

Assessing benthic habitat quality using biotic indices in the Laizhou Bay, China

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Abstract

As an important part of the Bohai economic rim, the Laizhou Bay has been stressed by serious eco-environmental problems in recent years. In this study, the Shannon-Wiener index (H'), AZTI's marine biotic index (AMBI) and the multivariate AMBI (M-AMBI) were used to assess the ecological quality status (EQS) of the Laizhou Bay according to macrobenthos data collected annually in August 2011–2014. The results showed that the overall benthic habitat quality in the Laizhou Bay was assessed as “Good”. However, 25% of the samples were classified as “Moderate”, “Bad” or “Poor” status under degraded conditions. Ecological group III (EGIII) species which had a certain tolerance to environmental disturbances had a higher proportion in each station, and most of them had appeared the pollution indicator species *Capitella capitata*. This indicated that the benthic habitat in the Laizhou Bay had been disturbed and polluted to some extent. The comparison of the three indices evaluation result and the RDA analysis showed that the H' and M-AMBI were more suitable when the relative abundance of the single species was high and the macrobenthic community was significantly imbalanced; when the relative abundance of opportunistic species (EGIV and EGV) was high, the AMBI and M-AMBI could reflected the EQS objectively; in an undisturbed and polluted environment, all the three indices could indicate the benthic habitats quality. In summary, the better correlation between the three indices and environmental factors showed that they were well responsive to the tendency of the benthic habitats quality in the Laizhou Bay.

Key words: Laizhou Bay, macrobenthos, ecological quality status, Shannon-Wiener index, AMBI, M-AMBI

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1 Introduction

The degradation of coastal eco-environmental quality caused by human activities and climate change will directly affect marine ecosystem health and sustainable provision services for humanity. It will eventually threaten human health and safety (Halpern et al., 2012). Objectively evaluating the marine eco-environmental quality is a prerequisite for maintaining the health and safety of marine environments. The macrobenthos has a relatively stable habitat, sedentary lifestyle and longevity (Pearson and Rosenberg, 1978; Bakalem et al., 2009). Macrobenthic communities and species composition are sensitive to environmental disturbances and changes. Therefore, the biotic indices, for example, Shannon-Wiener index (H') (Shannon and Weaver, 1963), infaunal trophic index (ITI) (Word, 1978), benthic index of biotic integrity (B-IBI) (Weisberg et al., 1997), AZTI's marine biotic index (AMBI) (Borja et al., 2000), multivariate AMBI (M-AMBI) (Muxika et al., 2007) and benthic opportunistic annelida amphipods index (BO₂A) (Dauvin and Ruellet, 2009), are widely used to evaluate the benthic habitat health in the coastal waters (Brauko et al., 2016). Among them, the H' is widely used to evaluate the quality of aquatic ecosystems because the calculation of this index is simple, and it can accurately reflect the stability of the

benthic community structure (Shannon and Weaver, 1963). The AMBI is based on species' sensitivity/tolerance to an environmental stress gradient (Borja et al., 2000). The M-AMBI is a comprehensive index that integrates species richness, the H' and the AMBI through discriminant analysis and factor analysis (Muxika et al., 2007). This index has been inter-calibrated with other European methods according to the Water Framework Directive (WFD) principles (Borja et al., 2007) and has been widely used to evaluate benthic habitat quality in the coastal waters of Europe (Pitacco et al., 2018), Americas (Checon et al., 2018), Asia (Sun et al., 2018), and Africa (Sigamani et al., 2015). The three biotic indices have been successfully applied to evaluate the ecological status of estuaries and coastal waters impacted by strong human disturbances. However, there has been relatively few reports researching on the suitability of AMBI and M-AMBI in assessing the EQS in the estuary and coastal areas of China, only including the Changjiang (Yangtze) River Estuary (Cai et al., 2013a), Bohai Bay (Cai et al., 2014), Huanghe (Yellow) River Estuary (Luo et al., 2016), Laizhou Bay culture area (Li et al., 2017) and Liaodong Bay (Cai et al., 2013b). At present, the evaluation of the applicability and feasibility of the existing indices remains a challenge (Vačkář et al., 2012). Different indices need to be calibrated in specific

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areas or compared with other environmental quality factors (Labruno et al., 2006; Simbora and Reizopoulou, 2007).

The Laizhou Bay, one of the three major bays in the Bohai Sea, serves as a spawning and hatching site for many marine organisms (Gao et al., 2015), which is one of the main components of China's coastal economic belt (Xu et al., 2017). Due to the coastal development and sewage discharge, the environment of the Laizhou Bay is under enormous pressure (Jiang et al., 2015). For instance, the opportunity polychaete account for 37.5% in dominant polychaete species of the Laizhou Bay, which indicates that the polychaete species has been negatively affected by environmental pollution (Zhang et al., 2012). In the Xiaoqing River Estuary, the severe organic contamination and oxygen depletion have led to the low richness of macrobenthos species and the species composition simplification (Luo et al., 2014). The ABC curves showed that most sampling stations were under moderate disturbance and have been polluted in different degrees (Liu et al., 2014). The macrobenthic community is dominated by opportunistic species, which indicates the macrobenthic community are obviously polluted (Luo et al., 2017). The evaluation of the comprehensive ecological health index (CEHI), which is based on the water quality and sedimentary chemical parameters, showed that the marine ecosystem in the Laizhou Bay is in a sub-health state (Song et al., 2017a). While the health status of the Xiaoqing River Estuary was the worst, which could be attributed by the terrestrial pollution and the following eutrophication. The water quality of coastal waters in the southwest of the Laizhou Bay was more seriously polluted than that in central and eastern regions evaluated by the habitat quality composite index (HQI) and ecological response composite index (ERI) (Yang et al., 2014). Considering that the comprehensive multi-parameter evaluation indices rely heavily on the parameter weights, the biotic indices are more suitable for ecological health assessment in coastal waters affected by human activities (Garaffo et al., 2017).

Based on a benthic habitat quality assessment in the Laizhou Bay using the Shannon-Wiener index, AMBI and M-AMBI, this study compares the consistency and differences in the evaluation results of the three indices, analyses the relationships among the dominant species, three indices and environmental pressure gradient in order to (1) test the applicability of the three

biotic indices for assessing the benthic habitat health of the Laizhou Bay, (2) promote the application of biotic indices in ecological environment quality assessments in the coastal waters of China, and (3) provide services for China's offshore environment protection and management.

2 Materials and methods

2.1 Study area

The Laizhou Bay is located next to the northern part of the Shandong Peninsula and lies between the Qimu Reef in the east and the Huanghe River Estuary in the west. It is one of three bays in the Bohai Sea of China, with an area of 6 966 km² and a mean depth less than 10 m. The Laizhou Bay is a typical semi-enclosed shallow bay, and the water exchange capacity is weak (Zhuang and Gao, 2015). The Huanghe River, Xiaoqing River and other rivers flow into the area containing bountiful nutrient substances. As an important fishery and sea salt production area in northern China, the Laizhou Bay has rich fishery resources, including crab, clam and shrimp (Zhang et al., 2017). However, due to urbanization along the coast, the rapid development of aquaculture and reclamation projects, the marine ecological environment of the Laizhou Bay has experienced some negative effects, which indicates that the area has been polluted to varying degrees and the macrobenthos have been disturbed (Yang et al., 2014; Song et al., 2017a). In August of 2011 to 2014, a total of 13 sampling stations were established in the Laizhou Bay and its adjacent areas (37°10'–37°40'N, 119°00'–120°00'E) (Fig. 1). Four ecological survey cruises were conducted to obtain 52 surface sediment and macrobenthos samples. During these cruises, we measured the water depth and salinity at the sampling stations.

2.2 Sampling methods and analysis

The surface sediment and macrobenthos samples were collected using a 0.05 m² Van Veen grab. According to the marine monitoring standard, the mud was collected five times per station as one sample. Biological samples were washed with seawater through a 0.05 mm mesh. The macrobenthos specimens and residues were transferred to vials, fixed with a 5% (v/v) formalin solution, and then taken to the laboratory for quantitative analysis. The sulphide content was analysed using the volatile acid sep-

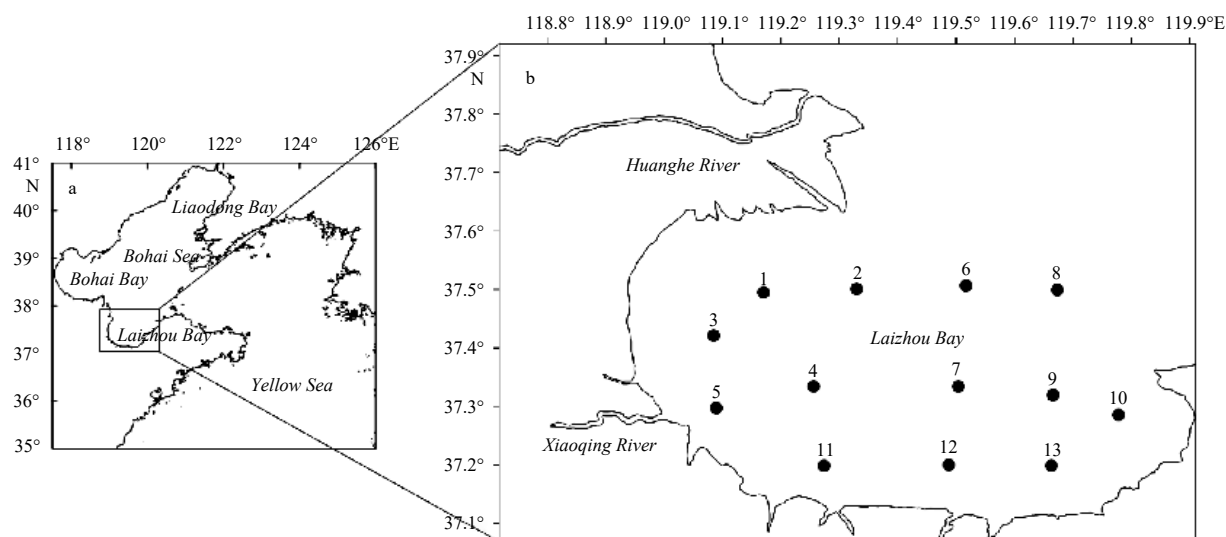


Fig. 1. The Laizhou Bay study area (a) and the distribution of the 13 sampling stations (b).

aration-iodine method. The concentration of petroleum hydrocarbons (TPH) was measured using fluorescence spectrophotometry. We ground air-dried sediment samples and passed them through an 80-mesh sieve. To remove the inorganic carbon, we mixed the sample with hydrochloric acid. The total organic carbon (TOC) was analysed using an elemental analyser (FLASH2000, Elementar, USA). A portable 301 CTD sensor was used to continually measure the depth and salinity of the water on site. The dissolved oxygen (DO) was continually measured using a YSI-500 dissolved oxygen meter.

2.3 Data analysis

The macrobenthos abundance was represented by the number of individuals per square metre in the surface sediments (ind./m²). The characteristics of the macrobenthos in the study area were analysed using the Shannon-Wiener index (H') (Shannon and Weaver, 1963). The dominant species were determined by dominance index (Y) (Chen et al., 1995), which consider both the abundance and occurrence frequency of macrobenthos, and it can well reflect the status of each species in the community. The indices were calculated using the following formulas:

$$Y = n_i/N \times f_i,$$

$$H' = - \sum_{i=1}^S P_i \log_2 P_i,$$

where n_i is the abundance of species i , N is the abundance of all species, f_i is the frequency of species i at all stations, S is the total number of collected species, and P_i is the percent abundance of species i . When Y is higher than or equal to 0.02, the species is defined as a dominant species (Chen et al., 1995).

The AMBI and M-AMBI values were calculated using the AMBI software (ver.5.0) on AZTI's web page (<http://ambi.azti.es>). In this study, 11 macrobenthos species were not assigned to the AMBI list, and the proportion of unassigned taxa at each station was lower than 20%, so they did not affect the reliability of the AMBI results (Borja and Muxika, 2005). According to the suggestion of Forchino et al. (2011) the high reference conditions were determined by increasing the highest diversity and richness values by 15% and decreasing the lowest AMBI value of all the samples in the four cruises by 15%. The optimal number of reference species was 58, the Shannon-Wiener index value was 5.31, and the AMBI value was 0.859 6. For the bad status, the references were based upon the azoic conditions (diversity and richness equal to 0 and AMBI equal to 6) (Borja and Tunberg, 2011; Song et al., 2017b). The values and ecological quality classifications of H' , AMBI and M-AMBI were shown in Table 1. The Shannon-Wiener index value and the corresponding classification of ecological quality status (EQS) were defined by Cai et al. (2002). The classification of ecological quality status corresponding to the AMBI and M-AMBI values were defined by Borja and Tunberg (2011).

CANOCO 5.0 software was used to analyse the relationships

among the biotic indices, dominant species and environmental factors. Before the analysis, the values of both biotic indices, the abundance of dominant species and environmental variables were all $\log_{10}(x+1)$ transformed. Detrended correspondence analysis (DCA) showed that the maximum gradient length was less than 3 SD, which was suitable for the redundancy analysis (RDA) based on the linear model (Šmilauer and Lepš, 2014). The significance of the correlations in the RDA was tested using Monte Carlo simulation.

3 Results

3.1 Macrobenthos composition and characteristics

A total of 179 macrobenthos were identified during the four cruises: 62 were classified as Polychaetes, 57 were Molluscs, 45 were Crustaceans and 15 were members of other taxa, including Echinodermata, Nemertea and Coelenterata. The four cruises average number of species was 95, and the abundance ranged from 18 492 to 58 895 ind./m². The macrobenthos was dominated by polychaetes in 2012, while the samples collected during the other cruises were dominated by molluscs (Fig. 2). The species abundance of EGIII accounted for a high proportion of the total abundance, accounting for more than 80% of the total abundance in both 2013 and 2014. This was due to the largest contribution being from *Arcuatala senhousia*, belonging to EGIII. High values of species richness were observed in the eastern Laizhou Bay (Stas 8, 9 and 10), while low values occurred in the southern area (Stas 12 and 13). The highest value of species abundance (8 664 ind./m²) was located at Sta. 7 in the central part of Laizhou Bay, while the lowest value of 320 ind./m² was located at Sta. 2 near the Huanghe River Estuary. Except at Stas 6, 11, 12 and 13, EGIII accounted for the highest proportion of the total abundance. In addition, at Stas 5 and 6, there were some pollution indicators belonging to EGV, such as *Capitella capitata*. These results indicate that the macrobenthos in the Laizhou Bay area has suffered from environmental disturbance and pollution. The dominant species in the Laizhou Bay are shown in Table 2. The composition of dominant species showed great inter-year variation. The proportions of opportunistic species in EGIV and EGV were relatively high, and the dominance of *Arcuatala senhousia* in EGIII was significantly higher than that of other species.

3.2 Shannon-Wiener index (H')

The Shannon-Wiener index has been widely used to monitor changes in marine benthic communities and to indicate and evaluate environmental pollution. In the study area, the H' values of the 52 samples collected during the four cruises varied from 0.13 to 4.62, averaging 2.90, and the corresponding ecological quality status was "Good". In 2011 and 2012, the mean H' value was higher than 3, with "High" status. In 2013 and 2014, the mean H' value was between 2 and 3, with "Good" status. The H' values from the four cruises did not significantly differ ($p>0.05$, $n=13$) (Fig. 3a). The mean H' value for Sta. 7, which was located in the mid-east portion of the bay, was between 1 and 2, with "Mod-

Table 1. The values and ecological quality classifications of H' , AMBI and M-AMBI

H'	AMBI	M-AMBI	Benthic community health	Site disturbance classification	EQS
$H'>3$	$0<\text{AMBI}\leq 1.2$	>0.77	normal/impovertished	undisturbed	High
$2<H'\leq 3$	$1.2<\text{AMBI}\leq 3.3$	$0.53\text{--}0.77$	unbalanced	slightly disturbed	Good
$1<H'\leq 2$	$3.3<\text{AMBI}\leq 4.3$	$0.38\text{--}0.53$	transitional to pollution	moderately disturbed	Moderate
$0<H'\leq 1$	$4.3<\text{AMBI}\leq 5.5$	$0.20\text{--}0.38$	polluted/transitional to heavy pollution	heavily disturbed	Poor
$H'=0$	$5.5<\text{AMBI}\leq 7.0$	<0.20	heavy polluted/azoic	extremely disturbed	Bad

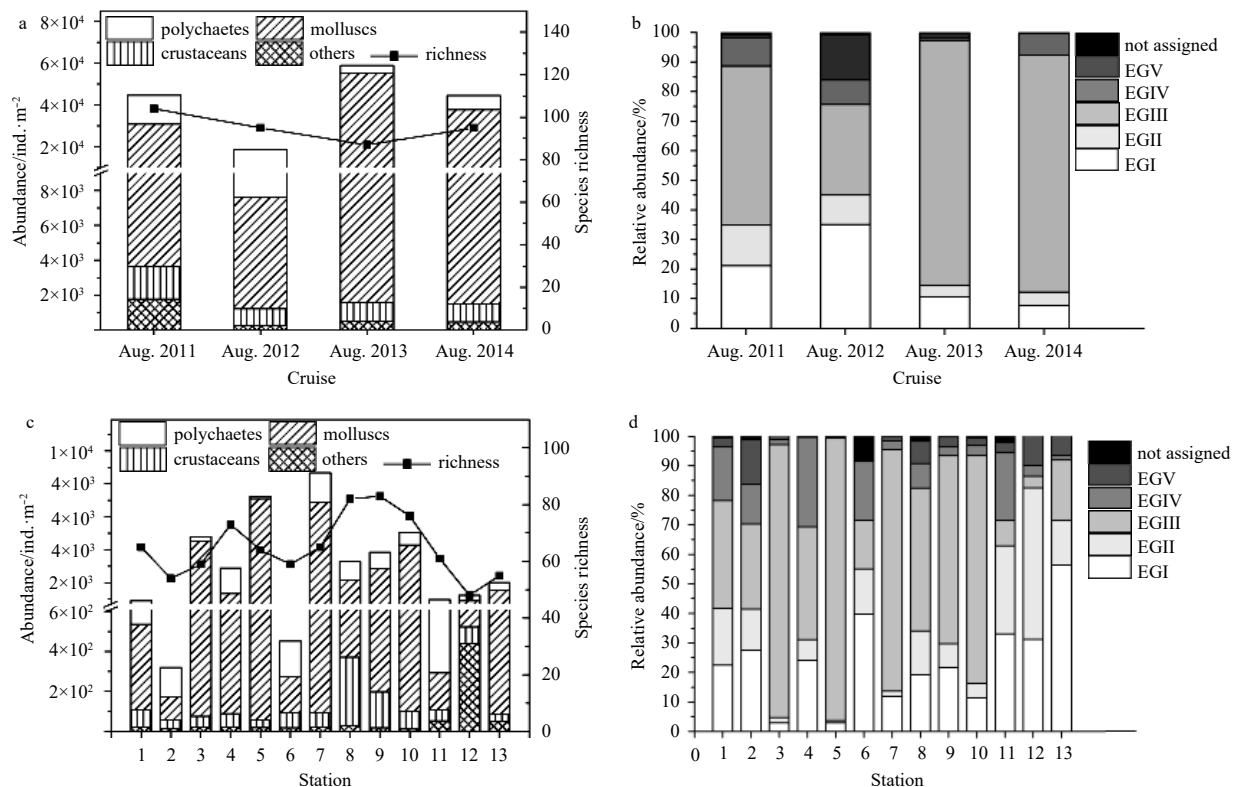


Fig. 2. Composition, abundance, species richness and relative abundance of the ecological groups during each cruise (a, b) and at each station (c, d) in August 2011 to 2014. Species are divided into polychaetes, molluscs, crustaceans and others. EGs represent different ecological groups: EGI, species sensitive to disturbance; EGII, species indifferent to disturbance; EGIII, species tolerant of disturbance; EGIV, second order opportunistic species; and EGV, first order opportunistic species.

Table 2. Dominant species of the macrobenthos sampled in the Laizhou Bay from 2011 to 2014

Dominant species	Ecological group	Dominance			
		Aug. 2011	Aug. 2012	Aug. 2013	Aug. 2014
<i>Mesochaetopterus japonicus</i>	EGI	0.026	0.186	+	+
<i>Alveolus ojanus</i>	EGI	0.043	+	+	+
<i>Gammaridea</i> sp.	EGI	+	0.028	+	+
<i>Glycinde gurjanovae</i>	EGII	0.039	+	+	+
<i>Amaeana occidentalis</i>	EGIII	0.022	+	+	+
<i>Arcuatala senhousia</i>	EGIII	0.168	0.134	0.819	0.601
<i>Cirratulus cirratus</i>	EGIV	0.063	0.023	–	+
<i>Prionospio queenslandica</i>	EGIV	–	0.020	+	+
<i>Heteromastus filiformis</i>	EGIV	+	+	+	0.028
<i>Capitella capitata</i>	EGV	+	0.107	+	–

Note: + and – indicate the dominant species present or absent during the different cruises.

erate” status, and the other stations had values higher than 2, with “High” or “Good” status. The H' value of Sta. 7 was significantly lower than that of Sta. 6 ($p < 0.05$, $n = 4$), and there were no significant differences among the other stations according to ANOVA (Fig. 3b).

3.3 AMBI

The AMBI values of the samples ranged from 1.01 to 3.64, averaging 2.16, and the corresponding ecological quality status was “Good”. The AMBI value in 2011 was significantly lower than that in 2012 ($p < 0.05$, $n = 13$). No significant differences were found among the other cruises (Fig. 4a). The mean AMBI values of the 13 stations ranged from 1.49 to 2.55, which indicated that the

benthic habitat quality was generally at a “Good” level and that the benthos health was slightly disturbed. The AMBI values of all the stations did not significantly differ according to ANOVA ($p > 0.05$, $n = 4$) (Fig. 4b).

3.4 M-AMBI

In the study area, the M-AMBI values of the samples ranged from 0.38 to 0.82, averaging 0.50, and the corresponding ecological quality status was “Good”. The mean M-AMBI values in 2012 and 2013 were significantly lower than that in 2011 ($p < 0.05$, $n = 13$). No significant differences were found among the other cruises (Fig. 5a). In addition, the mean M-AMBI values at Stas 3 and 7 were lower than 0.53, with “Moderate” status, and the val-

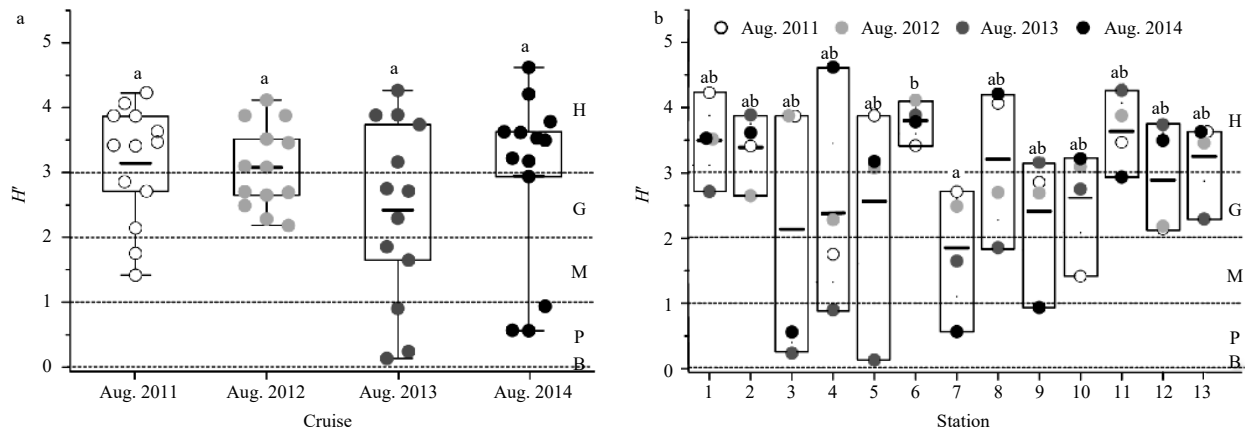


Fig. 3. Shannon-Wiener index values and EQS classes during 4 cruises (a) and at 13 stations (b) in the Laizhou Bay. The dots in the image represent the H' values of 52 samples, and the different grey shades represent different cruises. a. Thirteen samples were collected during each cruise. The minimal and maximal values are indicated with straight lines. The box indicates the 25th and 75th percentiles. The middle bold, horizontal line is the mean value. b. Four samples were collected at each station. The top of the box indicates the maximum value, the bottom the minimum value, and the middle bold line the mean value. H represents high EQS, G good, M moderate, P poor, and B bad. Differences among groups were analysed for significance using one-way ANOVA. The same letters above the columns indicate no differences ($p>0.05$). Different letters above the columns indicate significant differences ($p<0.05$).

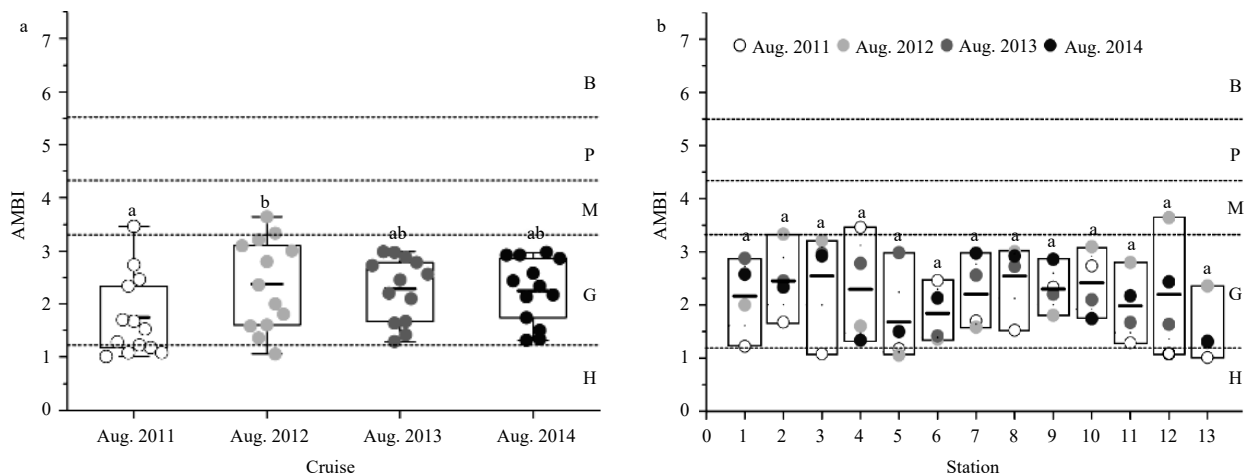


Fig. 4. The AMBI values and EQS classes for 4 cruises (a) and 13 stations (b) in the Laizhou Bay. The dots in the image represent the AMBI values of 52 samples, and the different grey shades represent different cruises. a. Thirteen samples were taken during each cruise. The minimal and maximal values are indicated by straight lines. The box indicates the 25th and 75th percentiles. The middle bold, horizontal line represents the mean value. b. Four samples were collected at each station. The top of the box represents the maximum value, the bottom the minimum value, and the middle bold line the mean value. H represents high EQS, G good, M moderate, P poor and B bad. Differences among groups were analysed for significance using one-way ANOVA. The same letters above the columns indicate no differences ($p>0.05$). Different letters above the columns indicate significant differences ($p<0.05$).

ues at the other stations were higher than 0.53, with “Good” status. The M-AMBI values at all the stations were not significantly different according to ANOVA ($p>0.05$, $n=4$) (Fig. 5b).

4 Discussion

The H' , AMBI and M-AMBI have some differences in assessing the EQS of benthic habitats in the Laizhou Bay. In order to facilitate the comparative analysis between the indices, the EQS of benthic habitats were divided into two categories: “undegraded” and “degraded” (Borja et al., 2008). The undegraded condition corresponded to a “High” or “Good” EQS, which indicated that the benthic habitat was undisturbed or slightly disturbed and the

benthic ecosystem was in a healthy state. “Moderate”, “Poor” or “Bad” EQS were defined as degraded conditions, which meant that the benthic habitat was moderately or more severely disturbed and the macrobenthos in the area was transitioning to a community indicative of contamination. Of the 52 samples used in the study, 42 samples (81%) were considered undegraded based on the H' value, 49 samples (94%) were considered undegraded based on the AMBI, and 41 samples (79%) were considered undegraded based on the M-AMBI.

The result for the EQS as evaluated by the H' , AMBI and M-AMBI values could be broadly divided into four typical cases (Table 3). Case I contained 39 samples (75%), which were evalu-

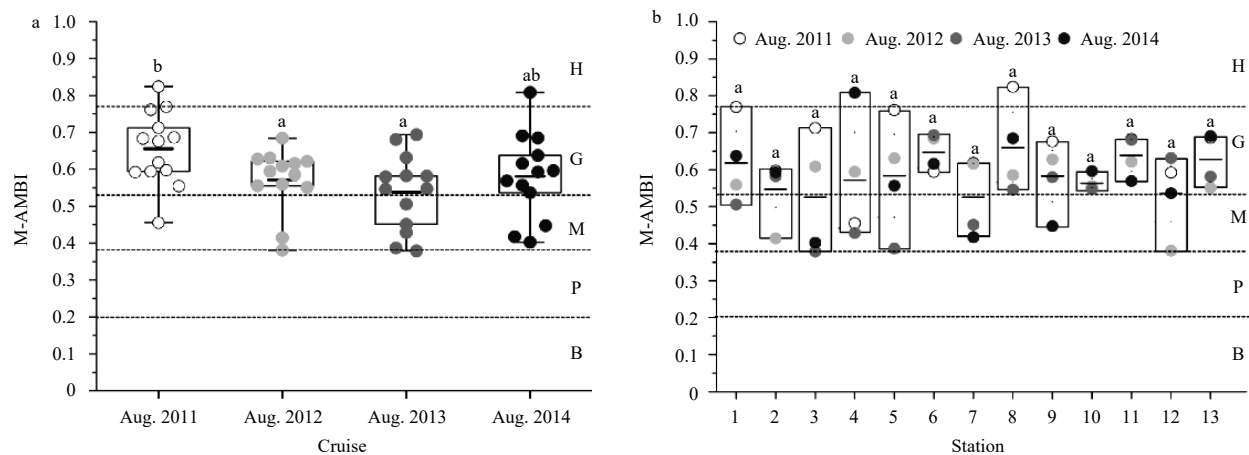


Fig. 5. The M-AMBI values and EQS classes for 4 cruises (a) and at 13 stations (b) in the Laizhou Bay. The dots in the image represent the M-AMBI values of 52 samples, and the different grey shades represent different cruises. a. Thirteen samples were collected during each cruise. The minimal and maximal values are indicated by straight lines. The box indicates the 25th and 75th percentiles. The middle bold, horizontal line indicates the mean value. b. Four samples were taken at each station. The top of the box represents the maximum value, the bottom the minimum value, and the middle bold line the mean value. H represents high EQS, G good, M moderate, P poor and B bad. Differences among groups were analysed for significance using one-way ANOVA. The same letters above the columns indicate no differences ($p>0.05$). Different letters above the columns indicate significant differences ($p<0.05$).

Table 3. The characteristics and evaluation of the samples in terms of H' , AMBI and M-AMBI

Case	Case I	Case II	Case III	Case IV
Characteristic	The sum of the relative abundances of EGI, EGII and EGIII was more than 50%, and the abundance of a single species accounted for more than 50% of the total abundance.	The sum of the relative abundances of EGI, EGII and EGIII was more than 50%, and the abundance of <i>Arcuatula senhousia</i> (EGIII) accounted for more than 50% of the total abundance.	The sum of the relative abundances of EGIV and EGV was more than 50%, and the abundance of <i>Capitella capitata</i> (EGV) accounted for 40% to 50% of the total abundance.	The sum of the relative abundances of EGIV and EGV was more than 50%, and the abundance of <i>Cirratulus cirratus</i> (EGIV) accounted for more than 70% of the total abundance.
Number of samples	39	10	2	1
The evaluation of the H'	100% of the samples were undegraded.	10% of the samples were undegraded; 90% of the samples were degraded.	100% of the samples were undegraded.	100% of the samples were degraded.
The evaluation of the AMBI	100% of the samples were undegraded.	100% of the samples were undegraded.	100% of the samples were degraded.	100% of the samples were degraded.
The evaluation of the M-AMBI	100% of the samples were undegraded.	20% of the samples were undegraded; 80% of the samples were degraded.	100% of the samples were degraded.	100% of the samples were degraded.

ated as undegraded conditions by the three indices. The sum of the relative abundances of EGI, EGII and EGIII was more than 50%, and the abundance of a single species accounted for less than 50% of the total abundance. The results above indicate that the three indices are highly consistent in identifying undegraded status.

Case II contained 10 samples. The sum of the relative abundances of EGI, EGII and EGIII was more than 50%, and the abundance of *Arcuatula senhousia* (EGIII) accounted for over 50% in each station. The H' were classified as “Moderate” or “Bad” status in degraded conditions, the AMBI was classified as “Good” status in undegraded conditions, and 80% of the samples were classified as “Moderate” under degraded conditions by the M-AMBI. These results occurred because the value of the H' mainly depend on the species richness and the homogeneity of the distribution of individuals among the species (Mulik et al., 2017). In this case, the relative abundance of *Arcuatula senhousia* was too high, which resulted a serious imbalance in the distribution of individuals among the species and desacered the H' value. The AMBI value is mainly based on the relative abundances of the

five ecological groups (Borja and Tunberg, 2011). Because of the absolute advantage of *Arcuatula senhousia* (EGIII), which has a certain tolerance to organic pollution, the results of the AMBI were classified as having “Good” status under undegraded conditions. The M-AMBI is a comprehensive index based on the species richness, H' and AMBI (Muxika et al., 2007). Therefore, the results of the M-AMBI were generally between the H' and AMBI, and most samples were classified as having “Moderate” status under degraded conditions. According to the above results, the AMBI could have overestimated the EQS (Luo et al., 2016; Qiu et al., 2018) because the high relative abundance of the single species and the imbalance among species has been indicated that the environment has been polluted and disturbed.

Case III contained 2 samples. The sum of the relative abundances of EGIV and EGV was greater than 50%, the number of species was greater than 30, and the abundance of *Capitella capitata* (EGV) accounted for 40% to 50% of the total abundance. All information provided by the Shannon-Wiener index was equivalent (Simboura and Reizopoulou, 2007). Therefore, when the species richness was not low and the distribution of individuals

among species was relatively homogeneous, the H' value was high, and the results were classified as having “Good” status under undegraded conditions. However, the high proportion of opportunistic species, which belong to the EGIV and EGV groups, indicates that the environment had been moderately or severely disturbed and the health of the macrobenthic communities had begun to deteriorate (Borja et al., 2003). Therefore, the EQS evaluated by the AMBI and M-AMBI was “Moderate”. In this case, the H' could have overestimated the benthic habitat quality. In Case IV, the sum of the relative abundances of EGIV and EGV was greater than 50%, and the abundance of *Cirratulus cirratus* (EGIV) accounted for over 70% of the total abundance. The three indices gave the same results, and only 1 sample (2%) was classified as “Moderate” or “Poor” status under degraded conditions.

The relationship among the dominant species, the three biotic indices and the environmental pressure gradient indicates the sensitivity of the macrobenthos to environmental disturbances and pollution (Berthelsen et al., 2018). The closer the relationship is, the more sensitive the indices are. The water depth, salinity, DO and concentrations of the TOC, sulphide, and TPH in the

surface sediments are shown in Fig. 6. In the Laizhou Bay, the water depth ranged from 3 to 15.5 m, averaging 7.7 m. The salinity ranged from 22 to 31, averaging 27. The DO concentration ranged from 5.7 to 10.22 mg/L, averaging 7.39 mg/L. The TOC concentration ranged from 0.09% to 0.96%, averaging 0.39%. The sulphide concentration ranged from 1.51 to 81.40 mg/kg, averaging 25.13 mg/kg. The concentration of TPH ranged from 9.41 to 366.00 mg/kg, averaging 64.80 mg/kg. Higher values of TPH were found in the Huanghe River Estuary and Xiaoqing River Estuary in the southwest of Laizhou Bay. According to the sea water quality standard (GB 3097-2007), the DO content of 96% of the sites met Standard I, while 4% of the sites exceeded Standard II. Although all the sedimentary chemical parameters conformed to the first class of the marine sediment quality standard (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2004), the contents of sulfides and TPH in sediments of different stations vary greatly, which showed that the sedimentary environment of the Laizhou Bay has been polluted to a certain extent.

The redundancy analysis (RDA) was performed to explore the

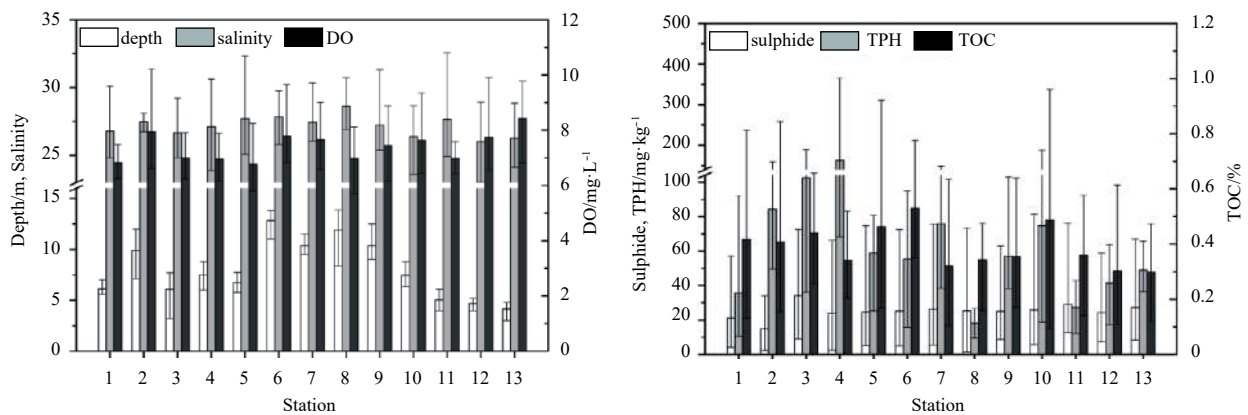


Fig. 6. Average, maximum and minimum values of benthic habitat environmental factors (depth, salinity, DO, TOC, sulphide and TPH).

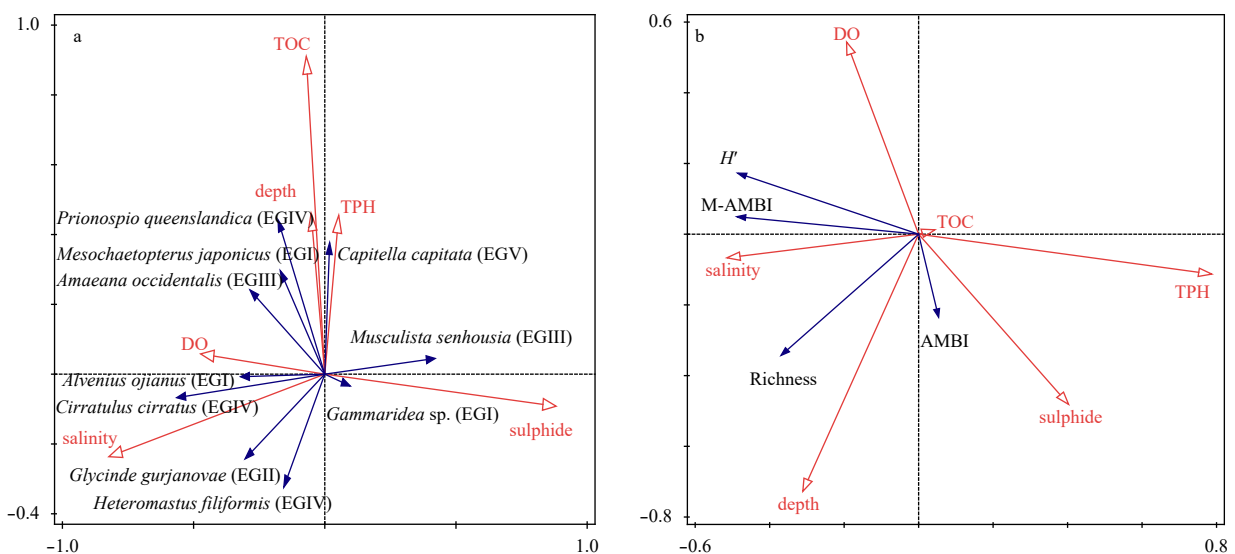


Fig. 7. Redundancy analysis (RDA) of the dominant species abundance (a), biological indices (b) and environmental factors in the Laizhou Bay. The angle between variables reflects the correlation between them (angles of approximately 90° indicate no relationship, angles of approximately 0° a highly positive correlation, and angles of approximately 180° a highly negative correlation).

relationships between the macrobenthos and the environmental factors in the Laizhou Bay. The relationship between the abundance of dominant species and the environmental factors is demonstrated in the RDA ordination diagram in Fig. 7a. The eigenvalues of the first two RDA ordination axes were 0.687 and 0.604, respectively. Monte Carlo tests for the all ordination axes were highly significant ($p=0.004$, $p<0.05$), indicating that the results were credible (Peng et al., 2012). A total of 69.2% of the cumulative variance in the species-environment relation was explained by the first two RDA ordination axes.

The first axis was positively correlated with sulphide but negatively correlated with salinity and DO, while the second axis was positively correlated with TOC, depth and TPH. *Arcuatula senhousia* was positively correlated with sulphide and negatively correlated with DO. *Capitella capitata* and *Prionospio queenslandica* were positively correlated with TOC, depth and TPH. *Alvinus ojanus* and *Cirratulus cirratus* were positively correlated with DO and salinity but negatively correlated with sulphide. *Heteromastus filiformis* and *Glycinde gurjanovae* were positively correlated with salinity and negatively correlated with TOC, depth and TPH. *Arcuatula senhousia*, belonging to the EGIII group, has some tolerance to changes in ecological conditions. In the study area, the abundance of *Arcuatula senhousia* accounted for 64.4% of the total abundance, and this species had the highest dominance. *Arcuatula senhousia* was sensitive to environmental pollution, which abundance increased with an increase in sulphide content and a decrease in DO content. The H' and M-AMBI could well reflect the state of habitat degradation. The 2 samples in Case II had the high TOC content, which lead to high abundance of *Capitella capitata*. The pollution indicator species *Capitella capitata* is the first opportunistic species belonging to the EGV group. The abundance of *Capitella capitata* increased with an increase in TPH and TOC, which indicated that *Capitella capitata* responds well to organic pollution in benthic habitats. The AMBI and M-AMBI could well reflect the degradation state. The 1 sample in Case IV had the high TPH content, the abundance of *Cirratulus cirratus* (EGIV) accounted for more than 70% of the total abundance, and the evaluation result of the three indices were degraded. These were consistent with the chemical contamination of sediments.

The relationship between the biotic indices and environmental factors is indicated by the RDA ordination diagram in Fig. 7b. The eigenvalues of the first two RDA ordination axes were 0.602 and 0.390, respectively. The Monte Carlo tests for all ordination axes were highly significant ($p=0.008$, $p<0.05$), which indicated that the results were credible (Peng et al., 2012). A total of 97.0% of the cumulative variance in the species-environment relation was explained by the first two RDA ordination axes. The first axis was positively correlated with sulphide and TPH but negatively correlated with salinity, while the second axis was positively correlated with DO and negatively correlated with depth. The number of macrobenthic species was positively correlated with depth and salinity. H' and M-AMBI were positively correlated with salinity and negatively correlated with TPH and sulphide. The AMBI was positively correlated with depth, TPH and sulphide but negatively correlated with DO. In the study area, the macrobenthos was sensitive to the salinity gradient. With an increase in salinity, the species richness, H' and M-AMBI increased, and the benthic habitat quality became better (Luo et al., 2016). The high concentrations of sulphides and TPH in the sediments indicate that the organic pollution in the sedimentary environment is serious. Based on the relationship among the biotic indices, sulphides and TPH, it is obvious that the three in-

dices can well reflect the tendency towards organic pollution in the sedimentary environment. Samples from areas with serious organic pollution and poor habitat quality had low Shannon-Wiener index (H') and M-AMBI values, but the AMBI value was high (Keeley et al., 2012).

5 Conclusions

In comparison with European and American countries, water quality management in China mainly relies upon physical and chemical monitoring data. There is still a large gap between biological monitoring and evaluation technologies. However, there is no doubt that the health of biocenoses can directly reflect the ecological water quality. The AMBI, M-AMBI and other biotic indices were initially designed for specific geographical areas and used to evaluate the environmental quality in European coastal waters (Gillett et al., 2015), but these indices have been used in China recently (Li et al., 2017; Luo et al., 2016; Cai et al., 2014). Considering the complexity and diversity of the global offshore environment, these indices need to be applied in different areas and be inter-calibrated with physical, chemical parameters and other biotic indices. According to the assessment of benthic habitat quality in the Laizhou Bay, we found that the results of the H' , which has been widely used to indicate ecological quality in China, and the AMBI and M-AMBI, which were designed to evaluate the ecological status of coastal areas in Europe, were highly consistent in undegraded conditions but showed significant differences in degraded conditions. When the relative abundance of a single species in a sample is too high and the macrobenthic community is imbalanced, the AMBI could overestimate the benthic habitat quality. Similarly, the H' overestimated the EQS, when the relative abundance of opportunistic species belonging to EGIV and EGV was high. The three biotic indices were sensitive to hydro-chemical and sedimentary chemical parameter gradients, so it could well reflect environmental changes. *Arcuatula senhousia* and *Capitella capitata* in the Laizhou Bay could be regarded as indicators, when the environment was disturbed and polluted.

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