: Bivalvia; Po: Polychaeta; Ga: Gastropoda; Oph: Ophiuroidea; Cr: Crustacea; Ne: Nemertea. (After Gulbin et al., 2003, text-figure 2)

decrease compared with the 1995 survey; the polychaete Pectinaria hyperborea reached a density of 150–200 ind. m$^{-2}$ in 2004 and 226 ind. m$^{-2}$ in April 2011, whereas in 2012 this species was totally absent (Elovskaya, Fedorets, Kosyanenko, Rakov, & Vasilyeva, 2013). The major reason for these changes was bottom dredging to deepen the port.

### 2.2.4 Korean sector of the Sea of Japan

A few studies on the macrobenthic faunal communities in the southwestern coasts of the Sea of Japan (East Sea in Korea), along the east coast of the Korean Peninsula (South Korea), were conducted (Choi, 2016). The data on the macrobenthic communities were obtained from investigations conducted more than 20 years ago, hindering direct comparison of recent faunal data and old data sets to detect the temporal change in faunal composition for any specific location (Choi, 2016).

### 2.2.5 Yeongil Bay

An ecological study was carried out to determine the distribution patterns of benthic polychaetes in 1991: 72 polychaete species were found, and the mean density was 1,485 ind. m$^{-2}$; S. bombax, Pseudopolydora sp., Lumbrineris longifolia, Maldane cristata, and Polydora sp. were the major species that contributed to the abundance of the polychaete assemblages, and C. capitata, a well-known organic pollution indicator, occurred in the harbour region and the estuarine region of the bay (Shin, Choi, & Koh, 1992). The distribution pattern of polychaete assemblages seems to be influenced by the sedimentary facies and organic loads from Pohang city and seaport (Shin et al., 1992).
2.2.6 | Ulsan Bay

Ulsan Bay is located in south-eastern South Korea (Gyeongsangnam-do), approximately 72 km north–north east of Busan, the second largest city in Korea. The coastal waters of Ulsan Bay are polluted with heavy metals: the levels of Cd, Pb, mercury, Cu, Zn, Co, and Mn were very high in the tissues of the mussel Mytilus galloprovincialis and comparable to elevated concentrations of these elements in Mytilus sp. reported for other geographical areas (Szefer, Kim, Kim, Kim, & Lee, 2004). In Ulsan Bay, the concentrations of Cu, Pb, and Zn in bottom sediments began to increase during the 1960s but have remained almost unchanged since 1970 (Lee, Lee, Lee, & Matsumoto, 1988). Khim et al. (2001) reported that approximately 280,000 t domestic waste and 300,000 t of industrial waste were discharged daily into the coastal region from Ulsan city and industrial complexes. Ulsan city was historically a fishing port and agricultural marketing centre, but since the opening of rail and road connections to Seoul and Busan, in 1962, it has developed as an industrial centre. Now, Ulsan is home to the world's largest automobile production complex and is the fifth largest automaker, the largest South Korean shipyard and shipbuilder, and the world’s second largest petrochemical complex; it is regarded as one of the Great Industrial Cities of Japan, up to 66 marine invasive species were known by 2010; in Korea, 41 species are suspected to be invaders in coastal waters, but this estimate includes all functional and taxonomic groups of organisms (Lutaenko, Furota, Nakayama, Shin, & Xu, 2013; Seo & Lee, 2009; Zvyagintsev, Radashevsky, Ivin, Kashin, & Gorodkov, 2011). Among the invaders, there are many benthic organisms, such as polychaetes, bivalves, gastropods, echinoderms, barnacles, decapods, tunicates, and bryozoans, that have become abundant and widespread and inevitably impact in one way or another the local benthic community, thus contributing to long-term changes in coastal ecosystems. Bioinvasions create so-called 'novel' ecosystems containing new species combinations that arise through human action, environmental change, and the impacts of the deliberate and inadvertent introductions of species from other regions (Hobbs et al., 2006).

One of the important consequences of the naturalization of invasive species in Peter the Great Bay is the predominance of new inhabitants over native species, which leads to alterations in the ecosystem structure and trophic relationships and occasionally to imbalances in coastal ecosystems. Ovsyannikova (2008) showed that a successful naturalization of the invasive barnacle Amphibalanus improvisus led to displacement of indigenous cirripedes as the dominant macrobenthic species of the local fauna. This species has become widespread via ship fouling, and it was first recorded in the fouling of hydrotechnical facilities in Peter the Great Bay in 1969 (Zevina & Gorin, 1971) and then became a common component of ship hull fouling and an abundant species in aquaculture installations and other anthropogenic substrata; Zvyagintsev (2003, 2005) found this species in the fouling of all active vessels of cabotage and harbour navigation examined in the bay in late July (i.e. at the beginning of the period when A. improvisus young begin settling). This barnacle has been recorded in almost all hydrotechnical constructions examined as a characteristic species in fouling communities in Amursky Bay and Zolotoy Rog Bay. Great ecological plasticity and the ability to withstand almost complete desalination have allowed this species to occupy a free ecological niche and to naturalize in Amursky Bay (Zvyagintsev, 2003). Later in this bay, A. improvisus was recorded in 11 intertidal communities in the inner part (Ivanova, Belogurova, & Tsurpalo, 2008). Near Cape Rechnoy, this species formed a monodominant community in the middle horizon of the stony intertidal zone with a population density of 900 ind. m−2 and a biomass of 6.8 g m−2; at other sites, its population density reached as high as 17,000 ind. m−2 and 157 g m−2 (Ovsyannikova, 2008).

Another invasive barnacle in the Russian part of the Sea of Japan is Balanus amphitrite, a subtidal, widely distributed, tropical–subtropical species. According to Zevina and Gorin (1975), this species occurred in buoy fouling in Nakhodka, Strelok, and Amursky bays only in warm years. In Peter the Great Bay, Zvyagintsev (2003) found B. amphitrite in the fouling of 46% of active vessels examined, except for ships that spent no less than 20% of time in Zolotoy Rog Bay, where this species has been registered on all objects examined. Balanus amphitrite reproduction and larval settlement take place from August to October under a wide temperature range, from 13 to 22.5 °C.

Numerous settlements of the Mediterranean mussel M. galloprovincialis with a high population density in Peter the Great Bay, where it has been known since the 1970s (Schepel, 2010),
provide an example of ecosystem alteration through the bioengineering activity of this mollusc. The Mediterranean mussel, previously known along the continental coast of the Sea of Japan between South Korea and Peter the Great Bay in Russia, has recently spread to Olga and Vladimir bays, approximately 300–400 km northward; it is also present on Moneron Island (north-eastern Sea of Japan) and along the coast of Japan (Lutaenko & Kolpakov, 2016). The dominance of this mussel may lead to suppression and displacement of other species; increasing competition between native and alien species, in general, is an important ecological consequence of invasions.

Five species of invasive polychaetes are known in the Russian waters of the Sea of Japan, and some have become very abundant components of benthic communities (Bagaveeva & Zvyagintsev, 2000; Zvyagintsev et al., 2011). *Hydroides elegans* is a eurybiotic species that survives significant fluctuations in salinity and rather high pollution. It dominates the fouling fauna in Zolotoy Rog Bay, and its biomass increases towards the innermost part of the bay. In general, *H. elegans* was then at the stage of 'ecological explosion' (Zvyagintsev, 2000). *Pseudopotamilla occelata* inhabits intertidal and subtidal areas in Alaska, Oregon, California, and Japan, and it was found for the first time in 1980 in the north-western Sea of Japan (Zvyagintsev, 2003). Its naturalization in Peter the Great Bay resulted in significant changes in the upper subtidal benthic communities. Other invasive species in Russian waters are either at a stage of early acclimation or no data on their abundance and distribution are available, but they would inevitably play an important role in the long-term transformation of coastal ecosystems. An important consequence of the spread of invasive benthic species is the predominance of new inhabitants over native species, which leads to alterations in the ecosystem structure and trophic relationships and is exemplified by barnacles and bivalve molluscs.

China has become the largest producer, consumer, processor, and exporter of fishery (in the broadest sense) products in the world (Cao et al., 2015). Along with accelerated economic growth, many non-native marine species (including fishes, molluscs, algae, crustaceans, ascidians, etc.) have been introduced into China for aquaculture (Lin, Gao, & Zhan, 2015) or for the ornamental trade (Mu et al., 2008; Xiong, Sui, Liang, & Chen, 2015). In addition, ballast water is one of the main sources of non-native species in coastal and marine ecosystems (Drake & Lodge, 2004). Up to now, at least 213 non-native species have been found in China (including the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea; Xiong, Shen, Wu, Lu, & Yan, 2017). The Yellow Sea has the highest number of non-native marine species (86 species), followed by the Bohai Sea (72 species), the East China Sea (57 species), and the South China Sea (36 species). Most non-native marine species in Chinese waters were introduced from the Atlantic Ocean, Pacific Ocean, and Indo-Pacific and Indian Ocean, which is mainly due to the fact that the countries (or regions) of the main aquaculture and aquarium trade with China are adjacent to these three oceans (Xiong et al., 2017).

Non-native species are those that occur outside of their natural range. That natural range could be as far as another country or as close as a different region of the same country. Meanwhile, an invasive species is a non-native organism whose introduction causes or is likely to cause economic or environmental harm, or harm to human, animal, or plant health. For marine invasive species, one of the main differences between China and other countries is the intention of introduction. Introductions are mainly intentional (ornamental trade and aquaculture) in China, whereas introductions are mainly unintentional (shipping, fouling, etc.) in other countries. Many non-native species have escaped from seawater culture fences and farms (Liang & Wang, 2001; Lin et al., 2015; Zhao, Zhao, Li, Zhu, & Wu, 2006). Established species may spread widely and become invasive in new locations, sometimes after a lag phrase of many years in which populations remain small and localized (Bax, Williamson, Aguero, Gonzalez, & Geeve, 2003; De Siva, Nguyen, Turchini, Amarasinghe, & Aber, 2009; Jeschke & Strayer, 2005; Molnar, Gamboa, Revenga, & Spalding, 2008; O’Dowd, Green, & Lake, 2003).

In China, approximately one-third of non-native marine species (74) introduced into China have escaped and established feral populations throughout Chinese territorial seas (Xu & Qiang, 2011). According to Lin et al. (2015), among all species introduced internationally into China, 9.5% have had negative effects on local environments. These negative effects include ecosystem degradation (e.g. sea grass beds destroyed by the Japanese sea urchin *Strongylocentrotus intermedius*; Liu, Liao, Zheng, Wang, & Chen, 2007), biodiversity loss, and even species extinction (e.g. devastating predation on a native ecosystem by the vegetative marine invasive species *Spartina anglica* Hubb and *S. alterniflora* Loisel, which have caused a decrease in wading birds and destruction of benthic habitats in the Yellow River Delta and the coastline of Fujian Province in China; Chen, Li, & Chen, 2004). Moreover, some invasive species are associated with economic impacts, including increased operating costs (e.g. fouling by the Pacific oyster *C. gigas*; Sun et al., 2010).

It is generally known that macro-organisms may be a major group of fellow travellers. Meanwhile, besides pathogens, three species have clear marine invasive records as fellow travellers (Lin et al., 2015), two of which are brown algae (*Costaria costata* and *Desmarestia ligulata*) and the other the red alga *Trichogloea lubrica*. All these three species were unintentionally transferred into China along with the introduction of *Undaria pinnatifida* from Japan (Lin et al., 2005). *Desmarestia ligulata* has become a harmful species in northern China, after its introduction along with the aquaculture species *U. pinnatifida*. In China, it reaches a length of 1 m, which is much longer than 30–50 cm in its native range (Liu et al., 2007). This brown alga releases sulphuric acid after death, which can greatly increase seawater acidity, which has significant negative impacts on marine ecosystems (Fabry, Seibel, Feely, & Orr, 2008). An outbreak of this species not only can influence local water bodies in China, but also might threaten neighbouring areas as acidified water is advected and spread by marine currents.

Intra and interspecific hybridizations are widely employed in breeding programmes to improve the economic properties of aquaculture species, through hybrid vigour or positive heterosis such as growth rate, disease resistance, and environmental tolerance (Bartley,
Ranching refers to the release of cultured juveniles (usually non-native aquaculture species) into unenclosed environments for harvest at a larger size in 'put, grow, and take' operations (Bell, Leber, Blankenship, Loneragan, & Masuda, 2008). Mass release poses the highest risk for the establishment of populations, and the established non-native species may become harmful after successful localization. For example, established Japanese sea urchin *S. intermedius* populations have threatened local environments and biodiversity in China, by destroying seaweed beds and aquaculture facilities and competing with native species for food and space (Liu et al., 2007).

**3 | DIFFERENT PROCESSES IN THE WATER AREAS OF CHINA AND RUSSIA STUDIED**

Shallow-water soft-bottom macrobenthic communities have gone through different processes in the water areas of China and Russia studied over the past decades; for example, undergoing obvious changes except for some areas of the north Yellow Sea in Chinese seas versus generally remaining in a stable condition except for some heavily polluted or disturbed areas in Russian seas. The different human activities and related intensities in the two countries could explain the different changes in marine biota. The triggers that led to this process in China include being mostly subjected to considerable human impacts through overfishing, pollutant discharge, land reclamation, and so on. Different from Chinese seas, the Russian seas have endured less pressure or interference from coastal human activities, except in some port areas that are heavily polluted or disturbed by dredging operations, or due to commercial fishing and poaching.

Shallow-water soft-bottom macrobenthic communities in the Russian part of the Sea of Japan have generally been in a stable condition in terms of biodiversity richness, abundance, and biomass for the last decades except for some heavily polluted areas or those disturbed by dredging operations in port areas such as Vladivostok Port (Zolotoy Rog Bay and adjacent inlets) and Port Vostochny (Nakhodka Bay). In port areas, there are even dead zones with no macrobenthos and significant faunal reduction of meio- and macrobenthos, such as that with ostracods that happened in the second half of the 20th century. There are variations in benthic communities in some shallow secondary embayments, such as Amursky Bay and Vostok Bay, but available data on long-term changes in soft-bottom communities are often contradictory due to different sampling techniques and collecting efforts. Soft-bottom communities are still dominated by the same animal groups as decades ago (polychaetes and bivalves), but there are, perhaps, cyclic changes in the abundance of some groups caused by natural phenomena (e.g. hypoxia). However, the abundance of select large invertebrate species (bivalve and gastropod molluscs, sea urchins, sea cucumbers, and decapod crustaceans) changed considerably during the second half of the 20th century and in the 21st century due to commercial fishing and poaching. Hard-bottom communities are slightly changed in the dominance of large mussels, but their biodiversity is the same as in the 1970s.

As opposed to the Russian part of the Sea of Japan, the shallow-water soft-bottom macrobenthic communities in the Bohai Sea and Chinese sector of the Yellow Sea have undergone obvious changes in terms of species composition, biodiversity richness, abundance, and biomass, except for some areas of the north Yellow Sea with the low-temperature environment of the YSCWM. The climatic changes and anthropogenic activities (overfishing, especially bottom trawling and dredging, pollutant discharge, land reclamation, etc.) trigger these kinds of changes on marine biota by destroying habitats, reducing population recruitment, and shortening food chains. In recent years, the expanding occurrence of hypoxia and anoxia in shallow coastal and estuarine areas has also brought significant structural changes in benthic communities, even causing dead zones in some bottom areas, such as the coastal zones of the Bohai Sea and Changjiang Estuary.

In terms of marine invasive species, there are obvious differences in many aspects between China and Russia due to different national legislation related to marine biodiversity issues; namely, introduction pathways of marine invasive species, non-native species composition and number, threats and impacts of marine invasive species to native communities and ecosystems (changing original genetic diversity and altering coastal ecosystems), and economic and public health impacts (Lutaenko, 2010; Xiong et al., 2017).

For the purposes of aquaculture and ornamental trade, China has imported a large number of non-native marine species in recent years. Russia is one of the top 10 countries or regions that export aquaculture products to China due to the adjacent seas between the two
countries (Xiong et al., 2015). Some hitchhikers will inevitably mix with those exported live products. Accompanied by the Chinese Belt and Road initiative and with Russia as a key node on this route, the two countries will have more frequent ocean transport and trade. More non-native marine species will most likely be introduced into China in the foreseeable future.

4 | CONCLUSION

Protecting the marine environment has become a worldwide challenge. In recent years, the Chinese Government has implemented several laws and regulations to protect the environment and biodiversity, recover marine bioresources, and control marine invasive species, which has brought positive changes to benthic communities in some water areas of the Bohai and Yellow seas. At the same time, positive changes and recovery of benthic communities have been observed in both macro and meiobenthic components after decreased industrial activity in Russia in the 1990s and after removal of some scallop aquaculture farms.

Subtidal bottom communities in North East Asian marginal seas have changed under human influence in various ways, including their structure and composition and becoming modified to different degrees depending on pressure. However, there is still insufficient data due to a lack of long-term monitoring programmes and international cooperation. In this regard, there is a need for further detailed studies of marine shallow-water biotic variations and environmental changes. This review is a step towards understanding and comparing these changes.

Long-term monitoring programmes should be developed to reveal future benthic changes and to separate the effects of cyclic variations of benthic communities from the impacts of pollution and eutrophication. Standardization of sampling procedures is required to compare changes/alternations of benthos across various regions worldwide. Coastal water warming could influence the biodiversity and abundance of benthic communities, and its effect should not be neglected, whereas the arrival of invasive species and their further spread should be monitored with global cooperation in joint projects.

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