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ORIGINAL RESEARCH ARTICLE

Biogeochemistry-ecosystem-social interactions on the Chinese continental margins

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Abstract Chinese continental margins are experiencing remarkable environmental changes driven by anthropogenic activities and climate change. As an important habitat and sea-based fish farming resource in China, the Bohai was selected as a case study to understand how ecosystems and social interactions are influenced by multi-stressors. The Bohai ecosystem has been considerably modified. The Bohai coastline has been significantly changed (e.g., total sea area decreased and morphology changed) by sea reclamation and riverine sediment transport related to agriculture and erosion. Therefore, the strict reclamation policy and "Grain-for-Green" program have been issued to protect the coastline. Nutrient concentrations and

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composition have been changed by fertilizer application, wastewater discharge, and variations in seasonal patterns of riverine nutrient fluxes. Hence, pollution control and prevention are necessary. More seriously, fishing resources have been altered, as a result of environmental changes and overfishing. Therefore, a summer fishing ban and stock enhancement should be vital besides environmental improvement. This study can help to predict and mitigate impacts on global continental margins that are experiencing similar environmental stress.

1. Introduction

The ocean plays a critical role in supporting human societal essential goods and services, but ocean ecosystems have been considerably altered by traditional and emerging anthropogenic activities such as overfishing, pollution, and sea reclamation (Borja et al., 2016; Halpern et al., 2008), resulting in 41% of marine ecosystems being deeply affected by multi-stressors (Halpern et al., 2008, 2012). Coastal marine ecosystems, in particular the Chinese marginal seas, have demonstrated phenomena such as eutrophication, hypoxic events, harmful algal blooms, reduction in biodiversity, and changes in coastal morphology (Davidson et al., 2012; Evan et al., 2011; Landrigan et al., 2020). These changes are mainly caused by population increase, dam construction, and pollution discharge (Liu et al., 2012a; Ning et al., 2010; Wu et al., 2021).

The Bohai is a shallow, semi-enclosed continental margin of the northwestern Pacific, with a surface area of 7.7 × 10^4 km^2 and an average water depth of 18.7 m. The Bohai includes Liaodong Bay, Laizhou Bay, Bohai Bay, the central Bohai, and Bohai Strait which connects with the Yellow Sea (Figure 1). River water discharge into the Bohai has been substantially affected by anthropogenic activities, of which the Huanghe (Yellow River) discharge accounts for $>$ 75% of the total (Lin et al., 2001; Liu, 2015; Ren et al., 2002; Wang et al., 2017). The Bohai is well known as an important habitat and sea farm base for fishery resources in the Chinese coastal seas; the Bohai ecosystems, however, have been significantly modified by anthropogenic activities, resulting in eutrophication, low oxygen events, and extensive coastline changes (Su and Tang, 2002; Wei et al., 2019; Zhai et al., 2019).

As a continental margin, the Bohai has been studied extensively, resulting in abundant hydrology and biogeochemistry data. This paper reflects the themes and discussions of the Continental Margins Working Group which was established jointly by Integrated Marine Biosphere Research (IMBeR at https://imber.info/science/regional-programmes-working-groups/cmwg) and Future Earth Coasts. The objective of this paper is to outline spatial and temporal variations of the hydrological and biogeochemical variables of the Bohai, their multi-drivers and pressures, and the ensuing feedback to ecosystems and to society. This study is vital to understand how ecosystems and society interact in the Bohai so that the information here can be extrapolated globally to predict and alleviate the stresses on similar continental margins that are experiencing greater ecosystem and societal responses to environmental variations.

2. Drivers and pressures of hydrographic and biogeochemical variations

Since the 1950s, reforms of the socio-economic system, the rapid growth of the population, and industrialization have accelerated China's environmental change, which includes land and water degradation (Bryan et al., 2018). Along with natural drivers (i.e. climate change), drivers closely related to intensive human activities in the Bohai Rim region substantially altered Bohai ecosystems, including population pressure, urbanization, economic development, associated waste water discharge, fertilizer use, and fishing pressure.

2.1. Population growth and urbanization

Although the population growth rate has slowed down in recent decades due to the family planning policy, the population has increased by approximately 150% in the Bohai Rim region since the 1950s (Figure 2). In 2019, the population was ca. 260 million representing 18.6% of the total national population. In addition, the urbanization rate has increased by ca. 45% in the last 70 years; more recently the rate has exceeded 64% (Figure 2). As the population continues to grow and migrates to the economically developed coastal areas, more waste water is emptied into the Bohai. During 1985—2015, industrial waste water discharge was stable because of the improvement of industrial wastewater treatment capacity, while domestic sewage effluent had been gradually increasing (Figure 3), related to population growth and urbanization and representing 75% of the total waste water discharge.

2.2. Industrial structure and societal needs

China, as the second largest and one of the fastest growing economies in the world, is experiencing a contradiction between economic development and environmental protection. On the positive side, it is believed that people's pursuit of material and spiritual satisfaction is constantly improving. In addition, sustainability and strategic environmental health priorities, particularly for the Bohai Rim region, were established during the 18th National Congress (Wang et al., 2021). In the Bohai Rim region, the GDP exceeded CNY 1.8 × 10^4 billion in 2019, representing 18%

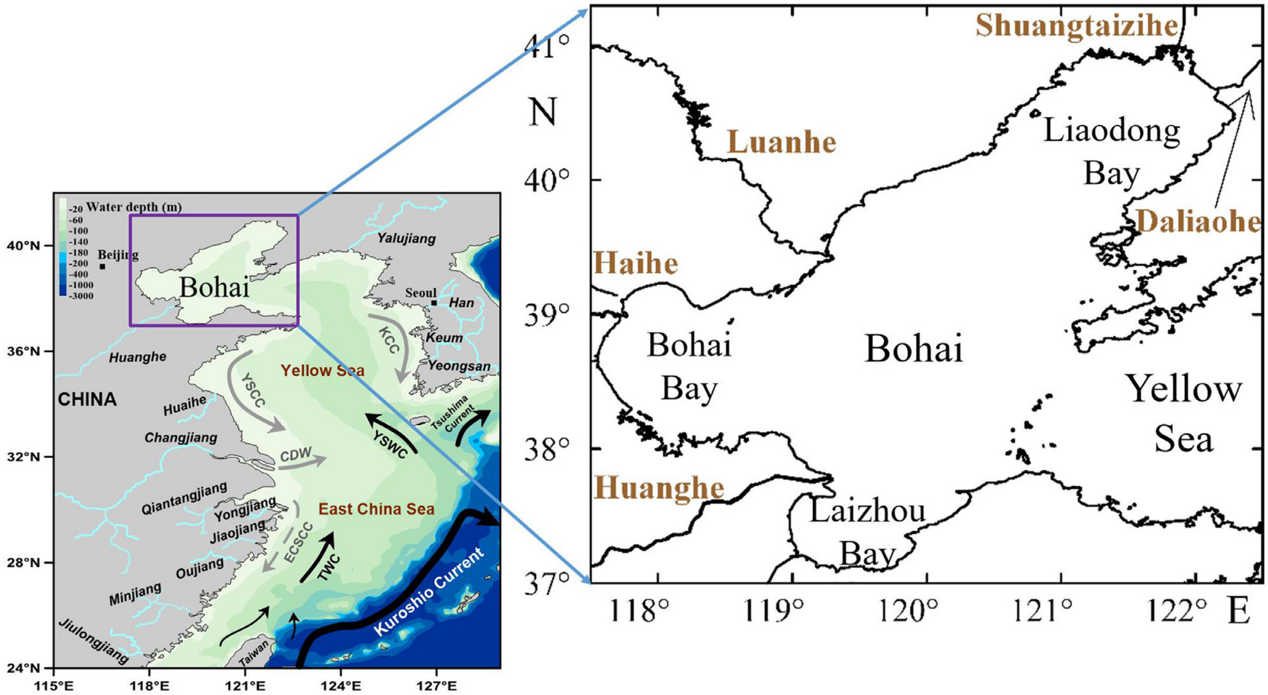

Figure 1 Map of the study area.

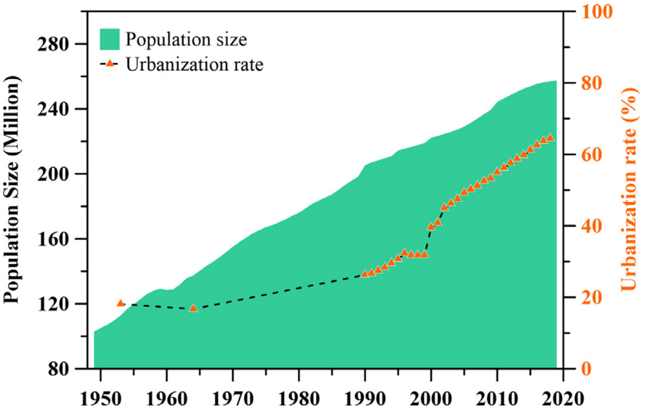

Figure 2 Population and urbanization rate in the Bohai Rim region since the 1950s (data source: https://data.stats.gov.cn/).

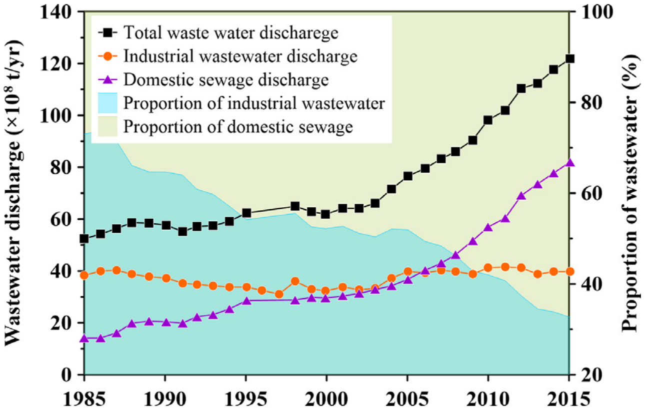

Figure 3 Waste water discharge in the Bohai Rim region since the 1980s (Wang et al., 2019).

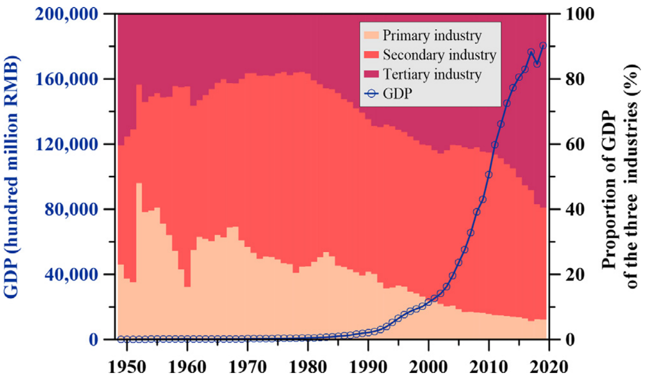

Figure 4 GDP and industrial structure in the Bohai Rim region since the 1950s (data source: https://data.stats.gov.cn/).

of the national total (Figure 4). Rapid economic development means intense drivers directly from human activities (Figures 3, 5, and 6), which likely drive the changes in the Bohai marine environment.

Although all major industries are experiencing growth, the industrial structure of the Bohai Rim region is constantly changing to promote the coordinated development of various industries in the national economy (Figure 4). In the last 70 years, the proportion of primary sector economic activities, mainly agriculture, forestry, animal husbandry, and fisheries, has continued to decline from about 50% in the 1950s to 6% in recent years; The proportion of the secondary sector, which is mainly industry, including construction, first increased and then decreased with the highest proportion (approximately 60%) in the late 1970s and approximately

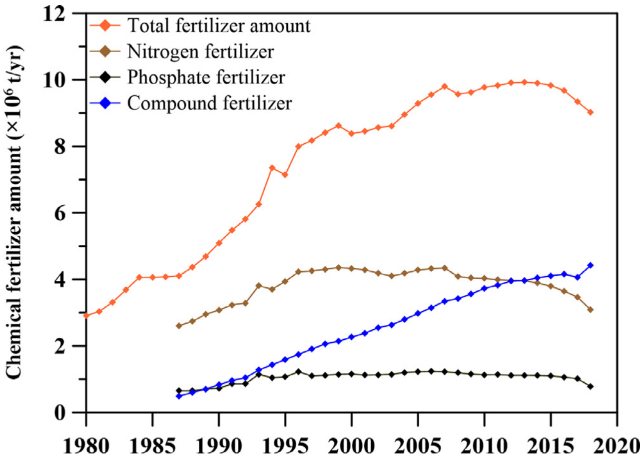

Figure 5 Fertilizer application rate in the Bohai Rim region since the 1980s (data source: https://data.stats.gov.cn/).

35% in 2019. The proportion of the tertiary sector, which is dominated by the circulation and service industries, first decreased and then increased with the lowest proportion (approximately 18%) in the late 1970s and approximately 59% in 2019 (Figure 4). In short, the industrial structure of the Bohai Rim region has evolved from being dominated by the primary sector in the 1950s, to the secondary sector in the 1970s, and is now dominated by the tertiary economic sector. This change in industrial structure means changes in human lifestyles, which is closely related to changes in stressors and the effects of human activities throughout each period. With the development and increase of the tertiary sector, people have been pursuing spiritual and cultural needs for a better life. Thus, a portfolio of national and regional management and policies has been established to improve the environment in the Bohai.

2.3. Coastline changes

Since 1978, China began to reform and open up, leading to rapid economic development and urbanization which, in turn, has led to large-scale exploitation of coastal resources. Coastline changes (expansion and retreat) are frequent in China, particularly in the Bohai, due to estuarine deposits, erosion, sea reclamation, and protection engineering (Hou et al., 2016; Meng et al., 2017; Suzuki, 2003). In the Bohai Rim region, coastline expansion occurs mainly in the southern Bohai Bay to the Huanghe Delta, and coastline retreat occurs mainly on the southern shores of Laizhou Bay (Duan et al., 2016; Hou et al., 2016).

The Huanghe has a high suspended sediment load due to extensive cultivation in the loess plateau in the middle reaches of the river (Wang et al., 2017). In the lower reaches, the shallow channel and highly elevated riverbed which is $>$ 8—10 m higher than the surrounding area, thus forming a unique “suspended river”, has created catastrophic disasters in the fluvial plain (Chen et al., 2012; Wang et al., 2017). Moreover, the main channel of the Huanghe has shifted often and has formed 11 delta lobes since 1855, affecting the coastline along Bohai Bay, the Huanghe Estuary, and Laizhou Bay (Yang et al., 2011).

The total area of the Bohai has decreased by 7.06% over the last 70 years from 81.3 $\times$ 10^3 km^2 to 75.6 $\times$ 10^3 km^2 with a shrinkage rate of $\sim$82 km^2/yr from the 1940s to 2014 (Hou et al., 2016). Over the past decades, the total length of the shoreline has increased by 1159.9 km, which is derived from an 80% decrease in the natural shoreline but an increase of 1977.9 km in artificial shoreline (Wei et al., 2019). Moreover, the area reclaimed from the sea has increased by 1988.5 km^2, with the further addition of areas under aquaculture and salt pans. The net effect is that construction land has increased and the area under agriculture has significantly decreased (Figure 7; Jin, 2020;

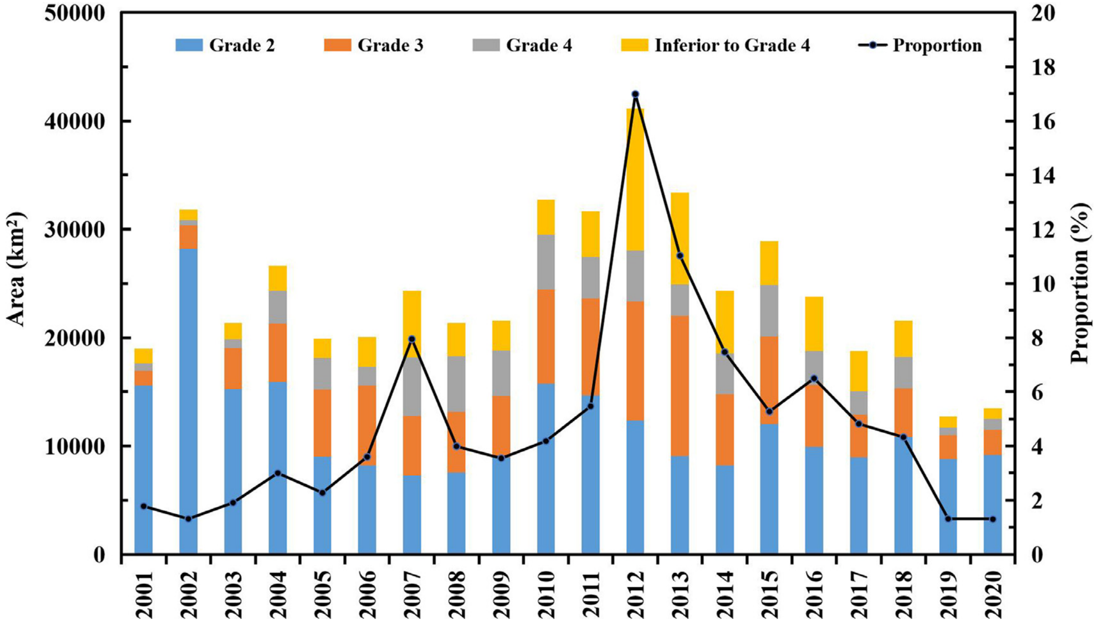

Figure 6 Area of varying sea water quality and the proportion of inferior to grade 4 sea water quality in the Bohai (data source: Bulletin of the Ministry of Ecology and Environment of China 2001—2020, http://www.mee.gov.cn/hjzl/sthjzk/jagb/).

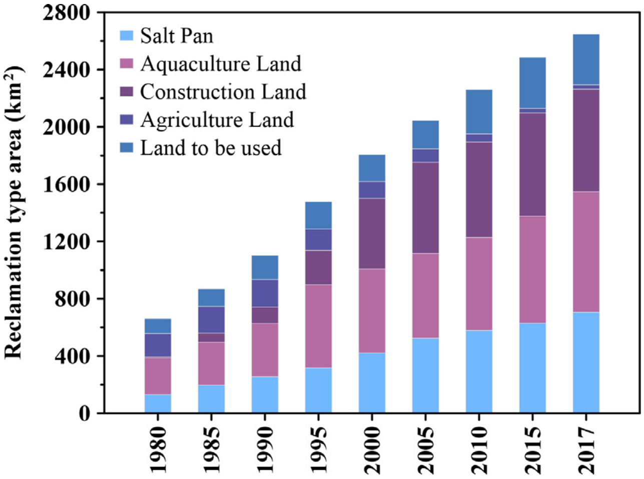

Figure 7 The total area (× 10^4 hm^2) of sea reclamation caused by the development of aquaculture, salt pans, agriculture, construction, and land to be used from the period 1980–2017 (Wei et al., 2019).

Wei et al., 2019). In addition, artificial wetlands increased by 162.6% from 1980 to 2017 while natural wetlands decreased by 66% (Wei, 2018).

Sea reclamation and coastline change have had a profound influence on the morphology and ecological environment of the Bohai; for example, the tidal regime has changed with M_2 amplitudes increasing up to 20 cm in 1976–2011 (Pelling et al., 2013). Based on time series data at the tidal gauges (i.e. Yangjiaogou and Longkougang gauges), the mean relative sea level rose approximately 2.1 mm/ yr in western Laizhou Bay and 1.7 mm/yr in eastern Laizhou Bay over the last 50–60 years (Deng et al., 2016). In addition, the intertidal wetlands diminished quickly and continuously (Duan et al., 2016), resulting in the loss and/or fragments of essential fish habitats (Jin, 2020; Meng et al., 2017).

2.4. Freshwater discharge and sediment load to the sea

The freshwater discharge and sediment load of the Huanghe have shown interannual oscillation since 1950 with a decreasing rate of 0.61 km^3/yr and 0.21 × 10^8 ton/yr, respectively (Figure 8). Of the reductions, human activities contributed ca. 55% and, in the 2000s, climate change accounted for the remainder (Miao et al., 2011). Historically, the days with no water flow near the Huanghe mouth increased ten-fold (up to 200 days) in the late 1990s due to the increasing demand for water and the decrease in precipitation (cf. Zhang et al., 2001). Water consumption by agricultural and industrial activities increased three times from the 1950s to the 2010s, of which the consumption of water through agricultural activities has decreased from ca. 90% to 70% of total water consumption (Chen et al., 2005; China Water Resources Bulletin at http://www.yrcc.gov.cn/).

Since 2002, the Huanghe Water Conservancy Commission has implemented 19 water-sediment regulation events (WSRE), using the reservoir-regulated flood water at the beginning of every flood season, except in 2016 and 2017.

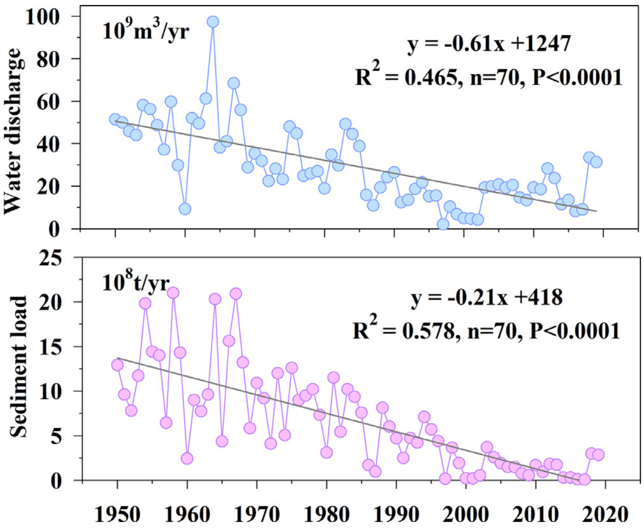

Figure 8 Annual freshwater discharge and suspended sediment load at station Lijin from 1950–2019 (data source: Huanghe Water Conservancy Commission, http://www.yellowriver.gov.cn/nishagonggao).

Generally, the WSREs have substantially alleviated the siltation in both the Xiaolangdi Reservoir and the lower reaches of the Huanghe to prolong the reservoir's operational life and increase the flood-carrying capacity of the downstream channel (Wang et al., 2017). Freshwater discharge and sediment load during the WSREs represented 18–56% and 8–63% with averages of 28% and 30% of the annual amount, respectively (Table 1). However, the riverbed in the lower reach has armored due to coarsening, and bed scouring via reservoir regulation is not sustainable (Wu et al., 2020). The WSREs have led to high monthly runoff and sediment load advancing up to two months earlier than was the case before the regulation events (Liu et al., 2012a). In particular, the Huanghe water has a long residence time in the Bohai with an average of 1.2 years (Liu et al., 2012b). In comparison, the WSREs and natural floods contributed 29% and 19% of annual freshwater discharge emptying into the Bohai during 2002–2012, respectively (Wu et al., 2017a). In addition, the Huanghe sediment load to the sea was mainly deposited in the delta in summer and resuspended and transported offshore in winter (Yang et al., 2011). Thus, changes in seasonal patterns of the Huanghe freshwater discharge and sediment load transport will have a far-reaching influence on the ecological environment of the Bohai.

2.5. Hydrographic variations in the Bohai

The drivers of hydrographic variations in the Bohai include winds, air-sea heat flux, and freshwater flux (river discharge, precipitation, and evaporation). All of them have apparent seasonal variations. The wind direction over the Bohai is northwesterly in winter and southeasterly in summer, and the wind speed is higher in winter (∼5 m/s) than in summer (∼2 m/s; Ren et al., 2017). More than 70% of precipitation concentrates from June to September while 35–50% of evaporation occurs from April to June (Fu et al., 1994). Since the annual precipitation (500–1000 mm) is lower than

Table 1 Annual freshwater discharge and sediment load, and the days and their proportion during the WSRS in annual freshwater discharge and sediment load as well, respectively in the lower reach of Huanghe during 2001—2019. The data without the regulation events in 2001, 2016, and 2017 are also provided for comparison. Data are from http://www.yellowriver.gov.cn/nishagonggao.

Year	Annual Flux		Water and Sediment Regulation Events				
	Water discharge (km^3/yr)	Sediment load (10^7 t/yr)	Day	Water discharge (km^3/yr)	Proportion in annual discharge	Sediment load (10^7 t/yr)	Proportion in annual sediment
2001	4.65	4.22					
2002	4.19	6.02	15	2.34	0.56	5.07	0.34
2003	19.21	40.36	24	4.22	0.22	15.06	0.63
2004	19.82	26.51	30	5.20	0.26	7.87	0.26
2005	20.68	18.07	23	4.13	0.20	6.17	0.27
2006	19.17	15.66	21	4.96	0.26	7.48	0.36
2007	20.40	15.06	30	6.66	0.33	9.84	0.33
2008	14.54	8.43	17	3.97	0.27	5.78	0.34
2009	13.29	6.02	17	3.76	0.28	4.07	0.24
2010	19.30	16.70	44	8.99	0.47	13.91	0.32
2011	18.51	9.26	22	3.86	0.21	4.26	0.19
2012	28.20	18.30	26	5.26	0.19	7.24	0.28
2013	23.69	17.30	20	5.28	0.22	5.58	0.28
2014	11.43	3.01	22	2.75	0.24	2.21	0.10
2015	13.36	3.14	24	3.08	0.23	1.86	0.08
2016	8.19	1.06					
2017	8.96	0.77					
2018	33.37	29.70	26	6.10	0.18	13.54	0.52
2019	31.22	28.26	54	11.11	0.36	16.33	0.30

the annual evaporation (1500—2200 mm), the freshwater discharge from rivers is important for maintaining salinity in the Bohai.

Over the period of one year, the change in these drivers is due to two factors; interannual oscillation and linear trend. The wind direction and speed during the period 1950—2011 showed interannual oscillations with periods from several years to 15 years (Ren et al., 2017). The strong wind events (>10.8 m/s) usually appeared in spring and had an apparent weakening trend during 1971—2008 (Wu et al., 2012). The precipitation around the Bohai during the period 1965—2014 had a declining trend (Zhao et al., 2018). However, in all months, the slopes of these trends are less than 0.78 mm/yr; that is a negligible value when compared to annual precipitation (>500 mm/yr) and therefore it is not expected to cause a significant change in salinity in the Bohai. On the other hand, the increasing and decreasing range of precipitation in the same month during the period 1965—2014 was close to its monthly mean value, indicating a possible larger impact from oscillation than from linear trend on the contribution of precipitation to salinity in the Bohai. The air temperature observed in the Bohai Rim region during the period 1951—2011 had a positive trend of ~0.03 degree/yr (Peng and Han, 2013).

2.6. Fertilizer application

With population growth and increasing human demand for food, fertilizer application generally increases to satisfy this demand. In the Bohai Rim region, nitrogen and phosphorus fertilizers first increased and then slowed down in the last 40 years; compound fertilizer has been increasing and its use has exceeded nitrogen fertilizer in recent years (Figure 5). Total fertilizer application had been increasing until 2013, but since then it has been stable with a recent decline in use. During the early stages, fertilizer application increases food production, but intensive fertilizer application induces fertilizer loss. It has been reported that the loss of fertilizer nitrogen in Chinese farmland can reach 19.1% of total fertilizer usage (Zhu et al., 2006). Thus, about 50—80 × 10^4 tons of nitrogen fertilizer (excluding nitrogen in compound fertilizer) are lost every year in the Bohai Rim region, which can be transported into the Bohai via riverine input and SGD, and affects the nutrient composition of the Bohai.

2.7. Nutrient inputs to the Bohai

External nutrient sources to the Bohai include river input, precipitation, submarine ground discharge (SGD), aquaculture effluents, and water exchange through the Bohai Strait. Internal nutrient sources mainly derive from nutrient regeneration in sediments and exchange between sediment and overlying seawater interface, which plays an important role in supporting nutrients for phytoplankton growth (Liu et al., 2003, 2011).

2.7.1. Nutrient transport from the Huanghe

During 2001—2019, nutrient concentrations exhibited a wide range of variations in the Huanghe with the concentrations of NO_3^-, DIN, dissolved organic nitrogen (DON), PO_4^{3-}, dissolved organic phosphorus (DOP), and $Si(OH)_4$ being 97–501, 105–524, 0.0–268, 0.03–0.95, 0.01–0.59, and 0.5–167 μM, respectively (Liu et al., 2012a; Wang et al., 2022; Wu et al., 2021). On average, DIN and PO_4^{3-} accounted for 91% and ca. 50% of total dissolved nitrogen and phosphorus, respectively. Among the rivers emptying into the ocean (Smith et al., 2003), NO_3^- concentration in the Huanghe is very high, PO_4^{3-} concentration is at the pristine level (0.50 μM) due to adsorption onto abundant sediment particles in the Huanghe, and $Si(OH)_4$ level is high due to high mechanical denudation and higher evaporation over precipitation in the Huanghe watershed (Cai et al., 2008; Li and Zhang, 2003; Liu et al., 2009). Therefore, the nutrient composition is characterized by a high ratio of N/P and a low ratio of Si/N.

Nutrient concentrations in the Huanghe showed high values in spring and low values in summer for NO_3^-, higher values for DON in summer than in other seasons, slightly low values for PO_4^{3-} and DOP in summer when sediment loads were highest, and no obvious seasonal variations for $Si(OH)_4$. Nutrient concentrations in the lower reach of Huanghe showed generally decreasing trends during 2001–2019 at rates of 0.34 μM/month for NO_3^-, 0.001 μM/month for PO_4^{3-}, and 0.26 μM/month for $Si(OH)_4$, respectively (Figure 9). The seasonal peaks of Huanghe freshwater discharge and nutrient transports have both been shifted by the WSREs with high monthly values appearing two months earlier than was the case before the WSREs (Liu et al., 2012a; Liu, 2015). Phosphate limitation of phytoplankton growth is aggravated during extremely high freshwater discharge periods (Liu et al., 2012a; Liu, 2015; Turner et al., 1990).

Nutrient transport fluxes from the Huanghe into the sea were $0.28–19.3 \times 10^8$ mol/month for DIN, $0.04–32.7 \times 10^7$ mol/month for DON, $0.07–26.9 \times 10^5$ mol/month for phosphate, $0.47–39.7 \times 10^5$ mol/month for DOP, and $0.02–92.5 \times 10^7$ mol/month for $Si(OH)_4$, respectively. Considering the drivers that influence nutrient levels in the Huanghe, the proportional contributions of different nutrient sources (Figure 10) to the Huanghe are estimated to be excess fertilizer run-off (46±1%) and sewage effluents (38±1%) for DIN, sewage effluents (86±1%) and excess fertilizer run-off (11±0.5%) for PO_4^{3-}, and runoff (48%±9%) and recharge water (47%±10%) for $Si(OH)_4$, respectively.

2.7.2. Atmospheric nutrient depositions

Based on limited observations, concentrations and depositions of water-soluble nitrogen and phosphorus from aerosols were reported to be higher in winter than in summer at Qinhuangdao, a coastal city in northeastern Bohai (Yu et al., 2020a). Atmospheric dry and wet depositions contributed 75.9, 70.6, 146.6, and 0. 1×10^8 mol/yr of NO_3^-, NH_4^+, DIN, PO_4^{3-}, respectively to the Bohai (China Council for International Cooperation on Environment and Development Annual Policy Report, 2020), and atmospheric DIN depositions to the Bohai could be up to 67.2×10^9 mol/yr (Shou, 2017). Atmospheric $Si(OH)_4$ deposition to the Bohai was 0.2×10^9 mol/yr (Liu et al., 2008). Compared to the riverine input (including the other rivers; Liu et al., 2009), atmospheric nutrient depositions ware 1–2 times that of the riverine input for NO_3^- and DIN, 38% of the riverine input for PO_4^{3-}, and 6% of the riverine input for $Si(OH)_4$.

2.7.3. Nutrient transport via SGD and other sources

The SGD in the Huanghe delta should be important, with the previously reported SGD value of 1280–1480 m^3/s in September 2006 and July 2007 using ^{224}Ra isotope (Peterson et al., 2008). Nutrient fluxes from SGD to the Bohai were 510, 3.6, and 240×10^8 mol/yr for DIN, PO_4^{3-}, and $Si(OH)_4$, respectively in November 2014 (Liu et al., 2017). These values were 7%, 43%, and 98% of the reported fluxes of DIN, PO_4^{3-}, and $Si(OH)_4$ delivered by the SGD of two bays (Eastern Laizhou Bay and Western Bohai Bay) of the Bohai (Wang et al., 2019a; Zhang, 2018; Zhang et al., 2016) and were used later for comparison, considering the substantial uncertainties of nutrients delivered by SGD. Nutrient fluxes delivered by SGD accounted for 70–90% of the sum of atmospheric deposition, riverine input, and SGD.

In addition, nutrients derived from feeding and non-feeding marine aquaculture effluents contributed <5% of dissolved nitrogen and phosphorus discharged from industrial wastewater and sewage effluents (Cui et al., 2005). Moreover, nutrient exchange through the Bohai Strait is limited (Liu et al., 2008).

2.7.4. Nutrient exchange at sediment and overlying seawater interface

Nutrient regeneration and exchange at sediment and overlying seawater interface is an important source of nutrients (Cowan et al., 1996; Liu et al., 2011). Based on pore water nutrient profiles in the Bohai, using a two-layer diagenetic equation (Liu et al., 2003), the benthic fluxes of nutrients during August 2008–2009 were calculated as follows: 162±174, −7.6±35.5, 1.0±0.8, and $145\pm103 \times 10^8$ mol/yr for NH_4^+, NO_3^-, PO_4^{3-}, and $Si(OH)_4$, respectively (Liu et al., 2011). In August 2015, the benthic fluxes of nutrients were similar at 133, −15.5, 1.4, and 240×10^8 mol/yr of NH_4^+, NO_3^-, PO_4^{3-}, and $Si(OH)_4$, respectively (Huang, 2016). Sediment was a source for DIN, PO_4^{3-}, and $Si(OH)_4$ in the Bohai. Compared to the sum of atmospheric deposition and riverine input, the benthic fluxes of nutrients contributed more PO_4^{3-} and $Si(OH)_4$, and less DIN. Thus, benthic nutrient fluxes can alleviate phosphorus limitation in the Huanghe Estuary.

2.8. Fishing pressure

Overfishing has a significantly negative influence on fishery resources in the Bohai Sea. Fishing effort is commonly used as an indicator to reflect fishing pressure, and fishing effort is represented by fishing vessel power. While fishing yield (or catch) and fishing efficiency can reflect the utilization status of fishery resources, and fishing efficiency is represented by catch per unit effort (CPUE). Based on statistical fishery data of China from 1979 to 2017 (Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 1979–2017), the fishing effort in the Bohai Sea continuously increased before 2002, which is reflected by the horsepower of marine fishing vessels. The horsepower of marine fishing vessels in the Bohai Sea exceeded 100 million kW in 1986, 200 million kW in 1996, and 300 million kW in 2002, then fluctuated from

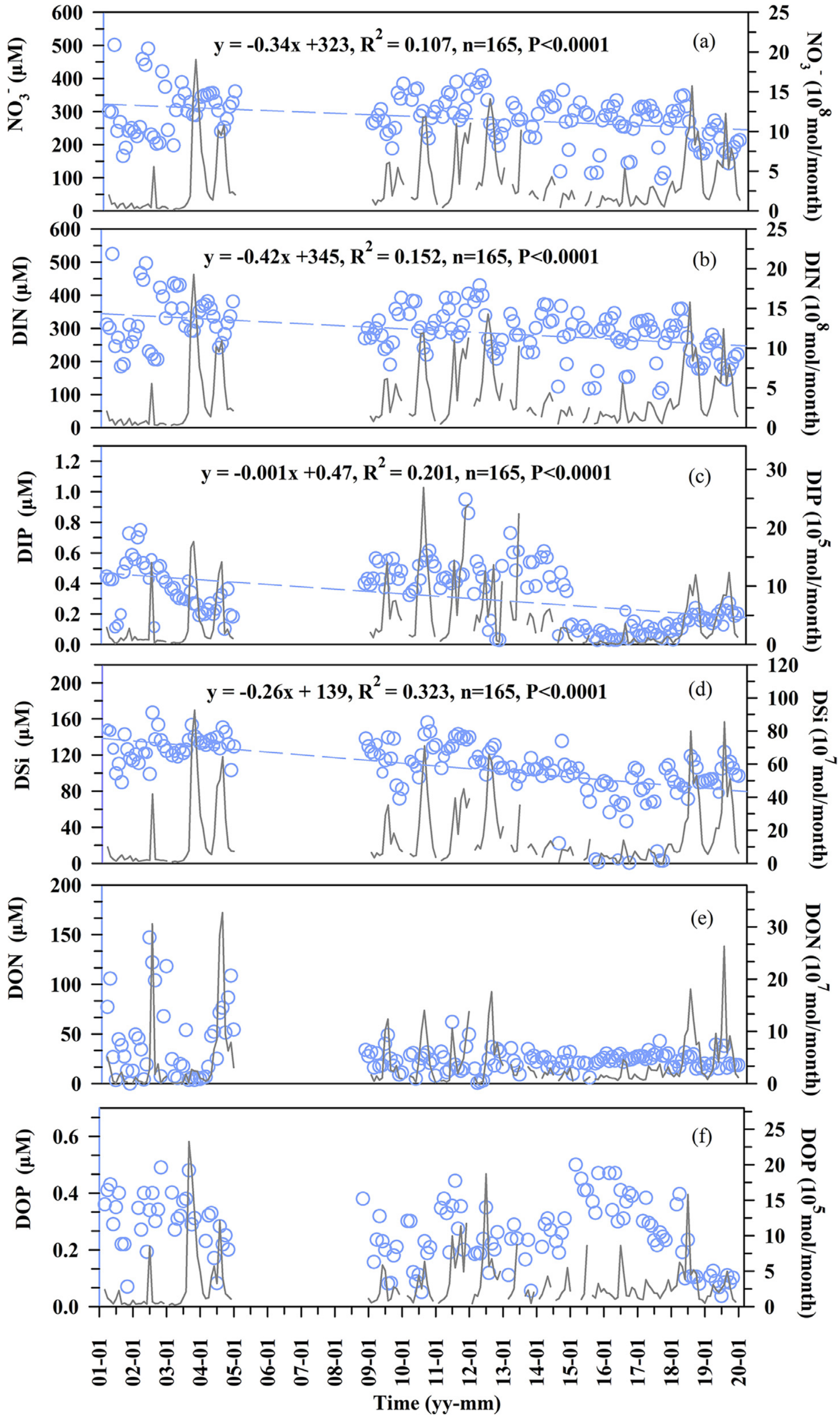

Figure 9 Monthly average concentrations (color data points) and fluxes (black lines) of nutrients in the lower reach of the Huanghe; the linear relationship lines for dissolved inorganic nutrients are also shown. Data are from Liu et al. (2012a), Wang et al. (2022), Wu et al. (2021), and the references therein.

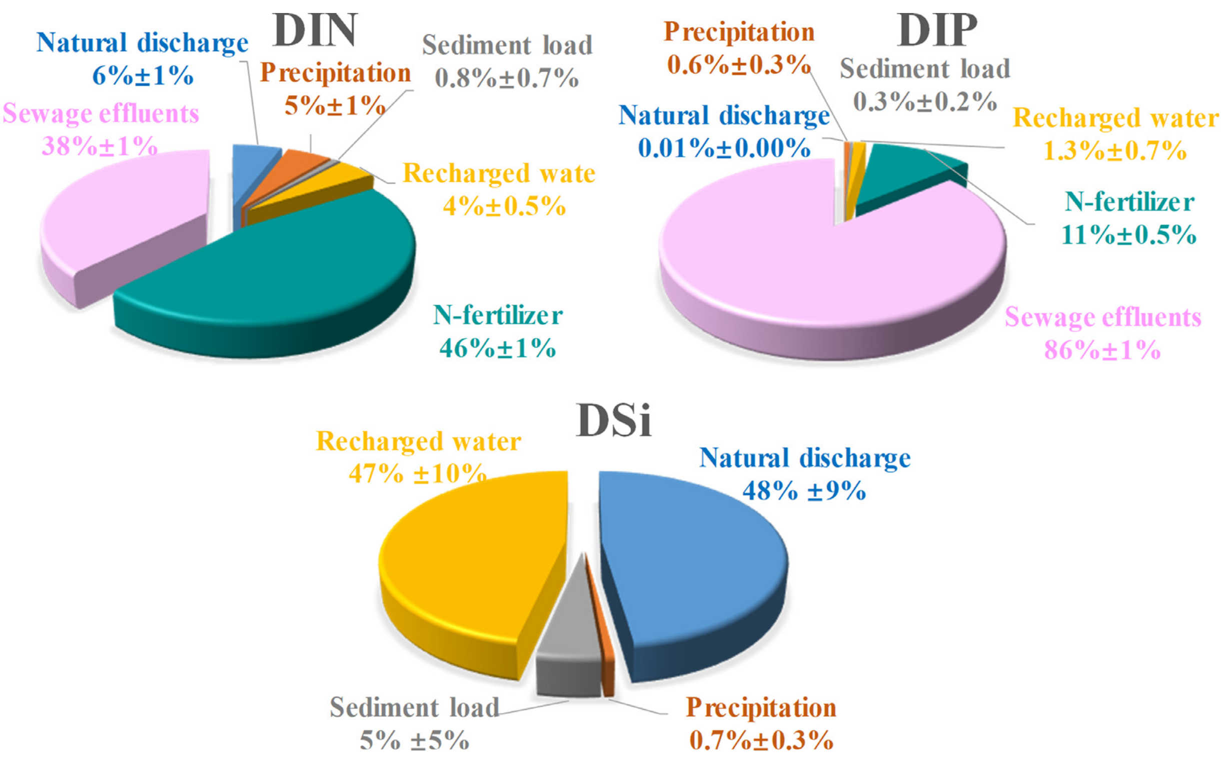

Figure 10 The proportions (%) of different nutrient sources to the Huanghe.

239 million kW to 340 million kW with an average of 286 million kW in recent years. For catch, the trend is incompletely consistent with the catch effort. It exceeded 1 million tons in 1993 and reached its maximum of 1.63 million tons in 1999. In the 21st century, it has been declining continuously and has stabilized at about 1 million tons since 2007. For CPUE, it showed a continuous downward trend from 0.52 tons/kW to 0.39 tons/kW in the 1980s. With the continuous improvement of fishing technology, the CPUE fluctuated from 0.39 tons/kW to 0.66 tons/kW in the 1990s. In the 21st century, overfishing has deteriorated, and the CPUE showed a decreasing trend with fluctuation, reaching a minimum of 0.29 tons/kW in 2017 (Hu et al., 2020). Since the 21st century, the fishing pressure of the Bohai Sea has been maintained at a high level, but the high fishing pressure showed low catch, indicating the decline of fishery resources in the Bohai Sea. In recent years, the fishing pressure in the Bohai Sea has decreased significantly, but the fishing efficiency (CPUE) has continued to decline, indicating that the reduction of fishing pressure has not effectively alleviated the declining trend of fishery resources and the fishing pressure should be continuously reduced to promote the sustainable development of fishery resources (Xu, 2011).

3. Status of environmental change in the Bohai

3.1. Hydrological change

The rising trend of sea surface temperature (SST) and sea surface salinity (SSS) has been recognized for twenty years (Lin et al., 2001). For the period 1960–1997, the trend of the annual mean of SST and SSS was 0.011 degrees/yr and 0.074/yr, respectively. Increasing air temperature and reduction in river discharge are likely the main causes for these positive trends (Lin et al., 2001). Using SST data measured at 11 stations along the coast from 1960 to 2012, the warming trend in the Bohai was reported to be 0.021 degree/yr with a high value in winter (0.03~0.04 degree/yr) and a low value in summer (0.01~0.02 degree/yr) (Li et al., 2018). Because a long time series of SST for the period 1901–2004 indicates the presence of a variation period of 40–50 years in the annual mean of SST in the Bohai (Zhang et al., 2005), it should be noted that the reported trend depends strongly on the length of SST records. The increasing salinity in the Bohai (Lin et al., 2001) was confirmed by other studies (Wu et al., 2004; Yu et al., 2009). However, the Huanghe discharge increased since 2003 (Figure 8). Although a numerical simulation suggested that its direct effect on reducing salinity was limited to Laizhou Bay (Mao et al., 2008), the increased freshwater should distribute over the entire Bohai after a year or more (Liu et al., 2012b) and eventually stop the increasing trend of SSS in the Bohai. Recently, the detachment of low salinity water from the Huanghe plume in summer, which forms an isolated patch of low salinity in the offshore area, was reported (Yu et al., 2020b).

A strong stratification in summer was reported in central Bohai where two cold bottom water masses were reported (Lin et al., 2006). Based on the collected data from the World Ocean Database for June, July, and August from 1970 to 1999, the vertical gradient of water temperature was estimated to be in the order of 0.4–0.6 degrees/m; this stratification intensity had a slightly decadal variation from 1970 to 1999 (Hu et al., 2014).

The schematic pattern for the circulation in the Bohai can be understood from the inflow in the northern Bohai Strait and the outflow in the southern Bohai Strait, which is the same throughout the year (Guan, 1994). Combined with the local currents in Bohai Bay, this exchange flow forms an anti-clockwise circulation in the southern area of the Bohai, which is also the same throughout the year. On the other hand, the local currents in Liaodong Bay have an opposite pattern in winter and summer. The inflow in the northern Bohai Strait follows the local currents in Liaodong Bay and, therefore, a large clockwise circulation forms from the central Bohai to Liaodong Bay in winter. However, the inflow in the northern Bohai Strait cannot enter Liaodong Bay in summer and the anti-clockwise circulation is limited around the head of Liaodong Bay.

Many studies have been undertaken to better understand the circulation dynamics in the Bohai (Hainbucher et al., 2004; Huang et al., 1996; Zhao and Cao, 1998; Zhou et al., 2017). The wind is the major driving force for winter circulation (Huang et al., 1996) while the horizontal density gradients or baroclinic forcing is the major driving force for summer circulation (Zhou et al., 2017). The tidal residual current is also an important component of circulation, but it exhibits a relatively large magnitude only in limited areas close to the coast (Wei et al., 2004).

Because the variations in circulation due to climate change are not as easily detected as water temperature and salinity, most reports on the long-term change of circulation are limited to some local features. For example, the change in the Huanghe summer river discharge strongly affects the circulation around the river mouth; a larger river discharge induces a more apparent northward or northwestward shift of diluted water and a stronger and faster current of diluted water (Shou et al., 2016; Yu et al., 2021). The change in coastline and water depth can induce a magnitude of ~0.05 m/s in the tidal residual currents close to the coast (Dong et al., 2020).

As a climate-related phenomenon, the long-term change of sea ice in the Bohai presents an interesting pattern. In winter, sea ice is found in a large area of Liaodong Bay and in the coastal area of Bohai Bay and Laizhou Bay (Shi and Wang, 2012). The sea ice annual maximum and average area presented a decreasing linear trend from 1958 to 2015 (Yu et al., 2020b), being a likely natural response to global warming. However, there were actually three different periods with different trends during the study period: a slightly increasing trend from 1958 to 1980, a strong decreasing trend from 1980 to 1995, and a moderately increasing trend from 1995 to 2015 (Yan et al., 2020). Such different trends resulted from oscillation with a period of ~30 years and ~17 years, associated with the Arctic Oscillation and North Atlantic Oscillation (Yan et al., 2020).

3.2. Changes in dissolved oxygen

In the Bohai, the accelerated daily depletion of bottom dissolved oxygen (DO; 2.0—2.8 μmol O_2/kg) was first noticed in the northern coastal area between June and August 2011 (Zhai et al., 2012). In August 2014, the low DO (<92 μmol O_2/kg) was reported as covering an area of 756 km^2, with an average water depth of 10.3 m above the seabed (Zhao et al., 2017). Oxygen depletion mainly occurred from mid-June to late August, driven largely by stratification, remineralization of organic matter, and lateral water exchange (Song et al., 2020; Zhao et al., 2017) in which pelagic respiration and sediment respiration contributed >60% and <40%, respectively (Song et al., 2020). Although the lowest DO values in the bottom water of the Bohai were still higher than the threshold for hypoxia (i.e., <63 μmol O_2/L), there has been a summertime declining trend since the early 1980s (Zhai et al., 2019; Zhao et al., 2017).

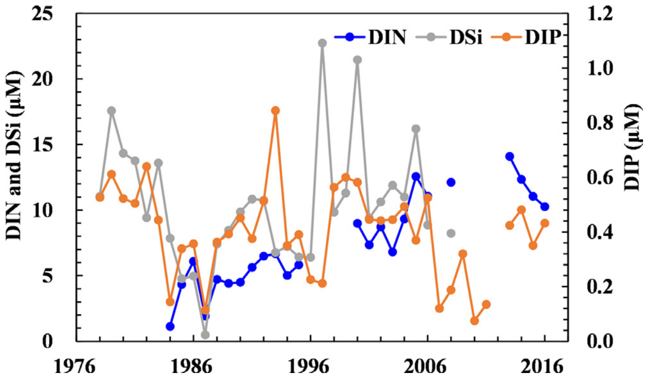

Figure 11 Annual average concentrations (μM) of nutrients in the Bohai (Wang et al., 2019b).

3.3. Nutrient characteristics and evolution trends in the Bohai

Nutrient concentrations are generally higher in the shallow coastal areas than in the central Bohai and Bohai Strait because of the effects of rapid population growth and economic development in the Bohai Rim region (Liu et al., 2011; Zhang et al., 2004; Zheng et al., 2020). There are also significant seasonal variations, with lower nutrient concentrations in summer than in winter. Nutrient concentrations are higher in bottom layer waters than in surface waters in summer when seawater stratification is obvious; in contrast, nutrients are also vertically constant in well-mixed winter (Wang et al., 2019b).

The changes in concentrations and composition of nutrients observed in the Bohai are mainly related to the Huanghe freshwater discharge together with other sources such as fertilizer application and sewage effluent (Liu et al., 2011; Ning et al., 2010; Wang et al., 2019b; Zhang et al., 2004). During 1978—2016, dissolved inorganic nitrogen (DIN) concentrations had increased since 1990 with the rate of increase becoming even greater since 2002. During the same period, the annual average PO_4^{3-} concentration had generally decreased, with a declining trend in summer and a slight rise in fluctuation trend in winter; the $Si(OH)_4$ concentration had firstly shown a slight decrease before increasing from 1987 (Figure 11). Thus, the N/P ratio increased and Si/N ratio decreased, indicating that PO_4^{3-} was a limiting nutrient for phytoplankton growth, leading to the limiting of $Si(OH)_4$ (Wang et al., 2019b). The incubation experiments off the Huanghe Estuary also demonstrated that photosynthesis was limited by PO_4^{3-} (Turner et al., 1990; Zhang et al., 2004).

3.4. Water quality status in the Bohai

3.4.1. Status of environmental parameters

National sea water quality standards cover 35 sets of parameters, the principal ones being smell, taste, suspended particulate matter, *E. coli*, fecal coliform, pathogens, water temperature, pH, dissolved oxygen, chemical oxygen demand (COD), DIN, PO_4^{3-}, cadmium, mercury, zinc, copper, lead, cyanide, sulfide, total petroleum hydrocarbon, DDT, BaP, methyl parathion, and radionuclides (^{60}Co, ^{90}Sr, ^{106}Rn, ^{134}Cs, ^{137}CS; National Sea Water Quality Standards of the P. R. China, 1997). As examples, and based on observation data, several sets of environmental parameters are addressed for levels of organic matter, trace metals, petroleum hydrocarbons, and microplastics.

The concentrations of dissolved organic carbon (DOC) in the surface water of the Bohai were 130.2–407.7 μM with an average of 225.9±75.4 μM in April 2010 (Chen et al., 2013). The concentrations of particulate organic carbon (POC) were 315–588 mg m^{-3} with seasonal patterns being highest in spring and lowest in winter in the Bohai surface water during 2002–2016. The POC concentration showed a decreasing trend prior to 2012, with an increasing trend until 2015, affected mainly by primary production and terrestrial inputs (Fan et al., 2018).

Using trace metal clean sampling and analytical techniques, several dissolved trace metals during summer in the Bohai were reported to be 15.1–30.4 nM, 10.9–23.1 nM, 0.72–1.37 nM, 0.091–1.00 nM, 0.6–3.3 pM, 2–26 pM, and 51–189 pM for Cu, Ni, Cd, Co, Zn, Ag, and Pb, respectively (Li et al., 2015, 2017). Trace metal levels were mainly affected by atmospheric deposition and riverine discharge (Liang et al., 2018), with their influence decreasing due to air pollution management and a decrease in freshwater discharge from major rivers emptying into the Bohai. In general, the concentrations of trace metals are at a pristine level in the Bohai in contrast to the other coastal seas (Li et al., 2015, 2017).

Total petroleum hydrocarbon concentrations were 23.7–508 μg/L in Bohai Bay with the highest levels in winter and the lowest in summer (Li et al., 2010). Marine oil and gas exploration increased methane concentrations by up to 4.7 times in surface water (Zhang et al., 2014). Thus, the Bohai was a source of atmospheric methane with sea surface CH_4 concentration of 2.27–25.63 nmol kg^{-1} and a saturation ratio of 107–1193% (Zhang et al., 2014). In general, petroleum hydrocarbon levels steadily decreased during 1996–2005 due to the decline of many industrial activities and a pollution control program in the Bohai Rim region (Li et al., 2010). Especially, ships are prohibited from directly discharging oily sewage into the water body in the Bohai, and the sewage discharge equipment is subject to lead-sealing management.

Microplastics are distributed widely in the Bohai with concentrations of 0.01–1.23 particles/m^3 (an average of 0.33 ± 0.34 particles/m^3), which included 51% polyethylene, 29% polypropylene, 16% polystyrene, 3% polyethylene terephthalate, and <1% polyvinyl chloride, polyurethane, and acrylonitrile, respectively (Zhang et al., 2017). The microplastic content is at a medium-low level in the Bohai compared to other continental margins (Zhang et al., 2017).

3.4.2. Status of sea water quality

Based on national standards, sea water quality is classified into four types according to function and protection objectives: Grade 1 applies to marine fishing, nature reserves, and rare and endangered protected regions; Grade 2 applies to aquaculture, bathing beaches, marine sports and/or recreation directly contacting water, and industrial use of water for food; Grade 3 applies to the waters affected by general industrial use and to scenic seashore areas; and Grade 4 applies to waters used for marine ports and development. The seawater quality of the Bohai went through three stages, from good overall to deteriorated, followed by gradual improvement along with the continued acceleration of coastal socio-economic development, an increase in the scale and intensity of resource utilization, and changes in ecosystem management and protection (Figure 6). At the start of the political and socio-economic reform since 1978, the ecological environment was good. From the 1990s to 2012, marine ecosystem quality deteriorated because of eutrophication, pollution, aquaculture development, land reclamation, and land use change due to intensified and low resource use efficiency during ocean exploitation (Su and Tang, 2002). During that period, the seriously polluted sea area extended to 1.3 × 10^4 km^2, representing 17% of the Bohai surface area. Since then, the marine ecological environment has improved, related to intensified pollution control and ecological restoration with the seriously polluted sea area decreasing to 1000 km^2, representing only 1.3% of the Bohai in 2019 (Figure 6).

4. Ecosystem responses to environmental change

4.1. Changes in phytoplankton composition and harmful algal blooms

The Bohai is an important fish habitat and sea farm base. However, the ecosystem of the Bohai has changed since the 1950s, threatening the sustainability of this fishery. Along with environmental change, phytoplankton composition has changed significantly since 1959 (Luan et al., 2018; Sun et al., 2002). Phytoplankton cell abundances were 8.33–472 × 10^4 cells/m^3, with diatoms accounting for 65.3–99.8% (average 92.5%) during 1959–2015, in which average phytoplankton abundances were 168, 216, 101, 28.0, and 68.7 × 10^4 cells/m^3 in the 1960s, 1980s, 1990s, 2000s, and 2010s, respectively (Figure 12). The abundance and species diversity declined in the last century before recovering in the 2000s. Phytoplankton succeeded from diatom-dominated communities with mainly centric diatoms such as *Coscinodiscus* spp. and *Chaetoceros* spp. to communities co-dominated by diatoms (*Thalassionema* spp., *Paralia sulcata*) and dinoflagellates (such as *Tripos* spp. and *Noctiluca scintillans*). Accordingly, there is an increase in the ratio of dinoflagellates to diatoms in this century compared with last century, with average dinoflagellates to diatoms ratios of 0.34, 0.16, 0.97, 1.52, and 1.24 in the 1960s, 1980s, 1990s, 2000s, and 2010s, respectively (Figure 12). Moreover, phytoplankton biomass appeared in two peaks annually during

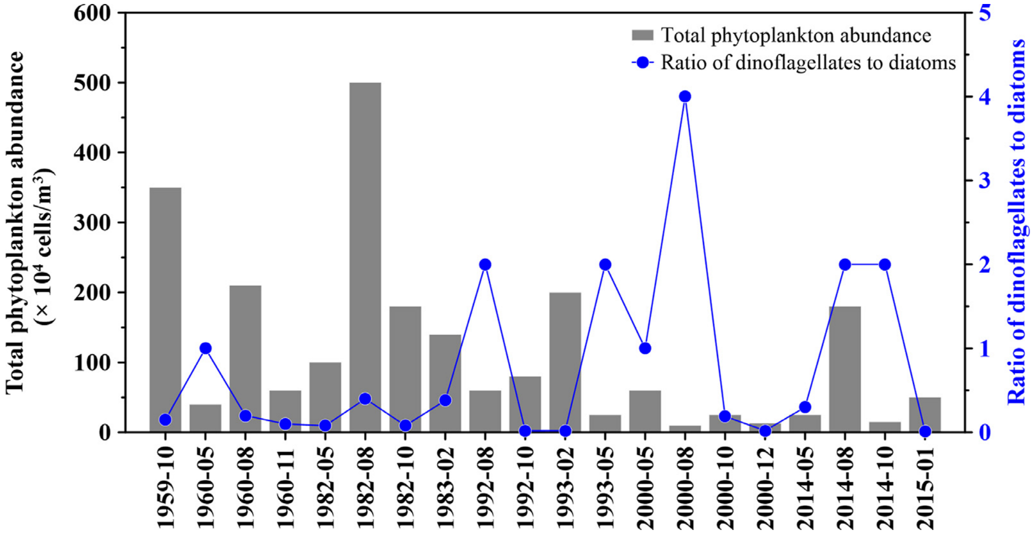

Figure 12 Long-term phytoplankton abundance and the ratio of dinoflagellates to diatoms (Luan et al., 2018).

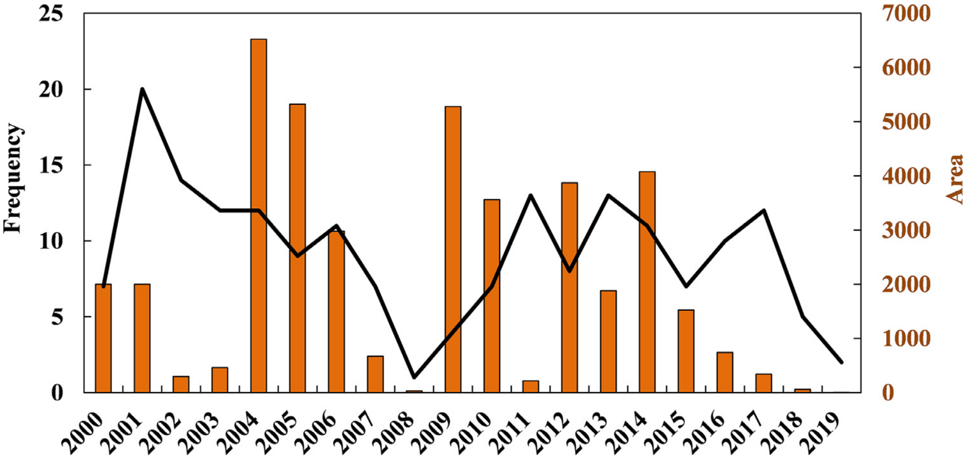

Figure 13 The occurrence frequency (times, black line) and spatial extent (km^2, orange bar) of harmful algal blooms in the Bohai from 2000 to 2019 (data source: http://english.mee.gov.cn/Resources/Reports//bomeaesoc/202012/P020201225370164112761.pdf).

1959—1999 (Fei et al., 1991). Since 2002, the second bloom of phytoplankton has been initiated earlier due to the effects of the Huanghe WSREs evidenced by only one peak of the surface Chl-α in spring-summer (Ding et al., 2020a; Liu et al., 2012a).

Harmful algal blooms (HAB) in the Bohai occurred mainly from June to August 1952—2014 when there were 142 times in total, with nearly 13% of HAB events covering an area of over 1000 km^2 (Song et al., 2016). The frequency and spatial extent of HAB outbreaks had increased significantly since 2000 although these have decreased in recent years (Figure 13). The dominant HAB causative species include *Aureococcus anophagefferens*, *Gyrodinium spirale*, *Noctiluca scientillans*, *Prorocentrum dentatum*, *Skeletonema costatum*, and *Phaeocystis globosa* (Song et al., 2016; Xu et al., 2017; Zhang et al., 2012). Moreover, a green tide caused by *Ulva prolifera* occurred near Qinhuangdao, threatening the ecosystems and the tourism of the western coast of the Bohai (Han et al., 2019).

4.2. Changes in zooplankton composition

The study of zooplankton composition and distribution characteristics in the Bohai began with the National Comprehensive Marine Survey in 1958—1960 (Office of Marine Comprehensive Survey, 1977). In the Bohai, dominant zooplankton species are copepods (such as *Paracalanus parvus*, *Centropages mcmurrichi*, *Calanus sinicus*, and *Labidocera euchaeta*) and chaetognatha (*Sagitta crassa*). Warm water species such as copepods (*Euchaeta rimana* and *Pontella spinicauda*), salps (*Cyclosalpa pinnata* and *Brooksia rostrata*), and chaetognatha (*Sagitta enflata*) were also observed mainly in winter (Bi et al., 2000) when the Yellow Sea Warm Current water is the strongest. Zooplankton abundance peaked in summer and two minor peaks in spring and autumn with dominant species of *Paracalanus parvus* and *Paracalanus crassirostris* in summer, *Acartia bifilosa* in spring, and *Oithona similis* in autumn, respectively (Bi et al., 2001).

Limited data imply that zooplankton abundance was higher in spring-summer of the late 1990s than those during the 1950s to the early years of the 1990s (Tang et al., 2003), but the long-term changes of zooplankton biomass in the Bohai have not yet been unraveled, except for some regions of the Bohai. In the Caofeidian coastal area in the northwest of the Bohai, zooplankton biomass showed an increasing trend according to observations in 1959, 1984, 1990, and 2004 (Wang et al., 2015a). Monthly observations in Laizhou Bay, an important spawning, nursery, aquaculture, and recruitment region, indicated that abundant zooplankton species succeeded; i.e., the abundant copepod *Calanus sinicus,* including C1-CV copepodites and adults, reproduce all year round, peaking in May and June (Zuo et al., 2017a), with *Paracalanus parvus* peaking in August (Wang et al., 2015b). Since 2000, *Centrapages dorsispinatus* has become the only dominant species of *Centrapages* from June to November, with a peak in September, replacing the previously dominant species, *Centrapages tenuiremis* (Zuo et al., 2017b).

Since the 2000s, giant jellyfish blooms caused by species *Nemopilema nomurai, Cyanea nozakii* and *Aurelia aurita* have been observed frequently in the Bohai (Dong et al., 2010; Wu et al., 2017b; Zheng et al., 2014). Increased giant jellyfish abundance caused changes in jellyfish composition; for example, the abundance of the edible jellyfish *Rhopilema esculenta* decreased with the increase of *Nemopilema nomurai* (Wu et al., 2017b; Zheng et al., 2014). Even human health and routine activities are threatened; in the summer of 2013, a giant jellyfish *Nemopilema nomurai* bloom occurred near Qinghuangdao causing approximately 1000 cases of human sting accidents and the death of one child (Wu et al., 2017b). In the summers of 2013 and 2020, the inflowing cooling water for the Hongyanhe Nuclear Power Plant in Liaoning Province was blocked by the jellyfish *Aurelia aurita,* temporarily disrupting the operation of the nuclear reactor (Qiu et al., 2020).

4.3. Changes in fishery resources

Along with changes in the environment and with plankton composition in the Bohai, fishery resources have also experienced decreases in biomass and changes in species composition (Jin, 2020; Ning et al., 2010). The serious decline of fishery resources was first noticed during the early 1990s when no egg of the Chinese shrimp *Penaeus chinensis* was collected in the Bohai, where there was an important spawning and nursery habitat for this species (Su and Tang, 2002). Based on monthly investigations of horizontal trawls during 1982 to 2019, the species number and abundance index of fish eggs and larvae showed a decline in the 20th century with an increase in recent years (except in winter; Bian et al., 2018). In the Bohai, the dominant fish species had shifted from 1959 to 2010. Since then, large-sized and economically dominant species (such as the large-head hairtail *Trichiurus lepturus* and small yellow croaker *Larimichthys polyactis*) have been substituted by small-sized and low-trophic-level species (such as the hairfin anchovy *Setipinna tenuifilis* and Japanese anchovy *Engraulis japonicus*), driven by both top-down effect (increasing fishing pressure) and bottom-up effect (substantial environmental variations; Bian et al., 2018; Jin, 2020; Shan et al., 2016). The mean trophic level in the Bohai reduced at an average rate of 0.17/decade in the last three decades of the last century, which was higher than the global trend (Zhang et al., 2007). In the Bohai, the food web has simplified (Shan et al., 2016), and the maturity of the ecosystems has declined, according to the comparison of the initial (1982) and end states (2008) of the Ecosim model, incorporating 17 functional groups (Lin et al., 2016). Fishing and environmental changes were regarded as the main factors affecting the changes in fishery resources of the Bohai (Lin et al., 2016).

5. Societal responses to changing biogeochemistry and ecosystems

5.1. The water-sediment regulation scheme

Since 2002, the WSREs have been instituted to reduce sediment deposition in the Xiaolangdi Reservoir and the lower reaches of the Huanghe. The WSREs have generally attained their aim, i.e., inducing bed erosion in the lower reach of Huanghe and mitigating siltation in the reservoir (Wang et al., 2017). However, the regulation events have led to unexpected disruptions, including high monthly water discharge values, with sediment load, and nutrient transports occurring two months earlier than was the case before the WSRE interventions; this has led to aggravated nutrient imbalance in the Huanghe Estuary and the Bohai (Liu et al., 2012a; Liu, 2015). However, the WSREs are not sustainable due to continuous sediment siltation in the reservoir and the sediment coursing in the downstream riverbed, which impedes sediment escape from the reservoir and impedes sediment transport downstream (Wu et al., 2020). The WSREs will, therefore, require modification.

5.2. Coastline protection and management

Sea reclamation and coastline change have a profound impact on the ecological environment of the Bohai, such as diminished intertidal wetlands and fish habitats lost/fragmented (Duan et al., 2016; Hou et al., 2016). In July 2018, the State Council of China issued a directive to strictly control reclamation to protect the coastline and its ecosystems. Moreover, measures, including the "Grain—for—Green" Program issued in 1999 to increase vegetation coverage, reduce erosion, and restore degraded ecosystems (Feng et al., 2016; Wang et al., 2016), can also decrease the sediment load to the rivers and the adjacent Bohai, thus alleviating coastline change and area shrinkage of the Bohai.

5.3. Pollution control and prevention

To restore and sustain the ecosystems of the Bohai, integrated management of the Bohai is necessary, including controlling pollutants from land-based sources and preventing marine pollution. For example, the main DIN and PO_4^{3-} inputs to the Huanghe and adjacent Bohai were excess fertilizer run-off and sewage effluent. In 2015, the Ministry of Agriculture of China (now called Ministry of Agriculture and Rural Affairs of China) issued a directive calling for zero

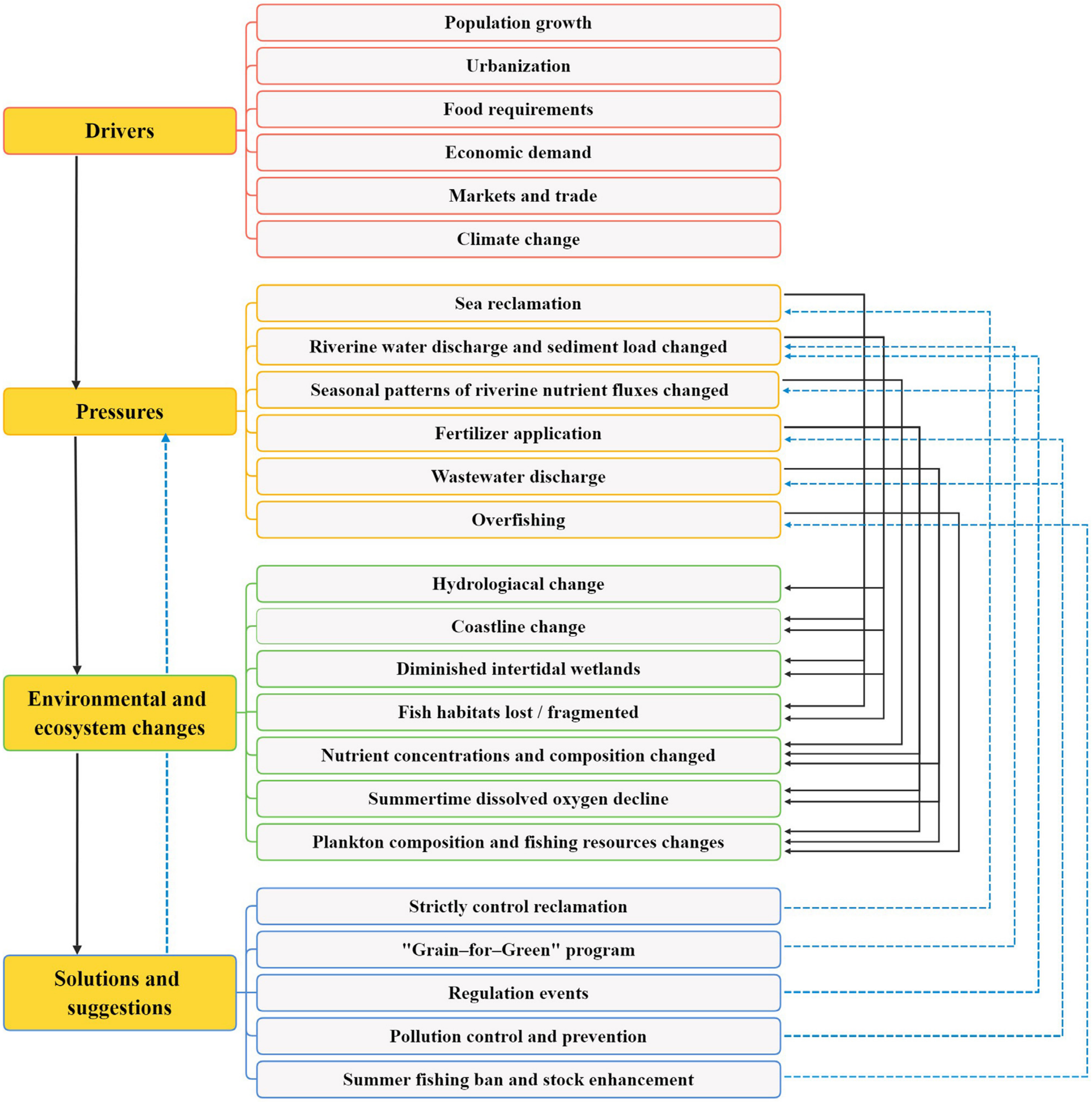

Figure 14 The interlinkage of the drivers and pressures on the environmental state variables and social responses as well.

growth of synthetic fertilizer application after 2020 and provided an upper limit for fertilizer application. Ameliorating the methods of fertilizer application and improving sewage treatment technology can reduce nutrient input into the Huanghe and the Bohai.

5.4. Fishery resources management and governance

The health of fishery resources reflects the status of broader ecosystems. The ultimate aim of integrated marine management is to restore fishery resources and biodiversity. A summer fishing ban, which was implemented in the Bohai during the fish nursing and spawning periods from June 1 to September 1 during 1995—2016 and then from May 1 to September 1 since 2017, combined with stock enhancement, has, to some extent, played a role in restoring fishery resources. The fish species composition in the Bohai was affected by both top-down and bottom-up effects (Shan et al., 2016); a closed fishing season can be an effective way to restore fishery resources besides controlling pollutant emissions and protecting the environment. Moreover, with the current fishery resources conflicts in the Bohai, the development of equitable quota allocation schemes is necessary if long-term ecological health and sustainability are to be achieved (Ding et al., 2020b). A complete 10-year fishing ban was issued by the Ministry of Agriculture and Rural Affairs of China to protect the biodiversity of the Changjiang

(Yangtze River), starting on Jan 1 2020; this might provide useful experience and insight for the development of strategies to restore ecosystem and fishery resources in the Bohai. The conservation of fishery resources and the restoration of water ecosystems is a complex task. A fishing ban only goes so far, so further integrated and systematic measures must be carried out, especially the prevention and control of pollution. In addition, the wetlands and estuaries provide crucial habitats for marine living organisms; protecting and restoring these wetland and estuary ecosystems can be vital for the restoration of the fishery resources of the Bohai. Lastly, controlling sea reclamation is crucial to the protection of the wetlands and shoreline.

6. Cause-and-effect relationships

As discussed above, the Bohai ecological environment has been significantly modified by multi-stressors. To better understand the impacts of the variety of stressors, the interlinkage of the drivers and pressures on the environmental state variables and social responses as well has been visualized (Figure 14). Mainly driven by climate change (air temperature increased) and generally decline in riverine freshwater discharge, SST and SSS have increased. Therefrom, the wintertime sea ice area has decreased but the summertime stratification has increased. With societal basic needs of seafood, economic demand, and urbanization, extensive sea reclamation (i.e. increases in aquaculture, salt pans, and construction land) in the Bohai Rim region has led to decrease in the total sea area of the Bohai and morphology change. Moreover, extensive cultivation in the loess plateau of the Huanghe has led to abundant sediment load transported into the Bohai. As a result, tidal regime has changed, intertidal wetlands have diminished, and essential fish habitats have lost and/or fragmented. Fortunately, strictly control reclamation has been issued to protect the coastline and its ecosystems, and the “Grain-for-Green” program has been issued to increase vegetation coverage and reduce erosion.

Nutrient concentrations and composition have changed due to fertilizer application and wastewater discharge. Moreover, seasonal patterns of riverine nutrient fluxes into the Bohai affect dynamics of nutrients and seasonal variations of Chl-α in the Bohai. Pollution control and prevention, e.g. calling for zero growth of synthetic fertilizer application could decrease nutrient levels and reshape nutrient composition in the Bohai. To know its effects, it is necessary to keep a continuous and long monitor on the ecosystems of the Bohai, which have changed along with environmental change, including phytoplankton and zooplankton composition and fishing resources. Besides environmental change, overfishing has significantly negative influence on fishery resources, which have experienced decreases in biomass and changes in species composition with large-sized and economically dominant species substituted by small-sized and low-trophic-level species (Bian et al., 2018; Jin, 2020; Shan et al., 2016). Ongoing summer fishing bun and stock enhancement can be an effective way to restore fishery resources to some extent. Further integrated and systematic measures can be vital for the restoration of the fishery resources, including pollution control and protecting and restoring coastal fish habitats.

7. Summary and knowledge gaps

The ecological environment of the Bohai has been altered by human activities and climate change. Urgent tasks include natural coastline protection and restoration; management of sea-based activities such as aquaculture, recreation and sea reclamation; integrated land-ocean pollution management; biodiversity conservation to enhance the protection and effective use of coastline ecosystems and resources; promoting the health and sustainable development of coastal areas; as well as encouraging public participation and bottom-up initiatives. A quantitative understanding of biogeochemistry-ecosystem-social interactions is also vital, including projections of human activities and future resource use, the potential risks from increased human activities, and the effectiveness of governance and management of sustainability strategies. Various models delineate changing biogeochemistry and its potential effects on ecosystems; coupled biogeochemistry-ecosystem-social models, in particular, are needed to help ensure the sustainability of the Bohai ecosystems. This study is vital to understand how to mediate future human- induced changes in the Bohai and extrapolate globally to predict and prevent similar marginal seas from experiencing major environmental changes.

Declaration of competing interest

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

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