Ecological Indicators 126 (2021) 107592

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Assessment of ecological stress caused by maritime vessels based on a comprehensive model using AIS data: Case study of the Bohai Sea, China

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ARTICLE INFO

Keywords:
Impact
Framework
Ecosystem
Stressor
Management

ABSTRACT

Increased maritime vessel activity has adversely affected the conservation of marine environments. The mobility and diverse operations of vessels increase the difficulty of marine spatial planning and protected-area management. This study proposed a "source-pathway-carrier-impact-response" (SPCIR) model to describe marine ecological stress caused by vessels (VES) and constructed a comprehensive assessment index system. The method was applied to the Bohai Sea in China using automatic identification system (AIS) data and geographic information system (GIS) spatial analysis. The results showed an obvious increase in VES from 2014 to 2018, with noise pollution, light pollution, and hydrodynamic interaction being the most prominent. Cargo vessels and oil tankers were the main stressors. Vessel activity seriously affected agriculture and fishery functions as well as marine-reserved zones in the Bohai Sea. The proposed SPCIR model can effectively identify the level and spatiotemporal characteristics of various vessel-related impacts and efficiently determine management priorities. It can provide a theoretical basis for marine area management and be conveniently adopted by management departments in various regions.

1. Introduction

Oceans play an essential role in global economic development. In recent years, with the deepening of economic globalization, import and export trade among countries has become more frequent. As much as 90% of international trade is conducted via marine transport, and such trade is growing at an average annual rate of 8.5% (Vespe et al., 2016). The development of maritime trade has brought prosperity to many coastal ports and increased the number of large vessels (Fiorini et al., 2016). Large container ships and tankers move through major ports and main shipping channels, bringing a constant flow of commodities. However, they also generate harmful pollutants, which damage marine ecosystems and even harm local coastal residents (Longépé et al., 2015; Tichavska and Tovar, 2015; Chen et al., 2017a). Moreover, numerous fishing vessels catch large amounts of seafood, which not only exhausts offshore fishery resources but also increases collision risks (Goerlandt and Kujala, 2011; Tassetti et al., 2019).

Today, marine vessel activity has become increasingly standardized as a result of environmental protection standards set by the International Maritime Organization (IMO), along with automatic identification systems (AIS) and vehicle tracking systems (VTS). Yet, it remains difficult to monitor the impacts of vessel activity. Heavy maritime traffic has profound effects on the marine environment, maritime traffic safety, and marine utilization management (Stefano et al., 2018; Svanberg et al., 2019). Thus, vessel activity is an important factor to consider in marine spatial planning, management, and ecological protection (Stelzenmüller et al., 2008).

Many studies have investigated the contribution of maritime vessels to ecological stress in areas such as fishing (Russo et al., 2016; Campbell et al., 2014), noise pollution (Erbe et al., 2014; McKenna et al., 2013), exhaust emissions (Jalkanen et al., 2014; Song, 2014), collision risks (Zhang et al., 2018; Pan et al., 2012), and oil spills (Eide et al., 2007). Piet et al. (2007) and Russo et al. (2013) used AIS data to investigate the scope and trend of fishing activities and to assess fishing stress in fishing areas. Meanwhile, Merchant et al. (2014) found that noise from vessels seriously affected the survival, reproduction, foraging, and communication of marine life. Chen et al. (2018) and Hassellöv et al. (2013) found that increased marine traffic caused serious air pollution, which could possibly contribute to ocean acidification. Using AIS data, Liu et al. (2019) developed a management framework for maritime collision

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https://doi.org/10.1016/j.ecolind.2021.107592
Received 23 October 2020; Received in revised form 24 February 2021; Accepted 6 March 2021
Available online 31 March 2021

risk while Eide et al. (2007) constructed a decision-making system for oil-spill risk that could help identify high-risk areas.

The use of AIS data is a common link in the abovementioned studies. AIS has proven helpful for marine ecological protection and for spatial planning; it can also help researchers determine the amount of pollution and the corresponding vessel-management measures. However, prior studies have mainly focused on measuring specific stresses or identifying the scope of influence. In terms of methods, quantitative models have been established that combine the quantity and location of vessels reflected by AIS with other vessel information (e.g., engine type, fuel type, fishing method, fuel load). Through such methods, the specific ecological stresses caused by vessels can be precisely calculated. However, since different ecological stresses are investigated across different fields, the methods may differ, which can create calculation difficulties. Moreover, data acquisition can be difficult and can take a long time, which can impede timely decision-making and evaluation. It is necessary, therefore, to construct a comprehensive framework to assess ecological stress caused by vessels. In truth, the negative effects of vessels on marine ecology are produced synchronously and thus should not be considered separately. Therefore, to effectively manage and protect marine environments, all negative effects should be taken into account.

Some studies have taken vessel quantity and channel distribution as evaluation indicators to assess the cumulative stress on marine ecosystems caused by human activity. However, such studies failed to consider that different navigation/operation statuses can have different effects (Tamis et al., 2016; Kelly et al., 2014; Halpern et al., 2009). Few studies have comprehensively considered the influence of maritime shipping. It is necessary, therefore, to design an assessment framework that fully considers the processes and characteristics of activities and establish an indicator system to quantify ecological stress caused by vessels.

Many sea areas around the world experience heavy vessel traffic,

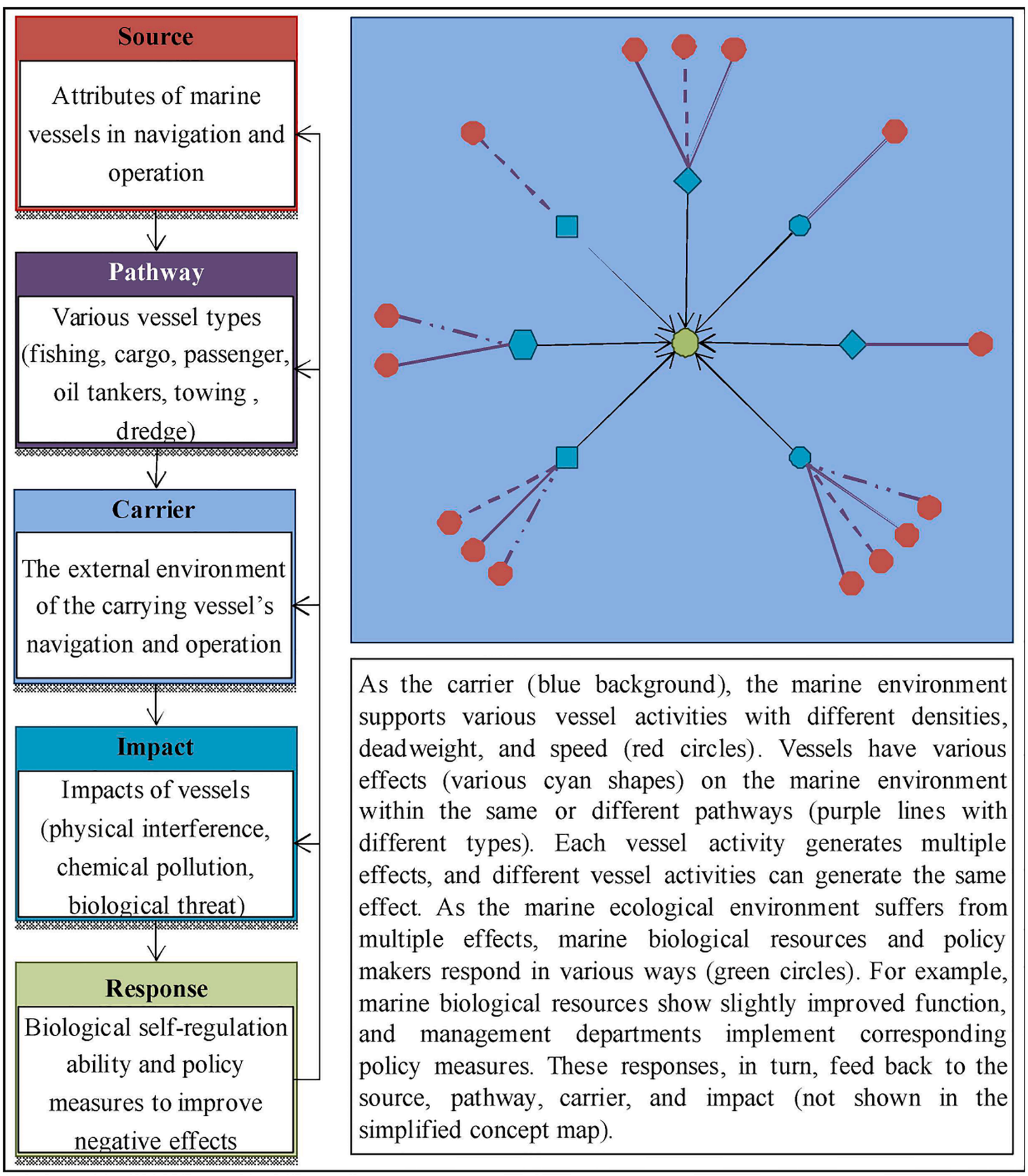

Fig. 1. SPCIR conceptual model.

which threatens environmental protection (Redfern et al., 2017; Bartnicki et al., 2011). The effects can be especially adverse for enclosed or semienclosed areas, such as the Mediterranean. Another example is the Bohai Sea, which is the largest inland sea in China. It is a vital maritime traffic channel in northern China that has important geopolitical advantages and greatly contributes to the coastal economy. There is intensive vessel activity in the area, including freight, passenger transport, fishing, and crude oil transport, all of which create complexities for marine environmental pollution and marine utilization management. Therefore, the Bohai Sea was considered an ideal area for this study's effort to assess marine ecological stress caused by vessels.

Based on the existing research described above, this study focused on assessing the comprehensive effect of maritime vessel activity and aimed to construct a spatial assessment model. Moreover, an indicator system was established in consideration of vessel type, operation status, marine environment, and ecological characteristics. Taking the Bohai Sea as a case, this study assessed the spatiotemporal characteristics of vessel-related ecological stress and identified high-stress areas and the main stressors to provide decision-making support for marine ecological protection.

2. Material and methods

2.1. Conceptual model

To assess ecological stress caused by vessels (VES), this study established a source-pathway-carrier-impact-response (SPCIR) model based on source-pathway-receptor (SPR) and pressure-state-response (PSR) models (Fig. 1). The SPR model describes how environmental pollutants flow from sources to potential receptors through different pathways. Instead of guiding the formulation of multicriteria decision-making through quantitative analysis, SPR qualitatively explores the influence paths, processes, and results of human activity in relation to natural environments (Narayan et al., 2012). PSR, meanwhile, is generally used for environmental evaluation through the weighted stacking of three indicators: socioeconomic development, environmental status, and recovery means. In PSR, the health of the ecological environment can be assessed quantitatively by simplifying interactions between humans and nature. However, as a result of poor spatiality, the PSR model is imperfect for helping decision-makers formulate targeted management measures (Wang and Xu, 2015). Considering these models, we developed an SPCIR model that establishes a process network of vessel activities causing ecological stress and a quantitative assessment indicator system. Furthermore, it has the characteristics of universality, standardization, and traceability.

Vessel-based activity is a dynamic source of pollution that differs from other types of activities. A sea area faces ecological stress from different vessels, which produce diverse impacts in varying degrees. For this reason, the main stressors cannot be easily identified by monitoring pollution indicators. It is necessary, therefore, to develop an effective way to describe and understand the complicated process of ecological stress caused by vessels. In this regard, the SPCIR model (Fig. 1) developed for this study aims to identify the key relationships between vessel activity and marine ecology. The following factors were considered in the source-pathway-carrier-impact-response linkages related to vessel operation: vessel density, type, deadweight, sailing speed, length, water depth, seabed sediment, seawater flow rate, biodiversity, and administrative policy. The proposed SPCIR model can indicate temporal and spatial changes in ecological stress and identify stressors in the region of interest. The management priorities of different zones are listed based on various vessel activities to help alleviate their harmful effects on the marine ecological environment.

2.2. Construction of assessment indicator system

An indicator system was built based on the SPCIR framework. In this system, the selected indicators can be adjusted according the characteristics of regions and activities.

Source (S) refers to activity characteristics, such as scale, frequency of occurrence, and distribution density. The stress of vessel-based activity on the marine environment is mainly related to vessel density (S1), sailing speed (S2), and deadweight (S3), which determine the influence degree of vessel activity on the quality and function of the marine ecological environment (Wolter et al., 2004).

Pathway (P) is the main mode of vessel activity, which divides the impacts of different vessel activities on the marine environment. For example, capturing biological resources is the main operation of fishing vessels; thus, the impact of such vessels is mainly "species capture" and not, for example, "oil pollution." The reverse holds true for oil tankers. Compared to using "vessel density" or "sailing route" to characterize the impacts of vessel activity, differentiating the impacts of different vessel types can greatly improve assessment accuracy. This study selected six vessel types: fishing vessel (P1), cargo vessel (P2), passenger vessel (P3), oil tanker (P4), towing vessel (P5), and dispersal vessel (P6). Guard vessels, hospital ships, and rescue vessels were not considered because of their relatively small quantity.

Carrier (C) refers to the marine environmental medium that bears the effect. The sensitivity coefficient of the carrier to activity is an important parameter in the assessment of ecological stress (Kaiser, 2003). The effect of the same activity will differ given the diverse characteristics of the carrier. For example, pollutants tend to purify more easily in waters with strong water-exchange capacity. When vessels sail in deepwater areas, they usually slightly interfere with hydrodynamic forces there; the smaller the particle size of seabed sediment, the easier it is to accumulate pollutants such as heavy metals, nutritive salt, and organic matter. Accordingly, the sensitivity of the marine environmental medium was represented by seawater flow rate (C1), water depth (C2), and seabed sediment (C3).

Impact (I) refers to the effect of vessel activity on the marine environment. Vessels have diverse negative effects on marine environments. Specifically, vessel navigation alters hydrodynamic forces, marine animals may be injured or killed by collisions with vessels, fishing vessels deplete marine biological resources, seabeds are damaged by dredging, and the ballast water of oceangoing vessels can cause nonindigenous species invasion. Meanwhile, vessels use various lights and horns for navigation, and the resulting noise and light pollution can affect marine life (Erbe, 2010; Jensen et al., 2009). Moreover, ocean acidification can occur as a result of sulfur dioxide and nitrogen oxides emitted by a vessel's fuel combustion (Hassellöv et al., 2013). Sewage and oil pollutants generated during navigation threaten marine species, resources, and ecosystems (Longépé et al., 2015). In consideration of such effects, and based on the Marine Strategic Framework Directive (MSFD), 10 impacts were determined: noise pollution (I1), light pollution (I2), toxic emission (I3), input domestic sewage (I4), oil pollution (I5), biological invasion (I6), target species capture (I7), death or injury by collision (I8), hydrodynamic interaction (I9), and substrate loss (I10).

Response (R) includes the autoregulation function of ecosystems as well as administrative control measures. High biodiversity can produce strong ecosystem resistance to external interference, which can stabilize the ecosystem and reduce damage (Cardinale et al., 2013). Thus, biodiversity (R1) was taken as an indicator to judge biological resilience and represent the autoregulation function of ecosystems. Regarding administrative measures, China adopted a zoning system to protect marine environments. This system divides sea areas into eight functional zones: marine reserved zone (Z1), port shipping zone (Z2), industrial and urban sea zone (Z3), marine conservation zone (Z4), minerals and energies zone (Z5), agriculture and fishery zone (Z6), special utilization zone (Z7), and tourism and recreation zone (Z8). Given different types of vessel activity, each zone presents different responses. Thus, marine functional zone (R2) was used to represent policy-based responses.

The definition of each index is elaborated in Table S1.

2.3. Indicator assignment

Indicators were assigned based on the following criteria: 1) Scientific: the assignment standard must have a scientific basis (e.g., referring to existing rules, regulations, or references). 2) Operable: indicators should have clear significance and be easy to access, calculate, compare, and analyze so that they have practical value for decision-makers, thus combining theory and practice. 3) Realistic: the criteria should be combined with actual situations since diverse vessels with different operations produce various ecological stresses. 4) Quantitative and qualitative combination: there should be both qualitative description and quantitative analysis. Qualitative problems should be quantified as much as possible via mathematical models to ensure objective and rational assessment.

All assessment indicators were assigned by three methods (Table 1): 1) a grading standard determined in accordance with relevant regulations in industry standards or previous studies, 2) normalization after calculation using empirical formulas, and 3) direct normalization of actual values.

Vessel density was calculated by the number of vessels passing through a 1-km^2 area in a unit of time, as follows:

$$D = Q/(T \times a) \tag{1}$$

where D is vessel density (number/km^2·d), and Q is the total number

Table 1
Criteria and scores of indices used in the SPCIR model.

Index name	Primary index	Secondary index	Pathway	Unit	Grading criteria 1	0.8	0.6	0.4	0.2	References
Ecological stress caused by vessels (VES)	Source (S)	Vessel density (S1)	All	number/km^2•d	Normalized by Formula 1 directly					—
		Sailing speed (S2)	All	knot	x ≥ 15	9 ≤ x < 15	6 ≤ x < 9	2 ≤ x < 6	x < 2	(Vanderlaan and Taggart, 2007)
		Deadweight (S3)	All	ton	x > 50,000	15,000 ≤ x < 50,000	5000 ≤ x < 15,000	1500 ≤ x < 5000	x < 1500	(MOT (Ministry of Transport of the People's Republic of China), 2014)
	Carrier (C)	Seawater flow rate (C1)	—	m/s	Normalized by Equation (5) directly					(Liu et al., 2015)
		Water depth (C2)	—	m	x < 20	20 ≤ x < 30	30 ≤ x < 40	40 ≤ x < 50	x ≥ 50	(MOT (Ministry of Transport of the People's Republic of China), 2014)
		Seabed sediment (C3)	—	—	Clay	Clayey silt	Silt	Sand	Gravel	(MNR, 2017)
	Impact (I)	Noise pollution (I1)	All	length/m	x ≥ 150	100 ≤ x < 150	50 ≤ x < 100	12 ≤ x < 50	x < 12	(IMO (International Maritime Organization), 2007)
		Light pollution (I2)	All	length/m	x ≥ 100	50 ≤ x < 100	12 ≤ x < 50	7 ≤ x < 12	x < 7	(IMO (International Maritime Organization), 2007)
		Toxic emission (I3)	P2, P4	—	Calculate using Formula 2 and normalize using Equation (4)					(Chen et al., 2017)
			Others	—	Calculate using Formula 3 and normalize using Equation (4)					—
		Input domestic sewage (I4)	P1, P3	—	Calculate using Formula 2 and normalize using Equation (4)					(IMO (International Maritime Organization), Marine Environment Protection Committee, 2003)
			Others	—	Calculate using Formula 3 and normalize using Equation (4)					—
		Oil pollution (I5)	P2	deadweight/t	x ≥ 50,000	30,000 ≤ x < 50,000	10,000 ≤ x < 30,000	5000 ≤ x < 10,000	x < 5000	(MOT, 2017)
			P4	deadweight/t	x ≥ 80,000	30,000 ≤ x < 80,000	5000 ≤ x < 30,000	1000 ≤ x < 5000	x < 1000	(MOT, 2017)
			Others	—	Calculate using Formula 3 and normalize using Equation (4)					—
		Biological invasion (I6)	P2, P4	deadweight/t	x ≥ 50,000	15,000 ≤ x < 50,000	5000 ≤ x < 15,000	1500 ≤ x < 5000	x < 1500	(IMO (International Maritime Organization), 2004)
			Others	—	—	—	—	—	—	—
		Target species capture (I7)	P1 in fishing state	—	Calculate using Formula 2 and normalize using Equation (4)					(Vespe et al., 2016)
			P6	—	Calculate using Formula 3 and normalize using Equation (4)					—
			Others	—	—	—	—	—	—	—
		Death or injury by collision (I8)	P2	—	Calculate using Formula 2 and normalize using Equation (4)					(Bakdi et al., 2020)
			Others	—	Calculate using Formula 3 and normalize using Equation (4)					—
		Hydrodynamic interaction (I9)	All	length/m	x ≥ 25	15 ≤ x < 25	8 ≤ x < 15	4 ≤ x < 8	x < 4	(MOT (Ministry of Transport of the People's Republic of China), 2014)
		Substrate loss (I10)	P6	—	Calculate using Formula 2 and normalize using Equation (4)					(Cunning et al., 2019)
			Others	—	Calculate using Formula 3 and normalize using Equation (4)					—
	Response (R)	Biodiversity (R1)	—	—	Normalized by Equation (5) directly					(Song et al., 2017)
		Marine functional zones (R2)	—	—	Z4	Z1, Z6	Z8	Z7	Z2, Z3, Z5	(MNR (Ministry of Natural Resources of the People's Republic of China), 2012)

*Empirical formulas were used to calculate indicators without relevant standards. Meanwhile, assignment standards for indicators may vary with the refinement and improvement of standard documents. P1: fishing vessel; P2: cargo vessel; P3: passenger vessel; P4: oil tanker; P5: towing vessel; P6: dispersal vessel.

of vessels passing through a statistical zone. T is the length of the time series, and a is the area of the statistical zone. When D becomes larger, traffic is heavier.

To determine the impact degree of vessel activity on the marine ecological environment, experts engaged in maritime management and marine environment protection were invited to explore the factors that characterize such impacts. Finally, the contribution of different vessel types, quantity of vessel positions, and proportion of specified vessel types were determined as the main characterizing parameters of the empirical formula. The established empirical formula needs to meet the following three requirements: 1) It can reflect the positive correlation between the number of vessels and the value of the impact index. 2) When the total number of vessels is the same, the larger the proportion of primary vessel types, the higher the corresponding value of the impact index. Lastly, 3) when the number of primary and secondary vessel types is the same, the priority of the contribution of primary vessel types to the impact index value is highlighted. The validity of the empirical formulas was verified under the four vessel distribution models (Table S2). The constructed empirical formulas are as follows:

$$I_1 = \sum\nolimits_{p=1}^{P}\left[D_p \times \left(1 + \frac{1}{A_p}\right)\right] \tag{2}$$

$$I_2 = \sum\nolimits_{q=1}^{Q}\left(D_q \times \frac{1}{A_q}\right) \tag{3}$$

where I denotes the intensity value of the impact indicators without relevant references and p represents the major types of vessels causing the effect. Specifically, cargo vessels (P2) and oil tankers (P4) are major exhaust-emitting vessels (Chen et al., 2017b; Zhang et al., 2017), fishing vessels (P1) and passenger vessels (P3) discharge sewage (IMO (International Maritime Organization), Marine Environment Protection Committee, 2003), fishing vessels (P1) in fishing state are the main types of vessels that capture biological resources (Jackson et al., 2001; Vespe et al., 2016), cargo vessels (P2) may cause injury or death through collision (Bakdi et al., 2020), and dispersal vessels (P6) damage seabed sediment (Kim et al., 2018; Cunning et al., 2019). q represents secondary vessels that produce such impacts. D is vessel density, and A indicates the proportion of p or q vessels among the total vessels.

To obtain precise assessment results, all indicators were standardized to 0–1 to suppress different orders-of-magnitude indicators that cannot be compared. The extreme standard method is expressed by the following equations:

$$X^* = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{4}$$

$$X^* = \frac{X_{max} - X}{X_{max} - X_{min}} \tag{5}$$

where X* and X are the standardized and actual value, respectively; X_{max} and X_{min} refer, respectively, to the historical maximum and minimum of the indicator over a period of several years. Equation (4) is applied for the indicators, where the higher the value, the more serious the ecological stress, while Equation (5) is the opposite.

2.4. Assessment model

To assess the marine ecological stress caused by vessels, the SPCIR model was established according to the indicator system (Fig. 1), and then indicators were assigned (Table 1). Ecological stress caused by vessels (VES) was then calculated by Formula (6):

$$VES = S \times W_1 + I \times W_2 + C \times W_3 + R \times W_4 \tag{6}$$

where W_1, W_2, W_3, and W_4 are the weights of source index (S), carrier index (C), impact index (I), and response index (R), respectively:

$$S = \sum_{m=1}^{M} S_m \times w_m \tag{7}$$

$$I = \sum_{i=1}^{I} I_i \times w_i \tag{8}$$

$$C = \sum_{n=1}^{N} C_n \times w_n \tag{9}$$

$$R = \sum_{u=1}^{U} R_u \times w_u \tag{10}$$

where S_m represents the value of the mth source index, I_i is the value of the impact indicators assigned according to Table 1, C_n is the value of the nth carrier index, R_u is the value of the uth response index, and w refers to subindicator weight.

To avoid assessment bias caused by subjective expert judgment, assignment standards were delineated based on industry-standard documents. Moreover, the relevant research on VES evaluation is still in the primary stage, with few available references. Therefore, the weights of indicators in the same grade were equal in this study (Gan et al., 2017; Schmidt et al., 2020).

This study used the equal interval classification method to divide the VES values. Since more than half of the indices have a normalized value range of 0.2–1.0, the dividing threshold was slightly adjusted. VES values between 0 and 1 were divided into four levels from weak to strong: 0.0–0.4 (low), 0.4–0.6 (medium), 0.6–0.8 (higher), and 0.8–1.0 (highest). These values were used to represent ecological stress levels caused by vessel activity; then, spatial statistical analysis was carried out.

3. Case study

3.1. Study area

Located in northern China, the Bohai Sea (117°35′∼122°15′E, 37°07′∼41°N) is composed of Liaodong Bay, Bohai Bay, and Laizhou Bay. It connects with the Yellow Sea through the Bohai Strait in the east (Fig. 2), with a total coastline length of 3,784 km and a total sea area of 77,284 km^2. There are many rivers along the banks of the Bohai Sea, such as the Yellow, Haihe, and Liaohe rivers. These produce abundant nutrients, which become bait for aquatic resources after entering the Bohai Sea. For these reasons, the Bohai Sea is rich in fishery resources.

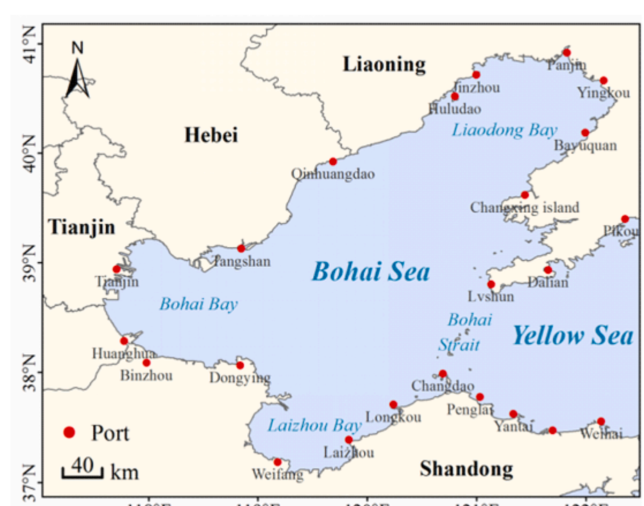

Fig. 2. Geographical location of the Bohai Sea.

Meanwhile, petroleum and mineral resource reserves are abundant, making oil and gas exploitation the leading industry in the marine economy of the area.

Given its superior natural conditions and abundant natural resources, the Bohai Rim Region has a developed marine economy. In 2019, gross ocean production reached RMB 2.636 trillion, accounting for 29.5% of all ocean production in China (MNR, 2020). Moreover, container throughput accounted for 33.57% of the total ports in China, and the foreign trade cargo throughput was 914 million tons, accounting for 23.7% of the total (MOT, 2020). The Bohai Sea is thus an important maritime transportation corridor in northern China. Inevitably, high-intensity maritime transportation has had several negative effects, including exhaust emissions, wastewater discharge (Zhang et al., 2017), collisions, oil spills, and alien invasion (Wang et al., 2018). Conflicts have also emerged with other marine resource development activities, threatening the implementation of ecological protection policies and marine utilization management.

3.2. Data preprocessing

The data used in this study mainly included seawater flow rate, seabed substrate, water depth, biodiversity, marine functional zones, and vessel positions. Data for substrate and water depth were obtained from the vectorization of the Atlas of the Comprehensive Survey and results of China's Offshore Oceans-Submarine Special Evaluation. Data for the level of biodiversity were generated by the interpolation of the actual measurement results of multiyear voyage sampling (Song et al., 2017). The multiyear average seawater flow rate was obtained using Delft3D software, as simulated by Liu et al. (2015) and Wang et al (2017). Data for marine functional zones come from the local government. Impact indexes such as light pollution, noise pollution, exhaust emission, and biological invasion were acquired by calculating the attribute characteristics of each vessel in the unit grid and then assigning them to obtain the mean values following the method shown in Table 1.

Vessel data in this study came from both shore- and space-based AIS, provided by Shipxy (http://www.shipxy.com). The data include static and dynamic information: ship name, length, draught, ship type, longitude, latitude, course, speed, deadweight, and navigation status. Characterized by high precision and rich, real-time content, AISs usually send data every few seconds and can effectively identify and trace vessels within the research area. Therefore, AIS data can be considered a reliable way to obtain the traffic-flow data of vessels in marine activity management.

AIS data from 2014, 2016, and 2018 were used to analyze the characteristics of marine vessel activities and the corresponding ecological stress. Given the large amount of data and the obvious characteristics of the daily, monthly, and seasonal changes in vessel activity in the Bohai Sea (Chen et al., 2020), uniform sampling was used to preprocess the AIS data to ensure maximum data representativeness after sampling. Specifically, data were sampled once every three days after January 1, and the first minute of each hour was selected. After that, missing data were supplemented in light of MMSI numbers and the names of vessels. Data with abnormal length, speed, and deadweight were eliminated. Finally, all data were imported into GIS according to the latitude and longitude information of vessels. The research area was divided into 5,040 5 km × 5 km grids to analyze marine vessel activity and spatiotemporal variations in ecological stress.

3.3. Results

3.3.1. Spatiotemporal characteristics of vessel density

A distribution diagram of vessel density in the Bohai Sea was obtained based on GIS (Fig. 3). Statistics were created for the average number of different vessels and change rates relative to the annual long series mean (Table 2). The results indicated that vessel activities were distributed in major port areas, traffic channels, and channel intersections, especially in Bohai Bay and the Bohai Strait. Additionally, these activities conducted in the Bohai Sea varied in density distribution (number/km^2•d), proportion, and daily average number of vessels (N/d).

Spatial distribution indicated that density was the lowest in 2014; only one small area, near Tianjin Port, was distributed with high density, with the highest being 39 number/km^2•d. Dalian Port and Bohai Strait followed close behind, with densities ranging from 15 to 23 number/km^2•d; densities in other sea areas were extremely low. Vessel density increased slightly during 2014–2016, with an average increase of 0.53%. However, the increase was mainly seen in Bohai Bay and Bohai Strait; areas with the greatest change increased by 50%. In general, density distribution in 2016 was similar to that in 2014, but it slightly increased compared to 2014, with the highest density being 119 number/km^2•d. However, density changes were relatively large during 2016–2018, and noticeable changes were seen in ports and channel areas. The highest vessel density, seen in 2018 in Bohai Bay and Bohai Strait, was 121 number/km^2•d—about three times that of 2014.

Table 2 shows statistics for the daily average times and proportion of fishing vessels (P1), cargo vessels (P2), passenger vessels (P3), oil tankers (P4), towing vessels (P5), and dispersal vessels (P6), indicating the change rate relative to the annual long series. These varied from 2014 to 2018. Specifically, in 2014, the vessels types mainly included cargo and fishing vessels. Later, the average daily vessels increased by 12.4% in 2014–2016, with P5 and P1 showing the highest increases (84.19% and 48.47%, respectively) while P2 and P6 decreased slightly. The period 2016–2018 saw noticeable growth in the number of vessels, especially P2 and P1. In general, from 2014 to 2018, the total daily average number of vessels in the Bohai Sea increased by 1.69 times, and P2 and P1 always accounted for over 75%, indicating that freight and fishing were the major vessel activities. The proportion of P4 followed close behind as the Bohai Oilfield was the largest in China.

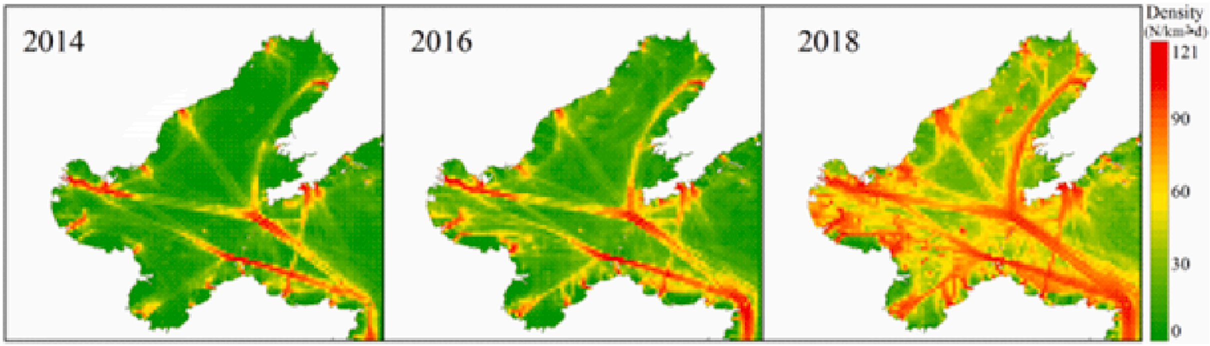

Fig. 3. Distribution of vessel density in the Bohai Sea.

Table 2
Statistics for the average number and change rate of vessels in the Bohai Sea.

Pathway	2014 Mean	Proportion (%)	2016 Mean	Relative Change	Proportion (%)	2018 Mean	Relative Change	Proportion (%)
Fishing vessel (P1)	59,014	20.8	87,621	+48.47%	27.47	128,422	+46.57%	26.7
Cargo vessel (P2)	165,034	58.16	158,740	−3.81%	49.78	236,411	+48.93%	49.16
Passenger vessel (P3)	12,936	4.56	10,777	−16.69%	3.38	13,881	+28.8%	2.89
Oil tanker (P4)	29,347	10.34	32,317	+10.12%	10.13	45,338	+40.29%	9.43
Towing vessel (P5)	14,664	5.17	27,010	+84.19%	8.47	50,287	+86.18%	10.45
Dispersal vessel (P6)	2748	0.97	2449	−10.88%	0.77	6585	+168.89%	1.37
Total	283,743	100	318,914	+12.40%	100	480,924	+50.8%	100

3.3.2. *Comprehensive analysis of VES*

According to the assessment results (Fig. 4), compared to vessel density distribution, VES had a wider range, and there was a considerable spatial difference between ecological stress and density in the Bohai Sea. In 2014 and 2016, areas with high VES were mainly distributed in the western Laizhou Bay and eastern Bohai Bay. This is because these areas are marine conservation areas or habitats for rare, endangered species. When vessel density was low overall, the stress indicators of highly sensitive areas stood out. The whole region saw uniform growth from 2014 to 2016, but the VES distribution pattern remained same. However, during 2016–2018, channel areas were the key places with VES increases. In 2018, marine conservation areas still experienced severe stresses while VES also escalated substantially in the central shipping areas of the Bohai Sea and the large ports (e.g., Dalian, Bayuquan, Qinhuangdao, and Tangshan). Generally speaking, these areas were characterized by high vessel density, heavy deadweight, and low biodiversity. The maximum VES values were 0.90 (2018), 0.77 (2016), and 0.73 (2014). The average levels for the entire research area were also high—namely, 0.59 (2018), 0.46 (2016), and 0.45 (2014)—indicating that VES was serious in the Bohai Sea.

In this study, there were hundreds of thousands of pieces of AIS information and 5,040 calculation grids every year. Vessel activity, seawater velocity, and marine organisms are all random variables, which meet the prerequisites for normal distribution verification in geostatistics—namely, a large number, randomness, and multiple sampling. Therefore, normal distribution was selected to verify the rationality of the assessment results. Moreover, normal distribution verification has been commonly used in previous geoscience research to

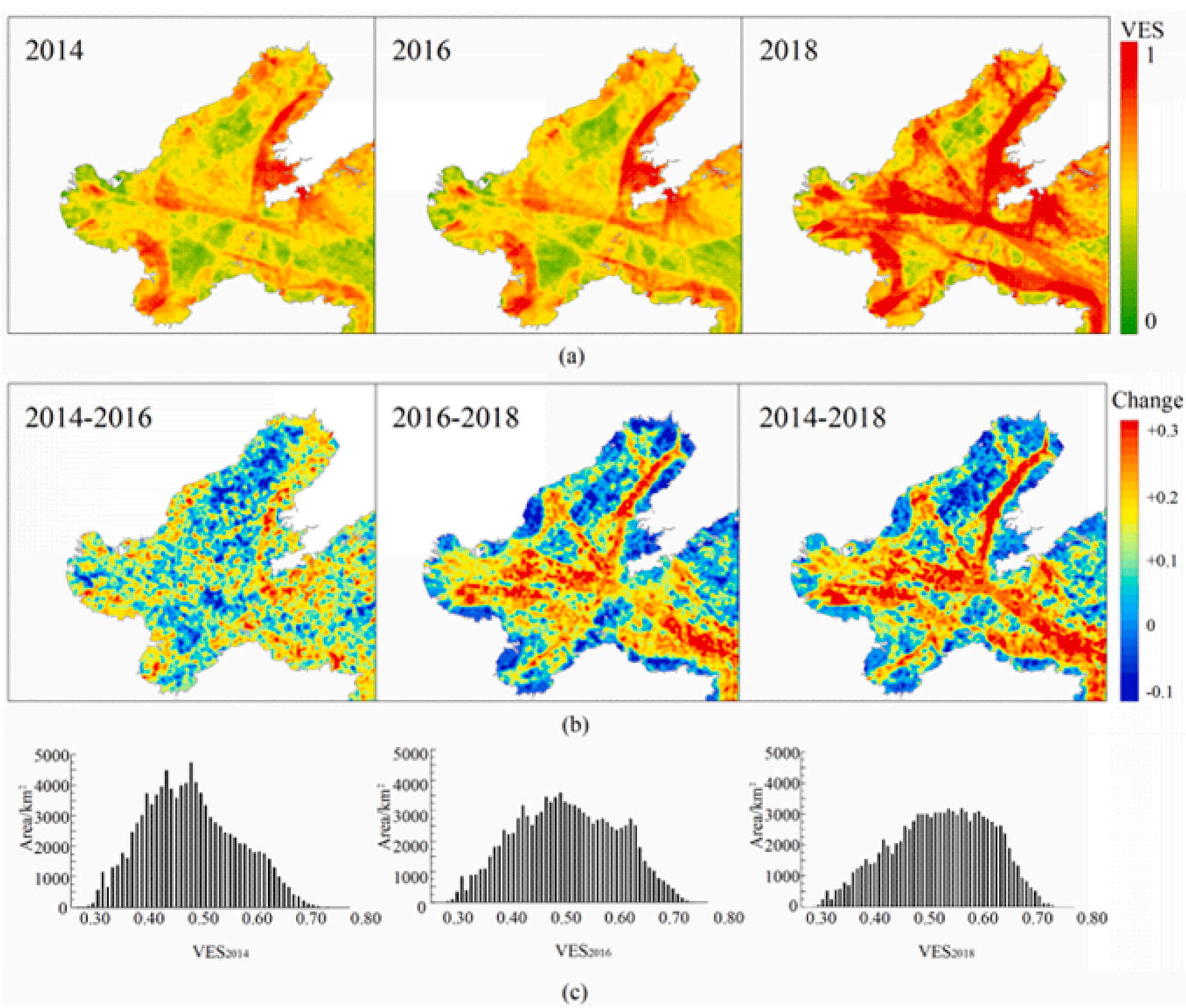

Fig. 4. (a) Ecological stress caused by vessels (VES) of the Bohai Sea, (b) spatial distribution of changes, and (c) VES normal distribution diagram.

verify the quality of the analysis results (Wayne, 1990; Kan and Chen, 2004; Liao et al., 2021).

Statistical analysis indicated that VES levels in the Bohai Sea met the normal distribution law of geostatistical data. The confidence interval of the data was tested using the K–S test. Significance at the $\alpha > 95\%$ confidence interval was passed for each year, indicating that the obtained results were scientific and credible.

3.3.3. Single-Factor spatial analysis

The area proportion of all indicators in each level was calculated to determine the spatial distribution and contribution of each indicator. Fig. 5 and Table 3 show the results.

(1) S1, S2, and S3 reflect the basic characteristics of vessel activity in the Bohai Sea. In most areas of Liaodong and Laizhou bays, vessel speed and deadweight were relatively low because these bays are rich in fishery resources, and there are numerous fishing vessels. The length, speed, and deadweight of fishing vessels are generally smaller than those of other vessels.

(2) I1, I2, and I9 have relatively high values, with polarized distribution overall. High values are centered in ports and key channel areas. Specifically, values are high for Bohai Bay, Weifang Port, Laizhou Port, Penglai Port, Tangshan Port, Qinhuangdao Port, Bayuquan Port, Dalian Port, Laotieshan–Bayuquan Channel, and Dalian Port–Penglai Port Channel. Meanwhile, the minimum is found in the offshore areas of Liaodong Bay and Laizhou Bay.

(3) The average value of I4, I5, and I6 is<0.2. Low-value areas account for over 80%, and those with high values are mainly distributed in a small range in ports or certain channels. This is the result of major vessels causing such impact distributions in fixed channels or ports.

(4) Clearly, I3, I7, I8, and I10 are low in over 60% of the region, but areas with high values are scattered in various areas of the Bohai Sea. Therefore, the resultant ecological effects must be taken seriously.

(5) The distribution law of C and R is far from obvious. C1, C2, and R1 are reverse indicators; the larger the original value, the smaller the normalized value. Both C1 and C2 are higher in the west than in the east; R1 is distributed low along the coast and high in the central sea area. The seabed sediments (C3) of the Bohai Sea are dominated by sand, followed by silt and other materials. The central Bohai Sea had a value of 0.4; this was because the government placed high value on seawater quality and marine utilization activities there, although marine function zones were not divided in this area.

3.3.4. Analysis of VES in different pathways

Fig. 6 shows the distribution of VES contribution by different

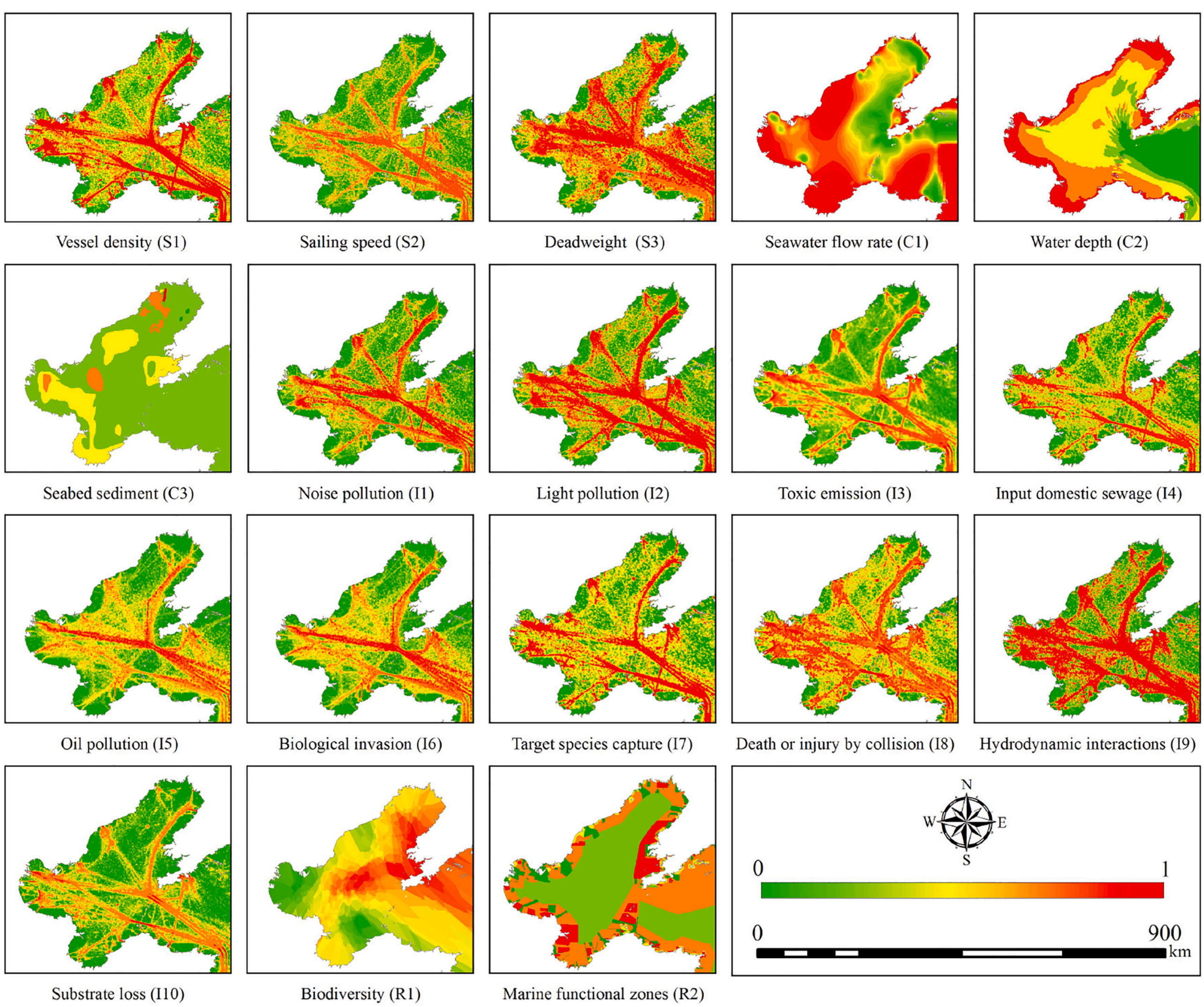

Fig. 5. Spatial distribution of normalized values of all indicators.

Table 3
Statistics of the characteristics single-factor data.

Index	Mean	SD	Area proportion (%)2			
			High	Relatively high	Moderate	Low
Sailing density (S_1)	0.365	0.172	0.160	0.889	25.917	73.034
Sailing speed (S_2)	0.442	0.262	0.760	26.321	14.980	57.939
Deadweight (S3)	0.432	0.286	7.474	18.082	12.468	61.976
Seawater flow rate (C1)	0.970	0.061	97.4606	2.094	0.306	0.134
Water depth (C2)	0.449	0.104	0.144	3.730	16.617	79.509
Seabed sediment (C3)	0.581	0.244	8.809	35.043	2.856	53.292
Noise pollution (I1)	0.500	0.319	27.104	11.492	7.392	54.013
Light pollution (I2)	0.572	0.364	33.596	12.392	7.113	46.900
Toxic emission (I3)	0.281	0.130	0.003	0.179	26.785	73.034
Input domestic sewage (I4)	0.148	0.214	0.105	8.850	0.943	90.101
Oil pollution (I5)	0.164	0.211	0.570	5.004	14.091	80.336
Biological invasion (I6)	0.183	0.227	0.983	6.618	12.275	80.123
Target species capture (I7)	0.341	0.168	0.105	9.776	26.385	63.734
Death or injury by collision (I8)	0.281	0.130	0.003	0.172	26.791	73.034
Hydrodynamic interactions (I9)	0.623	0.395	51.267	1.612	0.614	46.507
Substrate loss (I10)	0.206	0.214	0.160	0.889	25.917	73.034
Biodiversity (R1)	0.651	0.271	22.980	21.986	29.149	25.885
Marine functional zones (R2)	0.581	0.244	8.809	35.043	2.856	53.292

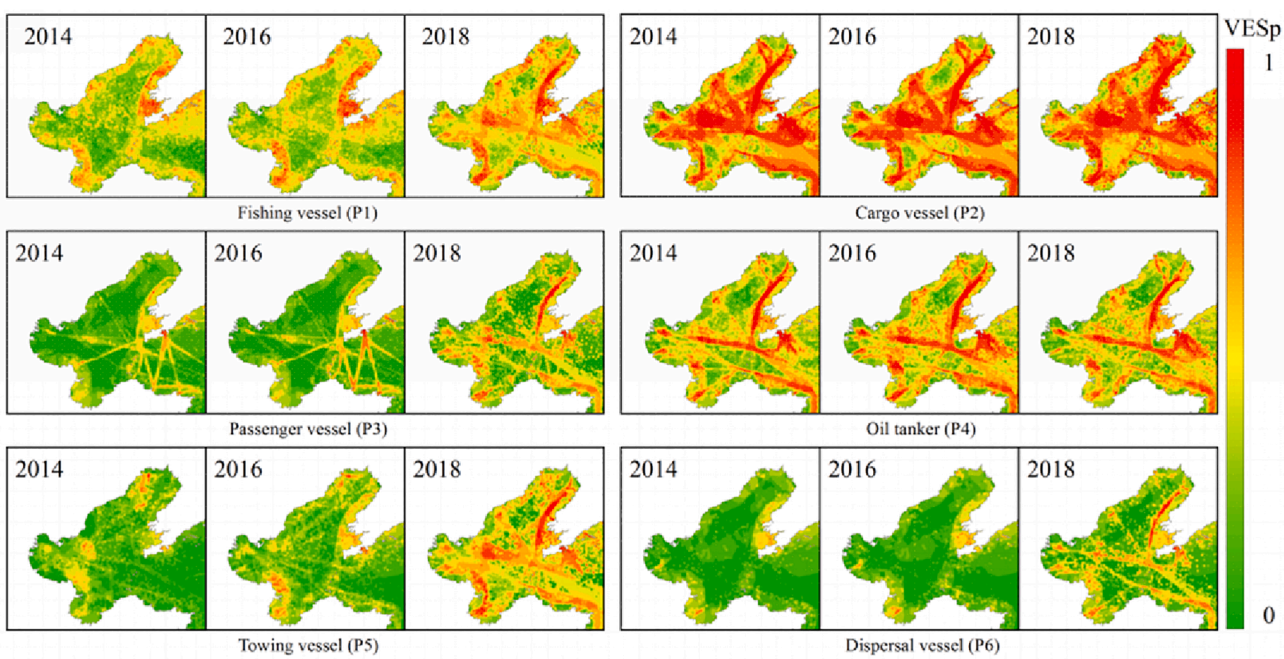

Fig. 6. Distribution of ecological stress caused by different vessels, 2014–2018.

pathways, revealing the spatial characteristics.

The spatial characteristics of each pathway subindicator are analyzed as follows. First, for fishing vessels (P1), VES was the highest in littoral sea areas and highly sensitive marine functional zones. It was substantially enhanced in the middle Bohai Sea, indicating that fishing modes there changed from inshore-dominated fishing to a dual mode of nearshore and high-seas fishing. Second, cargo vessel (P2) was the pathway with the largest number of vessels, largest vessel size, highest speed, and most extensive impact types. It affected nearly all areas of the Bohai Sea, especially the channel areas. Third, compared to other pathways, passenger vessels (P3), towing vessels (P5), and dispersal vessels (P6) produced low overall VES because of their small quantity. The VES of P3, P5, and P6 changed during 2016–2018 because of increased international travel to Bohai and sightseeing passenger ships. Further, vessel-towing and channel-dredging demand increased with the prosperity of Bohai shipping. Fourth, there was no obvious change in VES for oil tankers (P4) during 2014–2018; this was because the activities of tankers were closely related to the distribution of oil and gas fields. Meanwhile, there was no new large-scale offshore oil and gas field development in Bohai during the research period.

Since different vessel types dominate the stress placed on different areas, we analyzed the proportions of areas with different main pathway stressors (APS) and transfer matrices. This was intended to reveal changes in areas where different vessels were the major stressors and to analyze the change characteristics and stage features. Table 4 and Fig. 7 show the results. Moreover, areas in the transfer matrix were subjected

Table 4
Area proportions of different main pathway stressor zones, 2014–2018. P1: fishing vessel; P2: cargo vessel; P3: passenger vessel; P4: oil tanker; P5: towing vessel; P6: dispersal vessel.

	P1	P2	P3	P4	P5	P6	Total
2014	9.67%	84.21%	0.41%	4.50%	1.18%	0.03%	100%
2016	18.39%	72.56%	1.52%	4.85%	2.37%	0.31%	100%
2018	13.74%	70.58%	1.15%	9.74%	4.23%	0.56%	100%

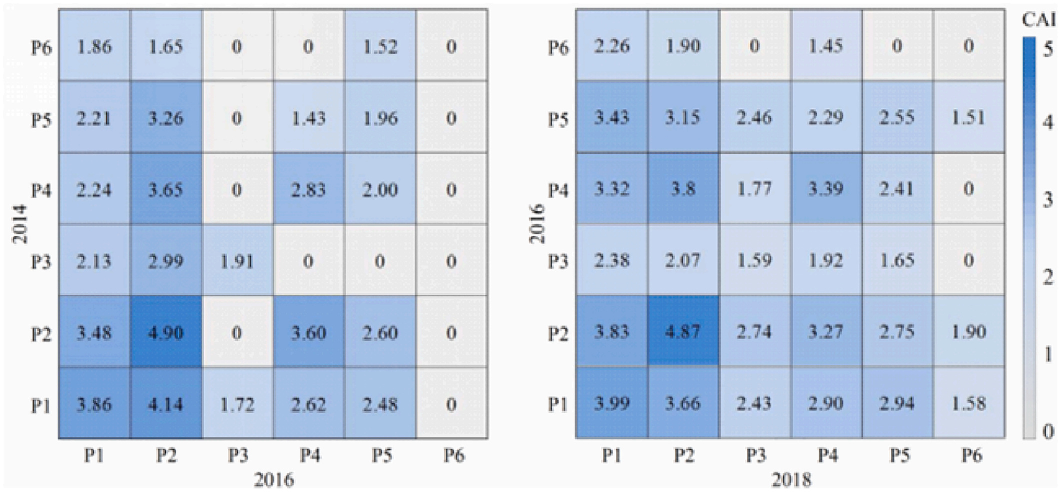

Fig. 7. Conversion matrix of the main pathway stressors in the Bohai Sea, 2014–2018. P1: fishing vessel; P2: cargo vessel; P3: passenger vessel; P4: oil tanker; P5: towing vessel; P6: dispersal vessel.

to base 10 logarithmic transformation since the transfer scales varied greatly for different vessels; the converted area indicator (CAI) was ultimately obtained. The major stressor changed in 25.60% of the Bohai Sea during 2014–2016, where P2 was mainly converted to P4 and P1. The APS of P2 decreased by 11.65%, and other P indicators increased. During 2016–2018, APS changed slightly, and other P indicators were all<2%, except that P1 decreased by 4.65% and P4 increased by 4.89%. However, there was still a stressor change in 26.11% of the Bohai Sea, and changed stressors were converted frequently among each other.

4. Discussion

4.1. Rationality analysis of the SPCIR model

The assessment of marine ecological stress caused by vessel activity in the Bohai Sea indicated that the SPCIR model is scientifically feasible, and the assessment results conformed to the normal distribution of the geostatistical data (Fig. 4-c). The assessment results accurately and intuitively reflected VES change trends. The main channels with frequent navigation usually experienced higher VES. VES intensity and scope are typically enhanced in ecologically sensitive areas, such as marine ecological conservation zones. This was demonstrated by the fact that an obvious correlation (Fig. 8) was not found between the VES spatial assessment data and vessel density.

Compared to previous studies, this study's model comprehensively accounts for diverse vessel activities, the complex processes of stress generation, the heterogeneity of marine ecological environments, and artificial control measures. Moreover, the indicator system thoroughly accounts for ecological stresses caused by diverse vessel activities. Using the SPCIR model, vessel activity management and marine ecological restoration can be targeted via governance. The model can also help decision-makers in other areas formulate management measures quickly and objectively.

4.2. Support for marine utilization management

Marine functional zoning provides an important legal basis for marine utilization and management in China. Function zones are divided according to geographical location, natural resource conditions, natural environment, and social demand. Specifying the dominant functions of different zones can help to regulate and solve conflicts over the utilization of marine resources. The high-level VES caused by fishing vessels (P1), cargo vessels (P2), passenger vessels (P3), and tankers (P4) overlapped with marine functional zones in 2018. Based on the VES

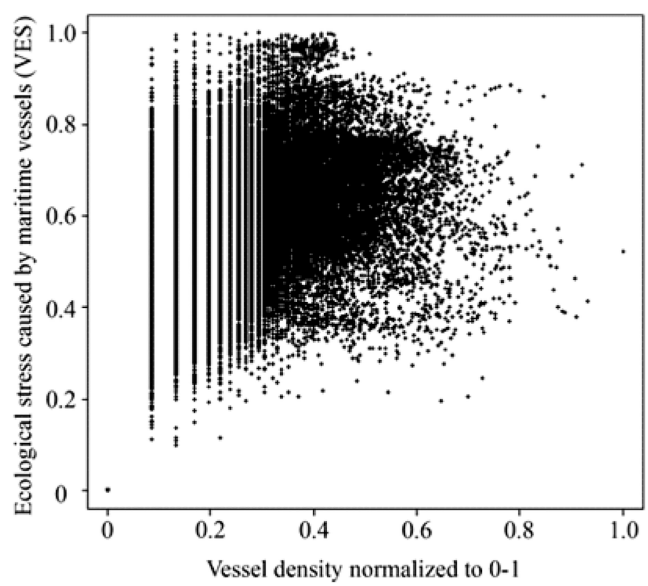

Fig. 8. Spatial correlation of VES and vessel density.

distribution of different pathways and the management requirements of marine functional zones, we identified areas where the dominant functions of marine functional zones were inconsistent with high-stress vessel activities. Meanwhile, towing and dredging vessels were not analyzed here because they provide support and assistance in maritime transportation, and their quantity, navigation, and operating areas are strictly regulated.

The result showed that areas with the abovementioned inconsistency accounted for 12.79% of marine functional zones, indicating a good overall situation (Fig. 9). Specifically, highly inconsistent areas were mainly located in the Harbor Seal Marine Reserved zones in eastern Liaodong Bay. In this area, the VES of P1, P2, P3, and P4 exceeded 0.8, indicating that diverse vessels produced extremely high stress. This would have severe adverse impacts on the reproduction of fish and shrimp, as well as the growth and development of harbor seals. Medium-inconsistent areas were in the agriculture and fishery zones of Bayuquan Port and central Laizhou Bay; the stressors were P2 and P4. Similarly, low-inconsistent areas were distributed in the southern Bohai Sea, with P1 and P2 putting stress on the marine conservation zone and P2 and P4 putting ecological stress on the agriculture and fishery zone. Therefore,

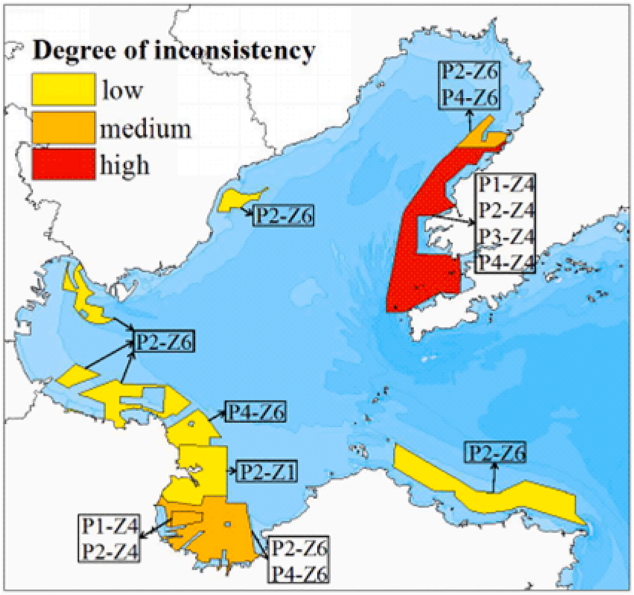

Fig. 9. Inconsistency degrees between marine functional zones and high VES caused by different pathways. VES: ecological stress caused by vessels; P1: fishing vessel; P2: cargo vessel; P3: passenger vessel; P4: oil tanker; Z1: marine reserved zone; Z4: marine conservation zone; Z6: agriculture and fishery zone.

the government should strengthen measures to control marine vessel activities in ecologically sensitive areas, including Laizhou Bay in the Bohai Sea and the eastern Liaodong Bay. In other offshore areas, attention should be paid to the effects of P2 and P4 on fishery resource recovery in agriculture and fishery zones.

4.3. Limitations and directions for future research

The impact indicators in this study were based on existing rules and regulations as well as previous studies. Further, AIS data containing various types of vessel information were used for calculation and assignment. While this method might be imperfect, it overcomes the limitations of pollutant monitoring, which cannot separate the effects of vessel activity from other types of activity, requires a longer time for data acquisition, and has low repeatability.

The comprehensiveness and accuracy of the AIS data depended on AIS installation rate and crew operation capability. China has abided by IMO regulations, ruling that AIS must be installed on international vessels weighing 300 t or greater, noninternational vessels that weighing 200 t or greater, fishing vessels>15 m in length, and all passenger vessels (Mazzarella et al., 2017). Some small fishing vessels have not installed AIS, which could have caused an underestimation of the ecological stress caused by fishing vessels. However, with improved awareness of maritime navigation safety, vessels not included in the regulations have voluntarily installed AIS, and AIS equipment installation has therefore become common (McCauley et al., 2016). Some countries, such as Mauritius and Ecuador, have achieved 100% AIS installation (Natale et al., 2015). It is believed that other countries will follow suit and gradually implement AIS on all vessels. When AIS equipment fails or the crew makes operational errors, incorrect vessel data are collected, which lowers accuracy (Tixerant et al., 2018); however, the likelihood of such occurrence is generally low. Therefore, although AIS data have some limitations, compared to other vessel-data sources, AIS is still the most accurate, providing an important tool that maritime management departments can use to ensure the safety of vessel traffic and protect the water environment.

Given the strong dynamics of vessel navigation and ocean hydrodynamics, and the mutual interactions between them, it is rather complicated to simulate the impact of a vessel on areas beyond its position. Therefore, the proposed SPCIR model ignores the indirect and diffuse effects caused by vessel activity in some scenarios. For example, in vessel navigation, the wake will erode the coastline or shallows several kilometers away from the vessel, the flow of seawater will transport pollutants to other locations, and invasive species will swim or drift when entering the sea. Thus, future research can aim to establish a marine hydrodynamic model that considers vessel navigation. It can also seek to further elaborate on the impact distance and the accumulation/attenuation of impact intensity in different cases to make the SPCIR model more comprehensive and accurate.

Moreover, the distribution of species habitats should be taken into account to assess VES for different marine ecosystems or marine animals. Moreover, emphasis should be placed on improving AIS data–based formulas for the quantitative evaluation of indicators. Improved formulas should contain more static and dynamic AIS information to improve assessment accuracy and reveal the complicated interaction laws between vessel activities and marine ecological environments. Such work should aim to support decision-making for marine utilization management and ecological protection.

5. Conclusion

This study proposed an SPCIR model and constructed an indicator system to evaluate marine ecological stress caused by vessel activity. An assessment of the Bohai Sea demonstrated that the method is practical and effective. The following conclusions are drawn: 1) There was an obvious increase in the density of marine vessels in the Bohai Sea from 2014 to 2018, with cargo vessels (P2) showing the greatest increase. 2) The Bohai Sea has seen increasingly serious VES; it is high overall, and noise pollution (I1), light pollution (I2), and hydrodynamic interaction (I9) are especially salient. Cargo vessels (P2) and oil tankers (P4) are the major stressors. 3) The effect scope of ecological stress from vessels far exceeds channel areas, and the effect of vessel activity is particularly noticeable in highly ecologically sensitive areas (e.g., agriculture and fishery zones and marine conservation zones). 4) The functions of marine functional zones in the southwestern and northeastern Bohai Sea were affected by vessel activity. It is urgent, therefore, to strictly manage the corresponding vessels (i.e., fishing vessels in marine conservation zones and cargo vessels and oil tankers in agriculture and fishery zones). These findings can support evaluating the implementation effects of marine spatial management measures and identifying target vessels for management, thus providing a theoretical basis for integrated coastal management.

Different from human activity on land, marine utilization is characterized by a strong spatial overlap. In other words, marine-based activities may be implemented simultaneously within a common sea area. Vessels are mobile pollution sources with high dynamics and are distributed throughout oceans. Therefore, it is necessary to quantitatively and spatially assess the level of ecological stress caused by vessel activity. Tracing stressors poses a particular difficulty in the protection and management of marine environments. This study has also provided a useful example for how to assess VES. As a decision-making assessment indicator system, the proposed method is fast, standardized, and repeatable. It can be used to evaluate VES in other sea areas. In fact, the method is more advantageous for assessing ecological stress in areas where multiple activities occur at the same time. Furthermore, the SPCIR model can guide the assessment of ecological stress caused by other marine activities in the future and provide a theoretical reference and decision support for integrated marine environmental management.

CRediT authorship contribution statement

Baijing Liu: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing. **Xiaoqing Wu:** Conceptualization, Validation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Xin Liu:** Conceptualization, Methodology, Validation, Data curation, Writing - review & editing, Supervision, Investigation. **Meng Gong:** Methodology, Software, Validation, Visualization, Writing - original draft.

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.

Acknowledgments

We thank the editors and reviewers for their detailed and constructive comments to improve the quality of the manuscript. This work was supported by the National Key R&D Program of China (grant number 2019YFD0900705), and Shandong Provincial Natural Science Foundation (grant number ZR2020MD014).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107592.

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