An evaluation of macrobenthos habitat suitability in the bivalve farming area near Xiaoqing estuary

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Abstract

Since macrobenthos play an important role in the energy flow and material circulation of marine systems, they can act as an indicator of ecosystem health. Because there are generally complex relationships between macrobenthos and environmental factors, the optimal model for simulating macrobenthos habitat is a nonlinear, nonparametric model with a relatively flexible structure. This study applied canonical correlation analysis (CCA) to identify the key ecological factors affecting the community characteristics of macrobenthos in the bivalve farming area near Xiaoqing estuary. Responses of species richness to environmental factors were studied using the generalized additive model (GAM), and the Margalef index (d_M) was used instead of individual indicator species to indicate diversity variation. Six factors were selected in the optimal model by stepwise regression: salinity (Sal), sediment organic matter (SOM), ammonium nitrogen (NH_4-N), phosphate in interstitial water (PO_4-P_{soil}), ammonium nitrogen in interstitial water (NH_4-N_{soil}), and nitrate nitrogen in interstitial water (NO_3-N_{soil}) in the substrates. The response curves generated by the GAM showed a unimodal relationship between taxa diversity and Sal and SOM, d_M was positively correlated with NH_4-N, and was negatively correlated with PO_4-P_{soil}. The model optimized by forward stepwise optimization explained 92.6% of biomass variation, with a small residual (2.67). The measured d_M was strongly correlated with the predicted d_M (Pearson $R^2 = 0.845$, $p < 0.05$). This study can increase understanding of the relationships between the macrobenthic community and aquaculture activities in the bivalve farming area near Xiaoqing estuary.

1. Introduction

Since the macrobenthic community plays a vital role in energy flow, material circulation, and information transfer of marine ecosystems, it is an important indicator of ecosystem health (Butkas et al. 2011; Zhao et al. 2019; Hajializadeh et al. 2020). The macrobenthos is widely used as an indicator of ecological health in marine monitoring and assessment due to the relatively weak ability of macrobenthos species to migrate, their long life cycles, and their different tolerances to stressors (Xu and Li. 2021). Estuaries are ecotones connecting freshwater and marine ecosystems and are important spawning and feeding grounds for many economically important fishes (Yang et al. 2020). Macrobenthos communities also play a key role in the functioning of estuarine systems. Estuaries are easily disturbed by anthropogenic activities, and the ecological status of benthic organisms are regularly assessed in estuaries and adjacent areas (Aubry and Elliott. 2006). There have been increasing anthropogenic pressures on coastal habitat, including by coastal development and the habitat degradation (Lotze et al. 2006). Consequently, there has been a decline in the biodiversity of the macrobenthos due to aquatic ecosystem habitat loss and degradation (Geist. 2011). In addition, the spatial and temporal distributions of the estuarine biological community may be directly or potentially affected by the changes in water and sedimentary environments (Shi. 2014). Benthic communities are directly affected by a variety of physical and chemical environmental factors, including temperature, salinity, hydrodynamic status, sediment type and particle size, and nutrient content (Zhang et al. 2012; Xie et al. 2016; Shadrin et al. 2019; Huang et al.

2022). Therefore, there is a need to explore the habitat requirements of macrobenthos communities and their responses to changes in environmental factors.

In general, the habitat requirements of the living environment are referred to “habitat suitability”. The evaluation of benthic biodiversity and the health of the ecological environment using the biological index method is the basis of habitat suitability and habitat health evaluation (Li. 2021). Various biological indices have been widely used in the evaluation of the marine environment, such as the Shannon-Wiener diversity index, AZTI's Marine Biotic Index (AMBI), and Multivariate-AMBI (M-AMBI) (Qiu et al. 2018; Ni et al. 2019). Models were established by the analysis of environment factors to evaluate the suitability of habitats. These habitat models can effectively analyze the conditions of living creatures and explore the drivers of environmental changes. Some advantages of these models include (Lu et al. 2021): (1) the prediction of the emergence of species based on abiotic and biological variables; (2) their ability to improve the understanding of relationships between species and habitat; (3) their ability to quantify habitat requirements.

A habitat suitability model is an effective tool for examining the combined influence of ecological factors on taxa (Yi et al. 2018a). A variety of habitat suitability evaluation methods have been applied in recent years. These include multivariate statistical methods such as the generalized linear model (GLM) and generalized additive model (GAM), fuzzy logic models, artificial neural networks (ANNs), and classification trees (Ahmadi-Nedushan et al. 2006; Yang et al. 2020). Most of these methods have been applied to habitat suitability and quality assessment. A comparison of the performances of the different models showed that GAM is ideal for analysis of habitat suitability due to its flexibility, simulation of complex nonlinear relationships, and accurate calculations (Yi et al. 2016). GAM is an expansion and a nonparametric modification of GLM, and is not only able to screen various environmental factors and fit the best model, but can also intuitively evaluate the relationships between the number of macrobenthos and various environmental factors in the form of a graph. GAM is able to detect complex relationships in data, and has been applied in numerous ecological applications to predict species distribution as a function of their environment (Glińska-Lewczuk et al. 2016; Wood and Augustin. 2002). GAM has also been widely used in the study of the relationships between fishery resources and environmental factors (Yan et al. 2021; Liu et al. 2021; Wu and Chen. 2020). However, there have been relatively few studies on the relationships between the benthic population and environmental variables in the bivalve farming area.

Recent applications of GAM models have mainly focused on natural river ecosystems, and there has been insufficient focus on the impact of habitat factors on macrobenthic communities in the bivalve farming area of tidal flats. Related previous studies have discussed the mode of habitat utilization and development by microbenthic communities in tidal flats, with the suitability of habitats evaluated based on theory (Wang and Zhu. 2009; Yang et al. 2010). The relationships between macrobenthic communities and ecological factors are usually nonlinear and highly complex, and it is often difficult to express these relationships using traditional mathematical equations (Yi et al. 2014; Gezie et al. 2017). While past studies have examined disturbances to macrobenthos and changes to community structure due to the impacts of fishery activities (Yuan et al. 2006; Liao et al. 2011), there have been few studies on habitat adaptability of macrobenthos in the bivalve farming area of Laizhou Bay. Therefore, the present study adopted the macrobenthos community of Xiaoqing estuary as a case study, key habitat factors affecting the community structures were identified by applying canonical correlation analysis (CCA) and correlation analysis, and a GAM was developed to analyze the relationships between the macrobenthos community and ecological factors. The community characteristics of macrobenthos were described using the Margalef diversity index (d_M), which is typically used to estimate the abundance of a taxa within a region.

The aim of the present study was to evaluate the effects of farming activities on the macrobenthic community in the bivalve farming area near Xiaoqing estuary. The specific objectives of the present study were to: (1) characterize the abundance and diversity of the cohabiting macrobenthic community in the bivalve farming area near Xiaoqing estuary and to explore the effects of farming activities on the macrobenthic community; (2) determine the influence of environmental parameters on the macrobenthic community, and; (3) establish a GAM model of macrobenthos based on the d_M.

2. Study Area And Methods

2.1. Study area

Laizhou Bay is in southern Bohai Sea, China, and is the largest bay in Shandong Province, accounting for ~ 10% of the area of the province. They bay acts as an important fisheries spawning and feeding ground in the Bohai Sea. The Xiaoqing River is the second largest river flowing into Laizhou Bay after the Yellow River. This river is a large-scale artificial river with navigation, irrigation, and sewage effluent disposal functions (Wang et al. 2018). The Xiaoqing River imports large quantities of organic matter and nutrient into Laizhou Bay, resulting in serious ecological damage to the Bay (Cui et al. 2013). The Xiaoqing Estuary is one of the main mudflat clam production areas of Laizhou Bay. The clam species that are farmed in this area include *Ruditapes philippinarum*, *Mactra veneriformis*, *Meretrix meretrix*, and *Cyclina sinensis*, with a collective annual output of ~ 20,000 tons.

The present study conducted four ecological surveys (in March, May, August, and October, 2021) to describe the distribution of the macrobenthos community and analyze the responses between macrobenthos and habitat factors in southwest Laizhou Bay. The present study established 12 sampling sites (S1–S12) in the bivalve aquaculture area between longitude 37.20° and 37.35° and latitude 119.05° and 119.15° to represent the different habitats (Fig. 1).

2.2. Sampling Method

2.2.1. Macrobenthos sampling

Three replicate macrobenthos samples were taken at each sampling station using a Van Veen grab of 0.025 m^2. Each sample was filtered through a 0.5-mm iron screen. The filtered-out specimens were then transferred to sample bottles and fixed with 5% formalin. The samples were identified, classified, counted, and wet-weighted (accurate to 0.0001 g) in the laboratory, and finally converted into abundance (ind./m^2) and biomass (g/m^2) according to the sampling area. All samples were collected, treated, and stored according to the "Specifications for oceanographic survey-Part 6: Marine biological survey" (GB/T12763.6-2007).

2.2.2. Determination of ecological factors

Apart from macrobenthos-related measures, the present study also measured seventeen parameters. The water quality parameters and physical features measured included water depth (H), water temperature (T), pH, dissolved oxygen (DO), salinity (Sal), chlorophyll-a (Chl-a), particulate organic matter (POM), phosphate (PO_4-P), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and nitrite nitrogen (NO_2-N). The variables associated with the substrate measured in the present study included: the quantity of sediment organic matter (SOM), median particle diameter (D_{50}), phosphate in interstitial water (PO_4-P_{soil}), ammonium nitrogen in interstitial water (NH_4-N_{soil}), nitrate nitrogen in interstitial water (NO_3-N_{soil}), and nitrite nitrogen in interstitial water (NO_2-N_{soil}). Some parameters (H, T, pH, DO, and Sal) were measured in the field using a multi-parameter water quality analyzer (SMARTROLL MP). Median particle diameter (D_{50}) was examined by a laser particle sizer (Mastersizer 3000). Nutrient concentrations were determinate by an automatic nutrient fluid analyzer (Auto Analyzer 3, Bran Luebbe, Germany) based on the "Specifications for oceanographic survey-Part 4: Seawater analysis" (GB/1737-8.4-2007). Water and sediment samples were collected and returned to the laboratory for the measurement of all other factors using methods corresponding to national standards.

2.3. Data Analysis Method

2.3.1. Distribution of macrobenthos

The present study used the Margalef diversity index (d_M) (Margalef, 1958) to describe the diversity of benthic macroinvertebrates in the study area. Species-level taxa were used for calculating the index. d_M was calculated as:

d_M =(S-1)/ln N (1)

In Eq. (1), S is taxa richness, i.e., number of taxa within a sampling area and N is the total number of individuals.

2.3.2. Statistical analysis

Kolmogorov-Smirnov (K-S) normal inspection was conducted to identify habitat factors, whereas Pearson's correlation analysis was conducted according with normal distribution index. Alternatively, Spearman correlation analysis was used inconsistently in cases in which the data followed a normal distribution (Yigezu et al. 2018). Factors with a significant influence on macrobenthos were then identified by Constrained Ordination (Takamura et al. 2009). All biological data and environmental data, besides for pH, were log transformed before analysis (Muylaert et al. 2000). Pearson's and Spearman correlation analysis were conducted in the SPSS 22 statistical software package.

Detrended correspondence analysis (DCA) was conducted on the relative abundance matrix of macrobenthos. A gradient length of the first axis of DCA > 3.0 standard deviation (SD) indicates a unimodal distribution of macrobenthos under which CCA is appropriate rather than linear distribution, under which redundancy analysis (RDA) is suitable (Glińska-Lewczuk et al. 2016). The maximal gradient length of DCA for macroinvertebrate communities is four. Macrobenthos species present in three or more samples with a relative abundance > 1% were selected for CCA to reduce errors in the analysis (Xiong et al. 2013). CCA was conducted in the software CANOCO version 5. Monte Carlo permutations were used assess the effect of explanatory variables.

2.3.3. Generalized Additive Model (GAM)

A GAM was developed to quantify relationships between the Margalef diversity index (d_M) and key ecological factors. The general form of the GAM is:

$$f(\mu(N)) = \beta_0 + Y_1(x_1) + \ldots + Y_n(x_n) \quad (2)$$

$$n = 0, 1, 2$$

In Eq. (2), f(.) is the connection function, μ(N) is the expected value of the response variable Y, β_0 is the intercept, and Yi(.) is the smoothing function for the i_{th} explanatory variable x_i.

Stepwise regression was used to assess the accuracy of the model according to the Akaike Information Criterion (AIC). The AIC value of the single-factor prediction function was detected, following which other environmental factors were progressively added to the single-factor prediction function until no further decrees in the AIC could be obtained.

The present study regarded the model with the smallest AIC value to be the optimal model. The significance of the prediction model was evaluated based on the results of F-test. The generalized additive model was implemented by the "mgcv" package in the R software (Wood, 2008), and basic data processing was completed in Excel 2019.

3. Results

3.1. Ecological factors and the composition of the macrobenthos community

3.1.1. Ecological factors

Table 1 lists the values for each of the measured ecological factors. 11 parameters such as water temperature and water depth in water bodies and 6 sediment parameters such as sediment particle size and nutrients in pore water were monitored.

Table 1 Values for each of the measured ecological factors

	Factors	Max	Min	Mean
Water	Water depth (m)	4.40	1.80	3.20
	Temperature (℃)	29.10	12.90	20.50
	pH	8.00	7.60	7.90
	DO(mg/L)	8.03	7.64	7.94
	Salinity (psu)	25.1	11.8	21.30
	Chlorophyll-a (μg/L)	9.95	2.15	5.04
	POM (mg/L)	20.00	3.80	8.69
	PO_4-P (μmol/L)	10.16	0.09	1.59
	NH_4-N (μmol/L)	109.89	2.96	35.20
	NO_3-N (μmol/L)	139.00	2.11	30.00
	NO_2-N (μmol/L)	12.61	0.30	3.84
Substrate	SOM (%)	0.20	0.01	0.03
	D_{50} (μm)	113.00	7.50	74.9
	PO_4-P_{soil} (μmol/L)	10.84	0.45	2.80
	NH_4-N_{soil} (μmol/L)	85.28	0.44	26.55
	NO_3-N_{soil} (μmol/L)	49.86	2.43	14.78
	NO_2-N_{soil} (μmol/L)	10.26	0.23	2.49

Abbreviations: POM, particulate organic matter; SOM, sediment organic matter; DO, dissolved oxygen; D_{50}, median particle diameter of sediment.

3.1.2. Composition of the benthic macrobenthos fauna

The macrobenthos taxa were classified to species level for further analysis. The four surveys obtained 84 macrobenthos species, including 61 families falling into nine phyla, nine classes, and 31 orders. Among these, there were 30 species of Polychaeta, including 12 orders, 21 families, and 25 genera, accounting for 35.7% of the total taxonomic unit; followed by 20 species of crustaceans, including 6 orders, 12 families and 15 genera, accounting for 23.8%; 17 species of Gastropods, including 4 orders, 14 families, and 12 genera, accounting for 20.2%, 12 species of Bivalvia, including 5 orders, 9 families, and 10 genera, accounting for 14.3%, and 5 other species. There were 4 orders, 5 families, and 5 genera, accounting for 6% of the total taxonomic unit (Fig. 2).

Fig. 2 Community structure of macrobenthos

Mactra chinensis, *Mactra veneriformis, Ruditapes philippinarum*, *Musculus senhousei,* and *Nephtys polybranchia* were the dominant species in the survey (Table 2).

Table 2 Dominant species of macrobenthos in different months

Group	Species	Dominance			
		March	May	August	October
Mollusca	*Mactra chinensis*	0.551	0.156		
	Mactra veneriformis			0.024	0.254
	Ruditapes philippinarum				0.024
	Musculus senhousei			0.035	
	Decorifera matusimana				0.033
	Cultellus attenuates		0.025		
Annelida	*Nephtys polybranchia*		0.024		0.024
	Notomastus latericeus Sars	0.296			
	Mediomastus californiensis				0.021
Arthropoda	*Heterocuma sarst*		0.078		

The results of cluster analysis and multidimensional scaling (MDS) showed a higher community stability in March and August than in May and October (Figs. 3–6) (No sediment was collected for S5 and S12 in March and S8 and S9 in October due to adverse weather conditions).

Fig. 3. Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in March

Fig. 4. Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in May

Fig. 5. Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in August

Fig. 6. Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in October

3.2. Effects of ecological factors on benthic macrobenthos

DCA analysis of the macrobenthos relative abundance matrix indicated a maximum gradient length of 4, following which CCA was applied to analyze the correlations between key habitat factors and macrobenthos (Table 3, Fig. 7). A Monte Carlo test (999 transpositions) showed significant differences between all axes and the first two axes ($P < 0.05$). The CCA ordination table indicated relatively large eigenvalues of the first two ordination axes of 0.7849 and 0.4837, respectively, which explained 38.88% and 62.84% of variance in dominant species data and in species-environment relationships. Axes 3 and 4 showed relatively low eigenvalues and interpretation rates.

Table 3 Results of canonical correlation analysis (CCA) of macrobenthos community structure and environmental factors

Axis1	Eigenvalues	Pseudo-Canonical correlation	Explained Variation (cumulative)	Explained fitted Variation (cumulative)
1	0.7849	0.9564	22.18	38.88
2	0.4837	0.8874	35.85	62.84
3	0.2887	0.8700	44.00	77.14
4	0.1316	0.6765	47.72	83.66

The ordination axes and environmental ordination axes of the two species were approximately vertical, and the correlation coefficients were 0.01 and 0.00, respectively. The results demonstrated that the relationship between benthos and environmental factors was reflected by a linear combination between ordination axes and environmental factors, and the ordination results were reliable. The CCA ordination diagram showed high correlations between Axis 1 and environmental factors NH_4-N, PO_4-P, NH_4-N_{soil}, and NO_2-N_{soil} and between Axis 2 and temperature (T), dissolved oxygen (DO), salinity (Sal), and NO_2-N. Therefore, these factors had a significant impact on the abundance of macrobenthos.

Fig. 7. Canonical correlation analysis (CCA) ordination chart of macrobenthos community structure and environmental factors

3.3. Responses of community diversity to ecological factors

The present study examined the relationship between each individual ecological factor and the Margalef diversity index (d_M). The model was constructed using the data sampled in March, May, and August, following which the relationships between the 17 environmental factors and d_M were assessed. Twelve environmental factors that had significant effects on taxa diversity (d_M) were identified (H, T, pH, Sal, DO, POM, SOM, NH_4-N, PO_4-P_{soil}, NH_4-N_{soil}, NO_3-N_{soil} and D_{50}). Since the correlation coefficients between DO and NH_4-N and between T and NH_4-N_{soil} exceeded 0.5, these variables were not simultaneously added to the model to avoid collinearity, and higher correlations between d_M and NH_4-N, NH_4-N_{soil}, and Sal were retained. The remaining nine environmental indicators were used to establish the GAM, and the model structure was optimized by forward stepwise regression (Table 5). The addition of the variables SOM, PO_4-P_{soil}, NO_3-N_{soil}, NH_4-N_{soil}, Sal, and NH_4-N significantly increased model performance ($p < 0.05$). Variables H, T, and pH were removed since their inclusion did not improve model performance. Model 9 represents the final form of the model: $d_M \sim s(SOM) + s(PO_4\text{-}P_{soil}) + s(NO_3\text{-}N_{soil}) + s(NH_4\text{-}N_{soil}) + s(Sal) + s(NH_4\text{-}N)$. The model explained 92.6% of variance (adjusted coefficient of determination $R^2 = 0.845$). The Pearson's correlation coefficient between the calculated d_M and the measured d_M was highly correlated at 0.9635 ($p < 0.05$, Fig. 8).

The response curve of d_M to environmental factors shows a unimodal relationship between species diversity and SOM and Sal. In addition, there was a linear relationship between species diversity and NH_4-N and PO_4-P_{soil}, and d_M was positively correlated with NH_3-N and negatively correlated with PO_4-P_{soil} (Fig. 9).

Table 5 Variance analysis table of the forward stepwise regression process

Model	Residual deviation	Cumulative deviation	AIC	*p*
Model 1	8.4899	19.5%	28.9733	0.0035
Model 2	7.7887	27.5%	27.3027	0.0014
Model 3	6.8724	43.4%	21.9143	0.0054
Model 4	4.5450	79%	3.5953	0.9830
Model 5	4.5103	79.6%	3.1832	0.7660
Model 6	4.4361	80.2%	2.6007	0.7332
Model 7	4.3078	80.7%	3.4475	0.0002
Model 8	2.9922	90.8%	−13.9273	0.0092
Model 9	2.6667	92.6%	−20.5398	0.0081

Notes: Only SOM was added to Model 1. The factors PO_4-P_{soil}, NO_3-N_{soil}, pH, POM and water depth were successively added into Models 2, 3, 4, 5, and 6. Models 4, 5, and 6 were not improved after the addition of pH, POM, and H ($p>0.05$). pH, POM and H were removed from Model 7. Models 7, 8, and 9 were improved after the addition of NH_4-N_{soil}, Sal, and NH_4-N ($p < 0.05$).

Abbreviations: AIC, Akaike Information Criterion.

Fig. 8. Calculated Margalef diversity index (d_M) versus d_M based on Model 9

Fig. 9. Response curves of the Margalef diversity index (d_M) to ecological factors in the generalized additive model (GAM) analysis

Notes: The vertical axes indicate the relative influence of each explanatory variable on the prediction. Shaded areas indicate 95% confidence limits.

3.4 Validation of the model

Sampling data collected in October 2021 were used to validate Model 9. As shown in Table 6, measured d_M values were strongly correlated with the d_M predicted by Model 9 (Pearson R^2 = 0.845, p < 0.05), with a small mean square error (MSE). This result confirmed the good performance of the model and its ability to effectively simulate the distribution of benthic fauna diversity in the bivalve farming area in the Xiaoqing estuary, Laizhou Bay (Fig. 10).

Table 6 Statistical summary of the performance of the optimal model (Model 9) in October

Site	Measured d_M	Predicted d_M	Site	Measured d_M	Predicted d_M
S1	0.3467	0.5320	S6	0.5758	0.1054
S2	0.8873	0.3592	S7	0.8546	0.9453
S3	0.3775	0.4296	S10	1.2792	1.2764
S4	1.2792	0.8639	S11	0.4293	0.4261
S5	1.0193	1.8208	S12	0.3941	0.4438
MSE	0.1363	R^2	0.845	p	0.0383

Notes: data shown with mean squared error (MSE), correlation coefficient (R^2), and significance level (p value) between predicted and measured data; No sediment samples were taken in sites 8 and 9 due to adverse weather.

Fig. 10. The spatial distributions of the measured and predicted Margalef diversity index (d_M)

4. Discussion

The present study investigated soft-bottom macrobenthic communities in southwest Laizhou Bay. The survey identified 84 species of macrobenthos. The order of the major taxonomic groups in terms of species numbers was: Polychaeta > Mollusca > crustaceans > echinoderms. This result is consistent with those of many previous studies and confirms the significant changes to the community structure of macrobenthos in Laizhou Bay. These changes included the gradual replacement of individual species with smaller body sizes by those with larger body sizes as the dominant species of the macrobenthos community (Luo et al. 2013; Zhou et al. 2010; Liu et al. 2014). This trend indicates that the decline in macrobenthos biodiversity is related to the effects of anthropogenic activities, such as pollution and eutrophication.

Macrobenthos inhabit the marine substrate environment and are characterized by strong regionality, weak activity, and limited ability to avoid unfavorable environments (Huang et al. 2021). The water and substrate environments have the greatest impacts on macrobenthos, thereby regulating the species occupying the macrobenthos community (Veiga et al. 2017). The results of clustering and non-metric multidimensional scale analysis indicated a high spatial variability and poor stability of the macrobenthic community in the survey area. These results are consistent with those of previous studies (Li et al. 2007; Ding et al. 2021). On the one hand, there is aquaculture of filter-feeding bivalve in the study area. These bivalve excrete a significant proportion of assimilated organic detritus to the sediment in the form of feces and pseudo-feces, resulting in hypoxia and sulfide accumulation due to a lack of diffusion in the substrate environment. Thus, the composition of the benthic community and the nutrient structure of aquaculture areas are deeply affected, with decreases in the diversity and richness of the community (Dubois et al. 2007; Ma et al. 2014). On the other hand, the surface sedimentary environment is disturbed by the harvesting of bivalve (usually by rake harvesting), resulting in damage to the macrobenthos (Han et al. 2011; Ding. 2020). There is a need to develop a reasonable layout for bivalve aquaculture since intensive aquacultural activities may have indirect impacts on macrobenthos through the modification of physical sediment characteristics (Liao et al. 2019). Meanwhile, other studies have shown that the ocean current is a key factor regulating the bio-deposition of organic matter and minimizing the impact of bivalve on benthic communities (Han et al. 2013). Bivalve farming may be considered in areas with higher or tidal currents. Moreover, the structure of the macrobenthic community may be influenced by unstable environmental factors, particularly the influence of river runoff and rainfall changes on the marine environment. In addition, studies in other sea areas have shown that the complex marine environment results in the formation of different habitat niches, which are inhabited by different benthic community structures, resulting in low similarities between the benthic communities of each station (Cai et al. 2013; Jia et al. 2022).

Different environmental factors play important roles in the distribution of benthic communities, thereby contributing to the high spatial and temporal heterogeneity in benthic community structure (Chapman and Wang. 2001; Mosbahi et al. 2016). Ocean currents and other factors have contributed to hydrodynamic factors in the ocean being more complex than those in fresh water. In particular, estuaries are affected by the interactions between land and sea, resulting in a more complex natural environment. Therefore, environmental factors have a more significant impact on the spatiotemporal changes in macrobenthic communities (Wang et al. 2021). The results of CCA showed that the macrobenthic communities were affected by environmental variables, mainly T, DO, Sal, NH_4-N, NH_4-N_{soil}, PO_4-P, NO_2-N, and NO_2-Nsoil, consistent with the results of previous studies (Verneaux and Schmitt. 2004; Sturdivant et al. 2013; Zhou et al. 2018; Wang et al. 2020; Dong et al. 2021). Many studies have shown that changes in runoff into the sea can lead to regional differences in salinity and nutrient input. Salinity then directly affects the distribution and composition of benthic communities (Currie and Small. 2005; Meng et al. 2021; Huang et al. 2021). The present study found a decrease in the abundance of species in August compared with that in other months. This result can be related to continuous heavy rainfall and increased river runoff during this month. An increase in the variation in salinity may increase the physiological pressure on macrobenthos, thereby resulting in increased rates of death or migration amongst the adult and juvenile populations and a decline in the number of species (Alongi. 1990). Therefore, there is a need to strengthen research on the spatiotemporal changes in salinity and to clearly describe the effects of salinity on the community structure of macrobenthos.

Since the comprehensive multi-parameter evaluation index relies heavily on the weights of parameters, the biological index is more suitable for the assessment of ecological health under the influences of anthropogenic activities (Gezie et al. 2017). Identifying the spatiotemporal distribution of the benthic community is essential for the conservation and sustainable development of local benthic resources. The relationships between various environmental factors, such as temperature and salinity, on benthic species richness are often not linear. However, GAM typically shows higher performance in analyzing the nonlinear relationship between dependent and multiple independent variables. Thus, the application of GAM has great significance for the study of benthic communities. The present study screened and fitted the response curves of the macrobenthic richness index to key environmental factors based on GAM. The results of the GAM indicated a significant response between d_M and environmental variables (Sal, SOM, NH_4-N, PO_4-P_{soil}, NH_4-N_{soil}, and NO_3-N_{soil}) ($p < 0.05$). The model simulations also showed a good fit to measurements, with a total residual deviation after model optimization of 2.67 and an AIC of −20.54. This result is consistent with those of previous studies (Zhang et al. 2021). The GAM indicated that d_M was positively correlated with NH_4-N and negatively correlated with PO_4-P_{soil}, consistent with the results of previous studies. NH_4-N is an essential nutrient for the growth of aquatic plants and algae in water, and the application of nitrogen to aquatic plants in previous studies improved the productivity of macrobenthos (Miserendino et al. 2008; Yang et al. 2020). Eutrophication results from increases in PO_4-P_{soil}, which in turn increase the biomass and diversity of plankton, but results in changes to the community structure and a reduction in the species richness of benthic communities (Zhang et al. 2021). Organic matter and nutrients are often the factors limiting the survival of benthic communities (Levin et al. 1998; Lv et al. 2016). There were high correlations between DO and NH_4-N, T, and NH_4-$N_{soil,}$ with increases in T and DO. Although there were clear changes in NH_4-N and NH_4-N_{soil}, the factors T and DO were removed to increase the degree of fit of the model. Other studies have suggested that DO is an important factor regulating the survival of benthos, with impacts on the abundance and distribution of macrobenthos (Luo et al. 2016). Therefore, the present study considered the interactions between these environmental factors, and the above environmental factors were added into the GAM to allow comprehensive future studies.

Salinity is an important environmental factors affecting the survival, growth, and distribution of benthic communities (Shou et al. 2013). The salinity of the benthic environment in the study area ranged between 21–25 psu. The model results showed a minimum d_M under a salinity of 22.5 psu. The rate of decline in d_M was highest under a salinity of 20–22 psu, whereas there was a gradual upward trend at a salinity of 24–25 psu. Exchanges in fresh and salt water inputs have resulted in changes to the structure of the benthic community in the estuary (Chainho et al. 2006).

The distribution of target species was predicted by exploring the relationship between species distribution and related variables using the species distribution model. The GAM has been widely used to explore relationships between species distribution and environmental factors in fishes (Hua et al. 2019) and submerged plants (Yang et al. 2020). However, there have been few studies on the relationships between macrobenthos and environmental variables in estuaries. The present study applied the GAM in combination with the common zero-value richness index to analyze the distribution of benthic resources in southwest Laizhou Bay. Although the results of the current study are consistent with field monitoring observations, certain limitations of the model remain since the model was established by considering the species richness index (d_M) only. The present study also considered a limited number of environmental factors. In addition, the present study did not consider the influences of spatial and temporal auto correlation on the modeling. Future studies can improve the accuracy of the model by considering the effect of time through the addition of an autoregressive process.

It was also worth noting that the establishment of the GAM model was based on environmental data surveyed in March, May, and August 2021. Therefore, the present study provides a preliminary exploration of the relationships between benthic biomass and environmental factors. Future studies should apply different methods (such as the habitat index, linear partial differential equation with first-order variable coefficient, and quantile regression) to integrate long-term quantitative and environmental data into future habitat suitability models. These models can then be used to more comprehensively analyze the distribution and dynamics of benthic organisms. Moreover, there have been changes to some environmental factors in the study area, such as salinity and inorganic salts, due to heavy rain, which may partially explain the deviation in the model results.

5. Conclusions

Macrobenthos in the bivalve farming area near Xiaoqing estuary, Laizhou Bay was dominated by Polychaeta, with individual species with smaller body forms gradually replaced by individual species with larger body forms as the dominant species of the macrobenthos community. The results of clustering and non-metric multidimensional scale analysis indicated that the macrobenthic community has been affected by bivalve farming. The GAM model showed that the Margalef index was correlated with environmental factors (Sal, NH_4-N, SOM, PO_4-P_{soil}, NO_3-N_{soil}, NH_4-N_{soil},). The optimal GAM model explained 92.6% of observed variation in microbenthic biomass, with a small residual (2.67). The measured d_M was strongly correlated with predicted d_M (Pearson R^2 = 0.845, p < 0.05). In general, the model showed good performance and could effectively simulate the distribution of benthic fauna diversity in the bivalve farming area in the Xiaoqing estuary of Laizhou Bay. The complementary use of different indices is recommended to assess the effects of farming activities on macrobenthos in China.

Declarations

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Authors contributions

Lulei Liu and Yuze Mao conceived the ideas, designed methodology and write the manuscript; Ling Zhu, Suyan Xue, Jiaqi Li, Changsheng Zhang, Wenhan Yu and Zhanfei Ma collected the data; Ang Li analyzed the data and result; Haonan Zhuang revised the language of the article. All authors contributed critically to the drafts.

Data availability

The datasets generated during and/or analysed during this study are available from the corresponding author upon request.

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Conflict of interests

The authors declare that there is no conflict of interests.

Ethical approval

No further permission or ethical approval was required under national standards guidelines.

References

Ahmadi-Nedushan B, St-Hilaire A, Bérubé M, Robichaud É, Thiémonge N, Bobée B (2006) A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Res Appl 22:503-523. https://doi.org/10.1002/rra.918

Alongi DM (1990) The Ecology of Tropical Soft-Bottom Benthic Ecosystems. Oceanogr Mar Biol 28: 381-496

Aubry A, Elliott M (2006) The use of environmental integrative indicators to assess seabed disturbance in estuaries and coasts: Application to the Humber Estuary, UK. Mar Pollut Bull 53:175-185. https://doi.org/10.1016/j.marpolbul.2005.09.021

Butkas KJ, Vadeboncoeur Y, Vander Zanden MJ (2011) Estimating benthic invertebrate production in lakes: a comparison of methods and scaling from individual taxa to the whole-lake level. Aquat Sci 73:153-169. https://doi.org/10.1007/s00027-010-0168-1

Cai WQ, Meng W, Liu LS, Zhu YZ, Zhou J (2013) Macrozoobenthos community structure of the Bohai Bay in spring time. Acta Scien Circum 33:1458-1466. https://doi.org/10.13671/j.hjkxxb.2013.05.004

Chainho P, Costa JL, Chaves ML, Lane MF, Dauer DM, Costa MJ (2006) Seasonal and Spatial Patterns of Distribution of Subtidal Benthic Invertebrate Communities in the Mondego River, Portugal-A Poikilohaline Estuary. Hydro 555:59-74. https://doi.org/10.1007/s10750-005-1132-2

Chapman PM, Wang F (2001) Assessing sediment contamination in estuaries. Environ Toxicol Chem 20:3-22. https://doi.org/10.1002/etc.5620200102

Cui Y, Zhang LJ, Luo XX, Zhang X (2013) Study on the Water Pollution and Eutrophication in the Xiaoqing River Estuary. Perodical of Ocean University of China 43:60-66. https://doi.org/10.16441/j.cnki.hdxb.2013.02.010

Currie DR, Small KJ (2005) Macrobenthic community responses to long-term environmental change in an east Australian sub-tropical estuary. Estuar Coast Shelf S 63:315-331. https://doi.org/10.1016/j.ecss.2004.11.023

Ding J K (2020) Health assessment of benthic habitats based on macrobenthos in three mariculture Bays. PhD Dissertation. Shanghai Ocean University.

Ding JK, Li JQ, Xue SY, Zhang WW, Huo EZ, Ma ZF, Yu WH, Mao YZ (2021) Health assessment for benthic habitats of macrobenthos in the sea area adjacent to the Xiaoqing estuary, Lai zhou Bay. Acta Ecol Sin 41:4806-4817. https://doi.org/10.5846/stxb202002290369

Dong J, Sun X, Zhang Y, Zhan Q, Zhang X (2021) Assessing benthic habitat ecological quality using four benthic indices in the coastal waters of Sanshandao, Laizhou Bay, China. Ecol Indic 129:107980. https://doi.org/10.1016/j.ecolind.2021.107980

Dubois S, Marin-Léal JC, Ropert M, Lefebvre S (2007) Effects of oyster farming on macrofaunal assemblages associated with Lanice conchilega tubeworm populations: A trophic analysis using natural stable isotopes. Aquaculture 271:336-349. https://doi.org/10.1016/j.aquaculture.2007.03.023

Geist J (2011) Integrative freshwater ecology and biodiversity conservation. Ecol Indic 11:1507-1516. https://doi.org/10.1016/j.ecolind.2011.04.002

Gezie A, Anteneh W, Dejen E, Mereta ST (2017) Effects of human-induced environmental changes on benthic macroinvertebrate assemblages of wetlands in Lake Tana Watershed, Northwest Ethiopia. Environ Monit Assess 189. https://doi.org/10.1007/s10661-017-5853-2

Glińska-Lewczuk K, Burandt P, Kujawa R, Kobus S, Obolewski K, Dunalska J, Grabowska M, Lew S, Chormański J (2016) Environmental Factors Structuring Fish Communities in Floodplain Lakes of the Undisturbed System of the Biebrza River. Water-Sui. 8:146. https://doi.org/10.3390/w8040146

Hajializadeh P, Safaie M, Naderloo R, Shojaei MG, Gammal J, Villnäs A, Norkko A (2020) Species Composition and Functional Traits of Macrofauna in Different Mangrove Habitats in the Persian Gulf. Front Mar Sci 7. https://doi.org/10.3389/fmars.2020.575480

Han QX, Li BQ, Han QY, Zhang Y, Wang YQ, Wang QC, Liu DY (2011) Preliminary study of the impact of fishery trawling on epifauna community in the coastal water of Weihai Port. Marine Science Bulletin 30:121-126. https://doi.org/10.3969/j.issn.1001-6392.2011.02.001

Han Q, Wang Y, Zhang Y, Keesing J, Liu D (2013) Effects of intensive scallop mariculture on macrobenthic assemblages in Sishili Bay, the northern Yellow Sea of China. Hydro 718:1-15. https://doi.org/10.1007/s10750-013-1590-x

Hua C, Zhu Q, Shi Y, Liu Y (2019) Comparative analysis of CPUE standardization of Chinese Pacific saury (Cololabis saira) fishery based on GLM and GAM. Acta Oceanol Sin 38:100-110. http://doi.org/10.1007/s13131-019-1486-3

Huang X, Xu J, Liu B, Guan X, Li J (2022) Assessment of Aquatic Ecosystem Health with Indices of Biotic Integrity (IBIs) in the Ganjiang River System, China. Water-Sui 14:278. https://doi.org/10.3390/w14030278

Huang Y, Li Y, Chen Q, Huang Y, Tian J, Cai M, Huang Y, Jiao Y, Yang Y, Du X, Liu Z, Zhao Y(2021) Effects of reclamation methods and habitats on macrobenthic communities and ecological health in estuarine coastal wetlands. Mar Pollut Bull 168:112420. https://doi.org/10.1016/j.marpolbul.2021.112420

Jia HB, Cao LY, Chai XP (2022) The changes of macrobenthic community structure and cause analysis in the Yangtze Estuary during summer from 2016 to 2019. Mar Envir Sci 41:180-186. https://doi.org/10.13634/j.cnki.mes.2022.02.015

Levin LA, Gage JD, Smith CR, Mullineaux LS, Levin LA (1998) Relationships between oxygen, organic matter and the diversity of bathyal macrofauna. Deep-Sea Res. Pt II 45:129-163. https://doi.org/10.1016/S0967-0645(97)00085-4

Li BQ, Li XZ, Wang HF, Wang YQ, Wang JB, Zhang BL (2007) Characters of a macrobenthic community off the Changjiang River Estuary. Acta Zool Sin 53:76-82. https://doi.org/10.1016/S1005-8885(07)60162-9

Li SD (2021) Habitat suitability and habitat quality assessment in Tongzhou Bay. PhD Dissertation. Nanjing Normal University.

Liao YB, Shou L, Zeng JN, Gao AG, Jiang ZB (2011) A comparative study of macrobenthic community under different mariculture types in Xiangshan Bay, China. Acta Ecol Sin. 31:646-653

Liao Y, Shou L, Jiang Z, Tang Y, Du P, Zeng J, Chen Q, Yan X, Chen J (2019) Effects of fish cage culture and suspended oyster culture on macrobenthic communities in Xiangshan Bay, a semi-enclosed subtropical bay in eastern China. Mar Pollut Bull 142:475-483. https://doi.org/10.1016/j.marpolbul.2019.03.065

Liu JC, Jia MX, Feng WD, Liu CD, Huang LY (2021) Spatial-Temporal Distribution of Antarctic Krill (Euphausia superba) Resource and Its Association with Environment Factors Revealed with R F and GAM Models. Periodical of Ocean University of China 51:20-29. https://doi. org/10.16441/j.cnki.hdxb.20200243

Liu XS, Zhao R, Hua E, Lu L, Zhang ZN (2014) Macrofaunal community structure in the Laizhou Bay in summer and the comparison with historical data. Mar Sci Bull 33:283-292. http://doi.org/10.11840/j.issn.1001-6392.2014.03.006

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JB (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. Science. 312:1806-1809. https://doi.org/10.1126/science.1128035

Lu X, Xu J, Xu Z, Liu X (2021) Assessment of Benthic Ecological Quality Status Using Multi-Biotic Indices Based on Macrofaunal Assemblages in a Semi-Enclosed Bay. Front Mar Sci 8. http://doi.org/10.3389/fmars.2021.734710.

Luo X, Sun K, Yang J, Song W, Cui W (2016) A comparison of the applicability of the Shannon-Wiener index, AMBI and M-AMBI indices for assessing benthic habitat health in the Huanghe (Yellow River) Estuary and adjacent areas. Acta Oceanol Sin 35:50-58. https://doi.org/10.1007/s13131-016-0842-9

Luo X, Zhang S, Yang J, Pan J, Tian L, Zhang L (2013) Macrobenthic community in the Xiaoqing River Estuary in Laizhou Bay, China. J Ocean U China 12:366-372. https://doi.org/10.1007/s11802-013-1955-9

Lv W, Liu Z, Yang Y, Huang Y, Fan B, Jiang Q, Zhao Y (2016) Loss and self-restoration of macrobenthic diversity in reclamation habitats of estuarine islands in Yangtze Estuary, China. Mar Pollut Bull 103:128-136. https://doi.org/10.1016/j.marpolbul.2015.12.030

Ma A, Liu XS, Li L, Qi M, Wang H, Ma J (2014) A comparative Study on community characteristics of Macrofauna Inside and outside Manila Clam Culture Waters, Jiaozhou Bay. Trans Oceanol Limnol 1:122-128. https://doi.org/10.13984/j.cnki.cn37-1141.2014.01.004

Meng Z, Han Q, Wang X (2021) Distribution pattern of macrobenthic composition, diversity and secondary production in Hangzhou Bay, northern East China Sea. Reg Stud Mar Sci. 47:101956. https://doi.org/10.1016/j.rsma.2021.101956

Miserendino ML, Brand C, Di Prinzio CY (2008) Assessing Urban Impacts on Water Quality, Benthic Communities and Fish in Streams of the Andes Mountains, Patagonia (Argentina). Water Air and Soil Poll 194:91-110. https://doi.org/10.1007/s11270-008-9701-4

Mosbahi N, Pezy J, Dauvin J, Neifar L (2016) Spatial and Temporal Structures of the Macrozoobenthos from the Intertidal Zone of the Kneiss Islands (Central Mediterranean Sea). Open Journal of Marine Science 06:223-237. https://doi.org/10.4236/ojms.2016.62018

Muylaert K, Sabbe K, Vyverman W (2000) Spatial and Temporal Dynamics of Phytoplankton Communities in a Freshwater Tidal Estuary (Schelde, Belgium). Estuar coast and shelf S 50:673-687. https://doi.org/10.1006/ecss.2000.0590

Ni D, Zhang Z, Liu X (2019) Benthic ecological quality assessment of the Bohai Sea, China using marine biotic indices. Mar Pollut Bull 142:457-464. https://doi.org/10.1016/j.marpolbul.2019.03.055

Qiu B, Zhong X, Liu X (2018) Assessment of the benthic ecological status in the adjacent waters of Yangtze River Estuary using marine biotic indices. Mar Pollut Bull 137:104-112. https://doi.org/10.1016/j.marpolbul.2018.10.006

Shadrin N, Kolesnikova E, Revkova T, Latushkin A, Chepyzhenko A, Dyakov N, Anufriieva E (2019) Macrostructure of benthos along a salinity gradient: The case of Sivash Bay (the Sea of Azov), the largest hypersaline lagoon worldwide. J Sea Res 154. https://doi.org/10.1016/j.seares.2019.101811

Shi SJ (2014) The Ecological Study of the Macrobenthos in the Bohai Sea, China. PhD Dissertation. Ocean University of China.

Shou L, Zeng J, Liao Y, Xu T, Gao A, Chen Z, Chen Q, Yang J (2013) Temporal and spatial variability of benthic macrofauna communities in the Yangtze River estuary and adjacent area. Aquat Ecosyst Health 16:31-39. https://doi.org/10.1080/14634988.2013.759497

Sturdivant SK, Brush MJ, Diaz RJ (2013) Modeling the effect of hypoxia on macrobenthos production in the lower Rappahannock River, Chesapeake Bay, USA. Plos One 8:e84140. https://doi.

org/10.1371/journal.pone.0084140

Takamura N, Ito T, Ueno R, Ohtaka A, Wakana I, Nakagawa M, Ueno Y, Nakajima H (2009) Environmental gradients determining the distribution of benthic macroinvertebrates in Lake Takkobu, Kushiro wetland, northern Japan. Ecol Res 24:371-381. https://doi.org/10.1007/s11284-008-0514-0

Veiga P, Redondo W, Sousa-Pinto I, Rubal M (2017) Relationship between structure of macrobenthic as

semblages and environmental variables in shallow sublittoral soft bottoms. Mar Environ Res 129:396-407. https://doi.org/10.1016/j.marenvres.2017.07.002

Verneaux VV, Schmitt A (2004) Relationships of macrobenthos with dissolved oxygen and organic matter at the sediment-water interface in ten French lakes. Archiv für Hydrobiologie 160:247-259. https://doi.org/10.1127/0003-9136/2004/0160-0247

Wang F, Zhu YH (2009) Development Patterns and Suitability Assessment of Tidal Flat Resources in Jiangsu Province. Res Sci 31:619-628. https://doi.org/10.3321/j.issn:1007-7588.2009.04.013

Wang L, Luo X, Fan Y (2018) Distribution and pollution assessment of heavy metals in surface sediments in Xiaoqing River estuary and its adjacent sea of Laizhou Bay. IOP conference series. Earth environ sci 128:12184. https://doi.org/10.1088/1755-1315/128/1/012184

Wang L, Luo X, Yang J, Zhang J, Fan Y, Shen J (2020) Assessing benthic habitat quality using biotic indices in the Laizhou Bay, China. Acta Oceanol Sin 39:49-58. https://doi.org/10.1007/s13131-020-1552-x

Wang Y, Liu J, Liu W, Feng Q, Li B, Lu H, Wang S (2021) Spatial variation in macrobenthic assemblages and their relationship with environmental factors in the upstream and midstream regions of the Heihe River Basin, China. Environ Monit Assess 193.https://doi.org/10.1007/s10661-020-08822-0

Wood SN (2008) Fast stable direct fitting and smoothness selection for generalized additive models. J R Stat Soc B 70:495-518. https://doi.org/10.1111/j.1467-9868.2007.00646.x

Wood SN, Augustin NH (2002) GAMs with integrated model selection using penalized regression splines and applications to environmental modelling. Ecol Model 157:157-177. https://doi. org/10.1016/S0304-3800(02)00193-X

Wu SN, Chen XJ (2020) Relationship between the recruitment of the Pacific-cohort of chub mackerel (Scomber japonicus) and the influence factors on the spawning ground based on GLM and GAM. Journal of Fisheries of China 44:61-70. https://doi.org/10.11964/jfc.20180811426

Xie Z, Zhang J, Cai K, Xu ZA, Wu D, Wang B (2016) Temporal and spatial distribution of macrobenthos communities and their responses to environmental factors in Lake Taihu. Acta Ecolo Sin 36:16-22. https://doi.org/10.1016/j.chnaes.2015.12.005

Xiong SG, Li HY, Wang XM (2013) Relationships between Macrobenthos and Environmental Variables in Tianjin Offshore Water. Adv Mat Res 838-841:2556-2560. https://doi.org/10.4028/www.scientific.net/AMR.838-841.2556

Xu Y, Li XZ (2021) Macrobenthos and evaluation of coastal ecosystem health. Science 73:30-34

Yan L, Li J, Zhang P, Yang BZ, Wang T (2021) Effects of spatiotemporal and environmental factors on the fishing ground of Sthenoteuthis oualaniensis in the South China Sea based on the Generalized Additive Model. Mar Pollut Bull. 40:217-223. https://doi.org/10.11840/j.issn.1001-6392.2021.02.011

Yang D, Zheng FJ, Liu Q, Liu HM, Guo PP, Tian N (2010) An Evaluation of the Suitability of Intertidal Zone Resources Based on a BP Neural Network: A Case Study of Dongying City, Shandong Province. Res Sci 32:2336-2342

Yang Z, Ye JQ, Yang Q, Guo H (2020) Zooplankton diversity and its relationships with environmental factors in the Liaohe estuary. Mar environ sci 39:25-30. https://doi.org/10.13634/j.cnki.mes.2020.01.004

Yang Y, Yi Y, Wang W, Zhou Y, Yang Z (2020) Generalized additive models for biomass simulation of submerged macrophytes in a shallow lake. Sci total environ 711. https://doi.org/10.1016/j.scitotenv.2019.135108

Yi Y, Cheng X, Wieprecht S, Tang C (2014) Comparison of habitat suitability models using different habitat suitability evaluation methods. Ecol Eng 71:335-345. https://doi.org/10.1016/j.ecoleng.2014.07.034

Yi Y, Sun J, Yang Y, Zhou Y, Tang C, Wang X, Yang Z (2018a) Habitat suitability evaluation of a benthic macroinvertebrate community in a shallow lake. Ecol Indic 90:451-459. https://doi.org/10.1016/j.ecolind.2018.03.039

Yi Y, Sun J, Zhang S, Yang Z (2016) Assessment of Chinese sturgeon habitat suitability in the Yangtze River (China); comparison of generalized additive model, data-driven fuzzy logic model, and preference curve model. J hydrol 536:447-456. https:// doi.org/10.1016/j.jhydrol.2016.03.005

Yigezu G, Mandefro B, Mengesha Y, Yewhalaw D, Beyene A, Ahmednur M, Abdie Y, Kloos H, Mereta ST (2018) Habitat suitability modelling for predicting potential habitats of freshwater snail intermediate hosts in Omo-Gibe river basin, Southwest Ethiopia. Ecol Inform 45:70-80. https://doi.org/10.1016/j.ecoinf.2018.04.002

Yuan W, Zhang ZN, Yu ZS, Deng K (2006) A Study of Macrofauna in The Northwest of Jiaozhou Bay. Periodical of Ocean University of China (S1):91-97. https://doi.org/10.16441/j.cnki. hdxb.2006.s1.018

Zhang Y, Cai YJ, Zhang Y, Gao JF, Li KY (2021) The response of benthic macroinvertebrate communities to environmental pressures in streams and rivers: A case study of Taihu and Chaohu Basins. Journal of

Lake Sciences 33:204-217. https://doi.org/10. 18307 /2021. 0111

Zhang J, Xu F, Liu R (2012) Community structure changes of macrobenthos in the South Yellow Sea. Chin J Oceanol Limn 30:248-255. https://doi.org/10.1007/s00343-012-1076-0

Zhang L, Xiong L, Li J, Huang X (2021) Long-term changes of nutrients and biocenoses indicating the anthropogenic influences on ecosystem in Jiaozhou Bay and Daya Bay, China. Mar Pollut Bull 168. https://doi.org/10.1016/j.marpolbul.2021.112406

Zhao C, Shao N, Yang S, Ren H, Ge Y, Zhang Z, Zhao Y, Yin X (2019) Integrated assessment of ecosystem health using multiple indicator species. Ecol Eng 130:157-168. https://doi.org/10.1016/j.ecoleng.2019.02.016

Zhou H, Hua E, Zhang ZN (2010) Community Structure of Macrobenthos in Laizhou Bay and Adjacent Waters. Periodical of Ocean University of China 40:80-87. https://doi. org/10.16441/j.cnki.hdxb.2010.08.012

Zhou Z, Li X, Chen L, Li B, Liu T, Ai B, Yang L, Liu B, Chen Q (2018) Macrobenthic assemblage characteristics under stressed waters and ecological health assessment using AMBI and M-AMBI: a case study at the Xin'an River Estuary, Yantai, China. Acta Oceanol Sin 37:77-86 https://doi/10.1007/s13131-018-1180-x

Figures

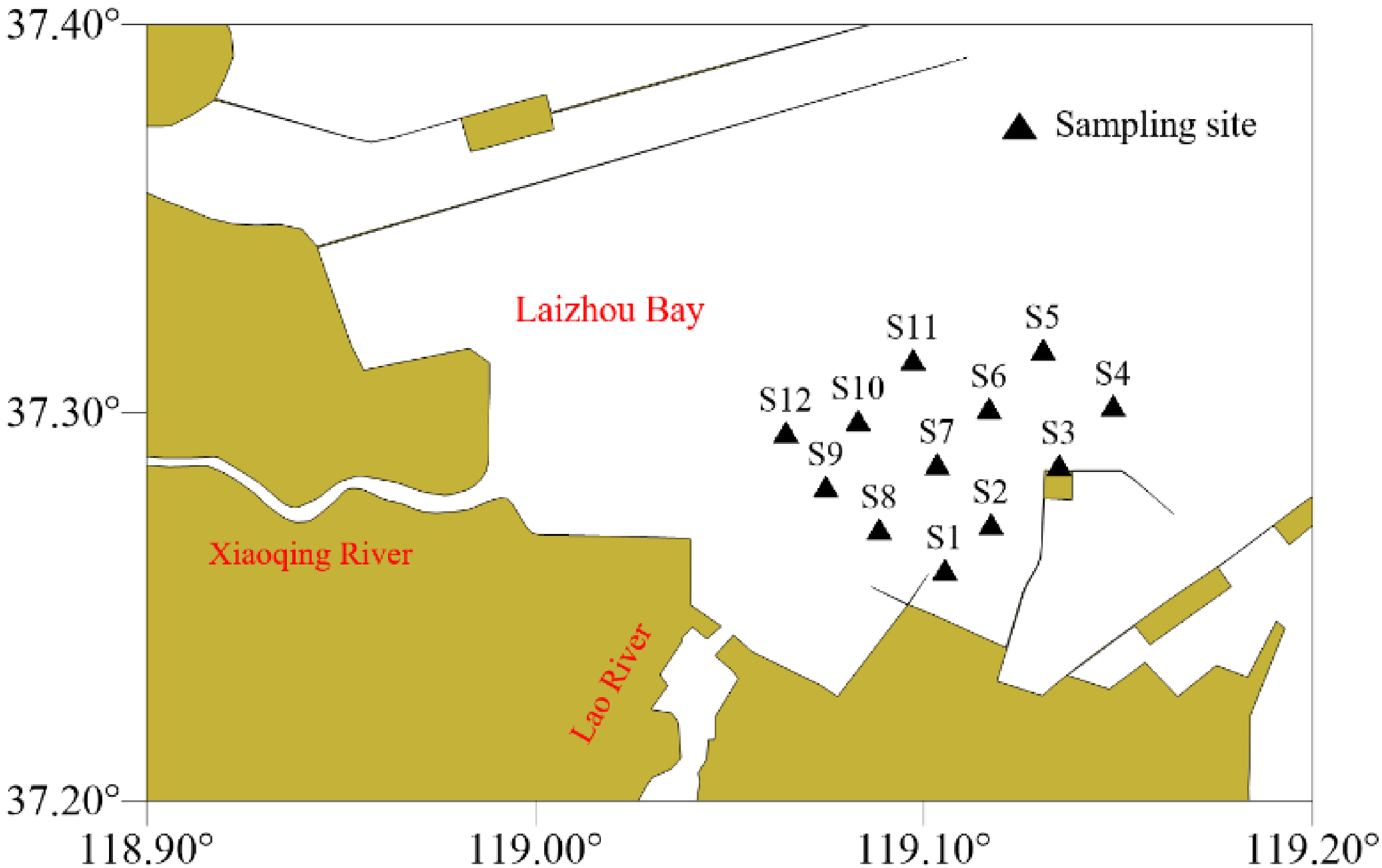

Figure 1

Locations of sampling sites of the present study in Xiaoqing Estuary, Laizhou Bay

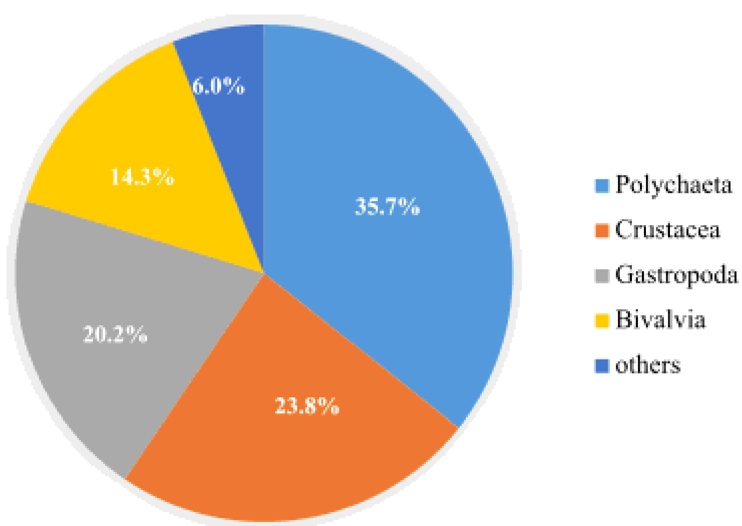

Figure 2

Community structure of macrobenthos

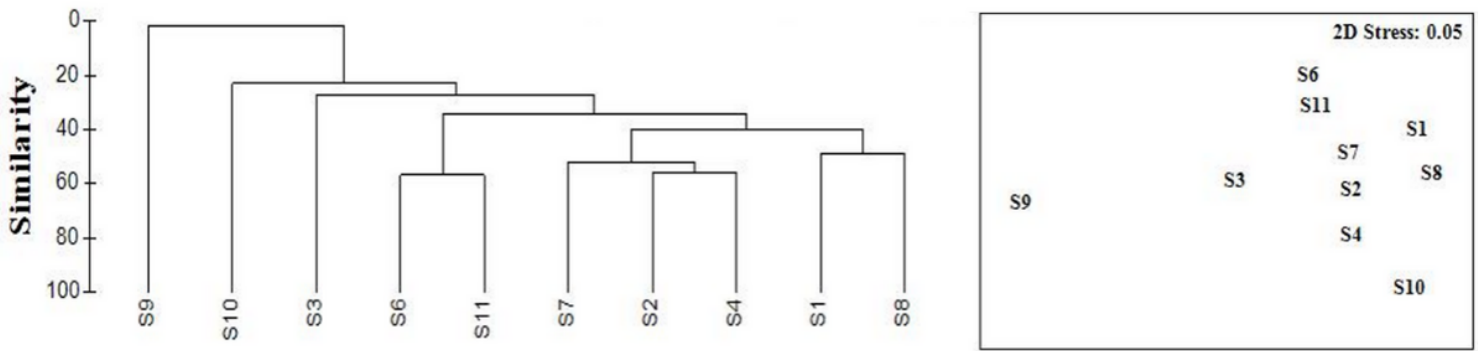

Figure 3

Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in March

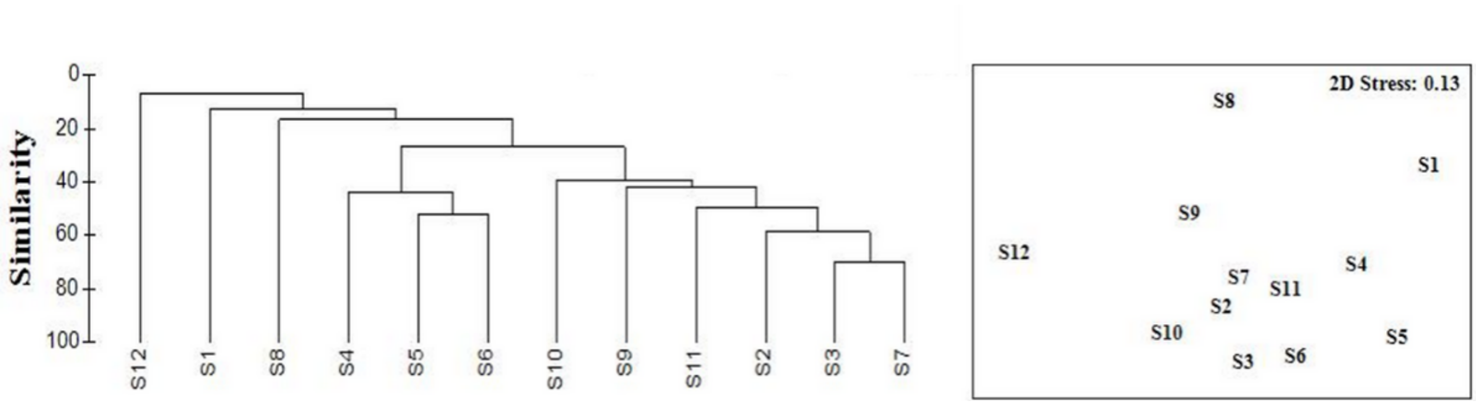

Figure 4

Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in May

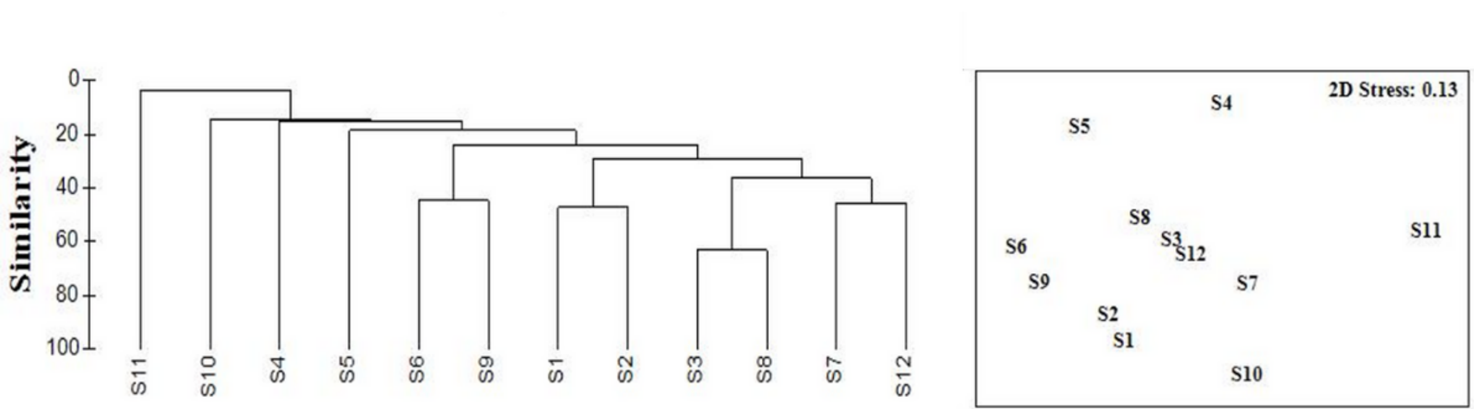

Figure 5

Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in August

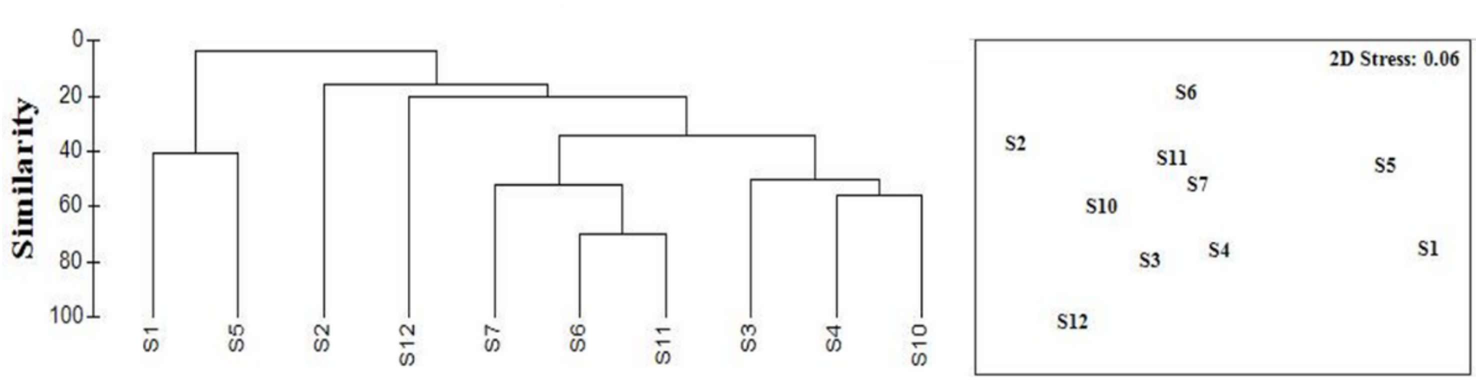

Figure 6

Results of cluster analysis and multidimensional scaling (MDS) for Macrobenthos in October

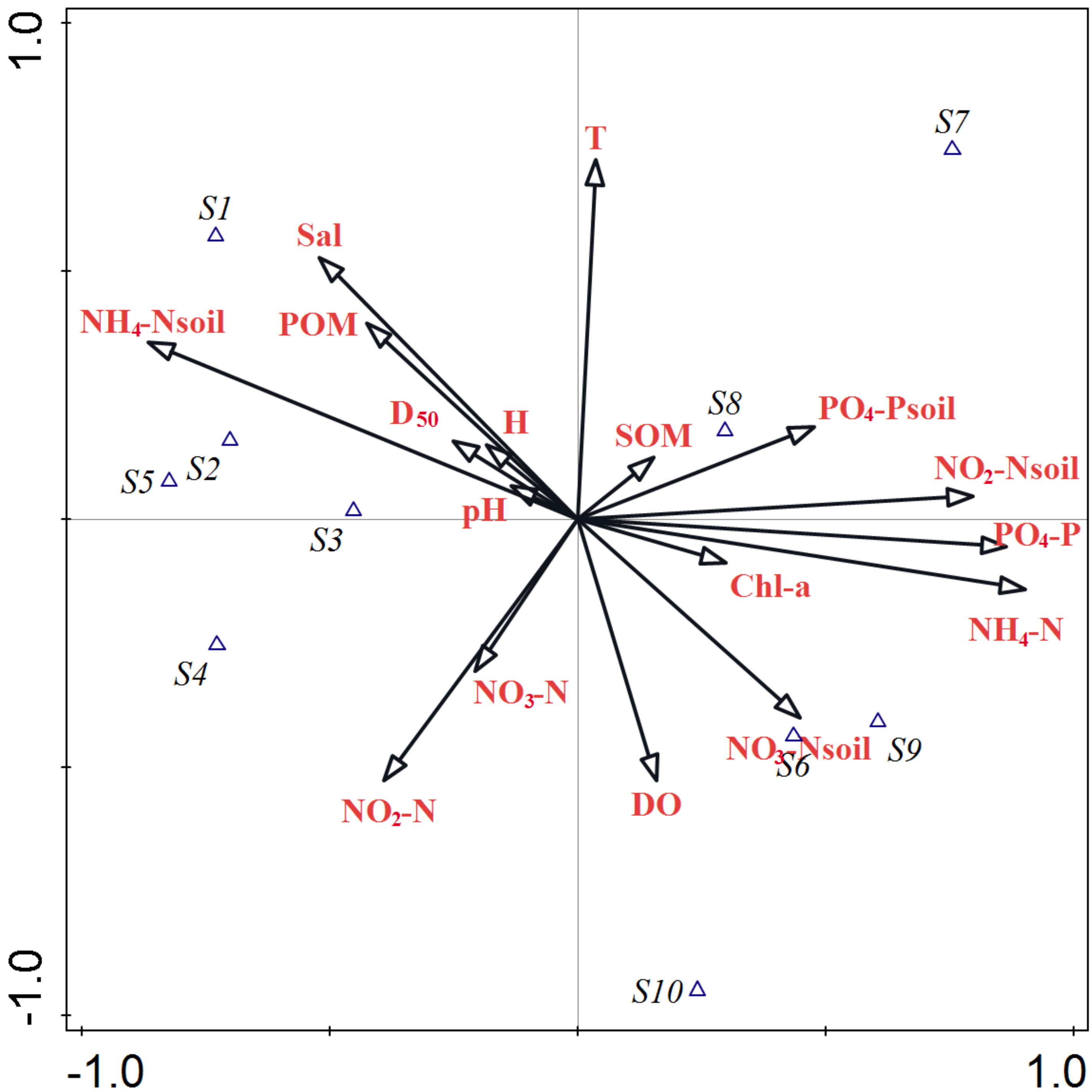

Figure 7

Canonical correlation analysis (CCA) ordination chart of macrobenthos community structure and environmental factors

(Notes: S1: *Notomastus latericeus Sars*; S2: *Mactra chinensis*; S3: *Nephtys polybranchia*; S4: *Heterocuma sarst*; S5: *Cultellus attenuatus*; S6: *Mactra venerformis Reeve*; S7: *Musculus senhousei*; S8: *Mediomastus californiensis*; S9: *Decorifera matusimana*; S10: *Ruditapes philippinarum*)

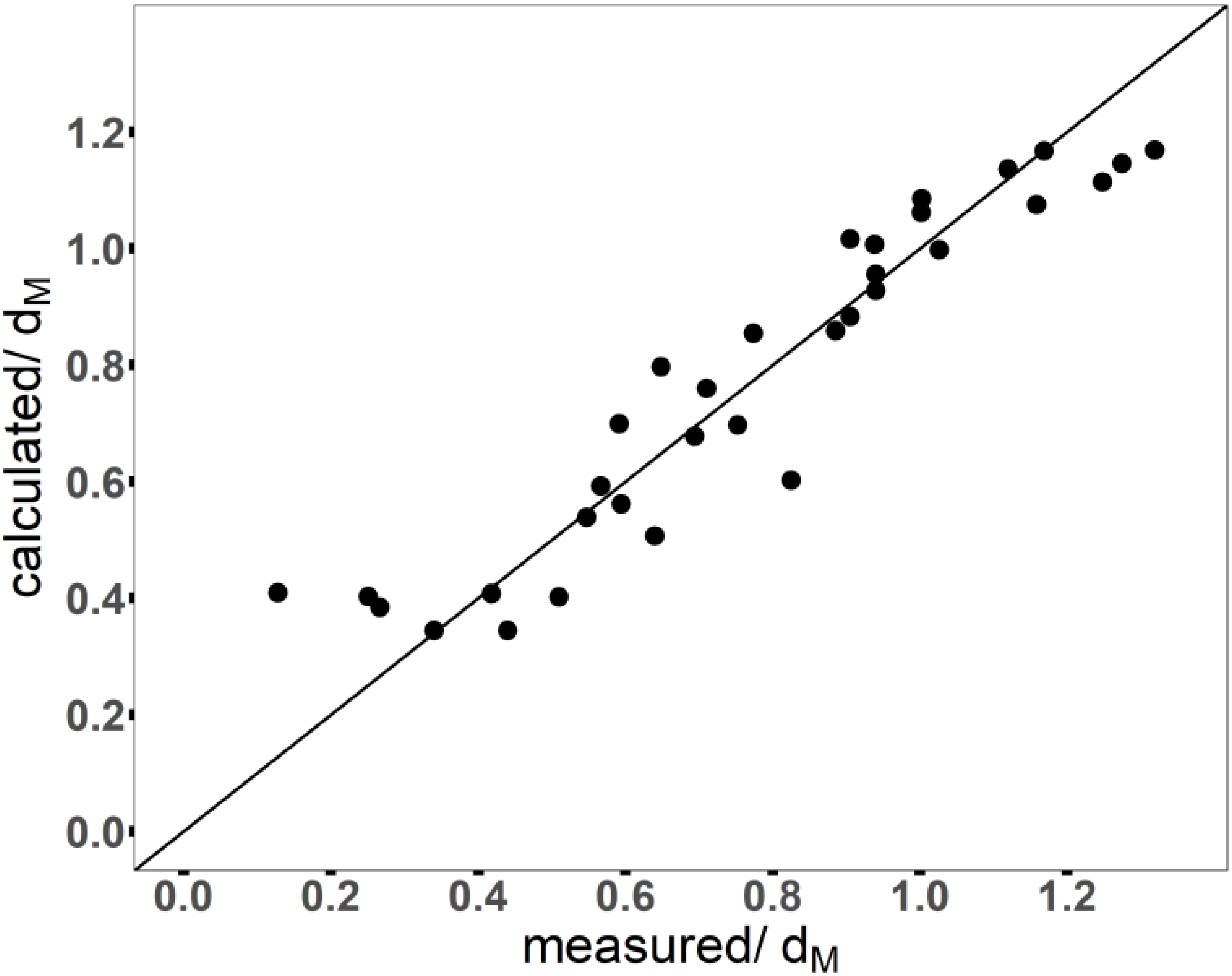

Figure 8

Calculated Margalef diversity index (d_M) versus d_M based on Model 9

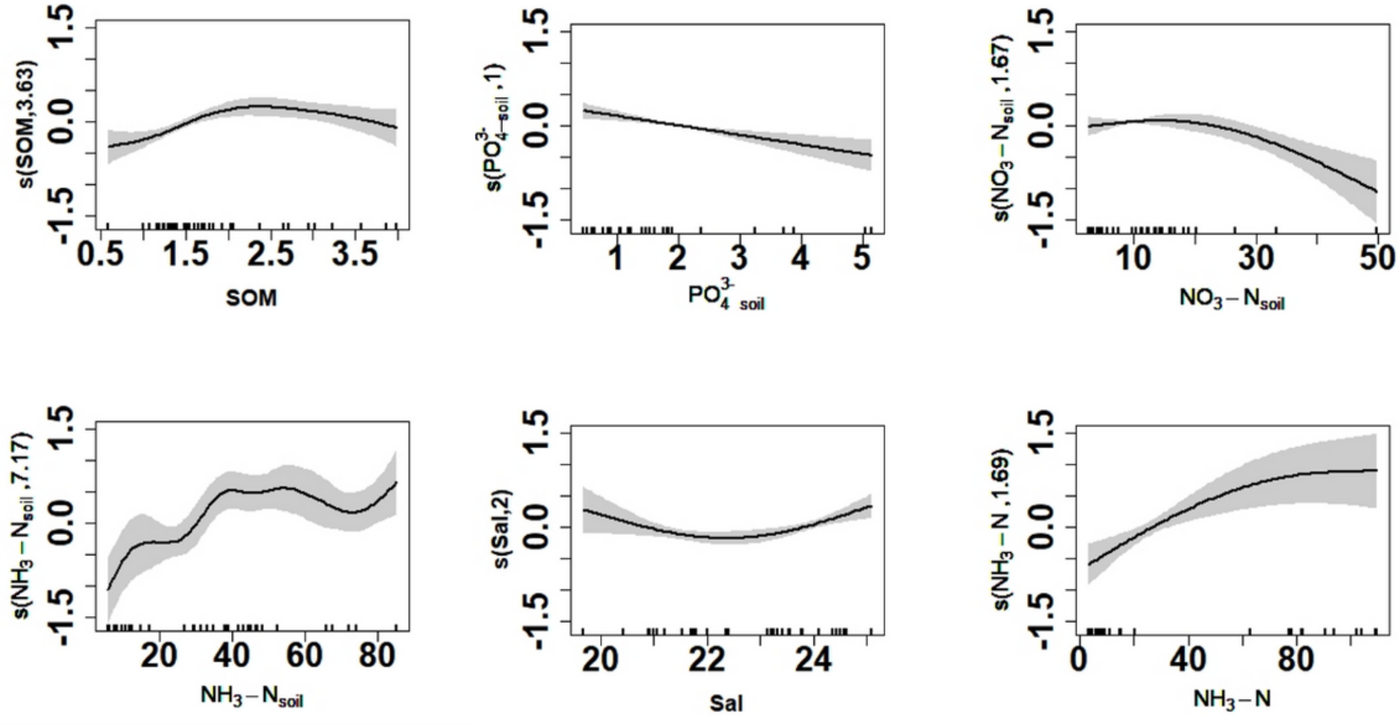

Figure 9

Response curves of the Margalef diversity index (d_M) to ecological factors in the generalized additive model (GAM) analysis

Notes: The vertical axes indicate the relative influence of each explanatory variable on the prediction. Shaded areas indicate 95% confidence limits.

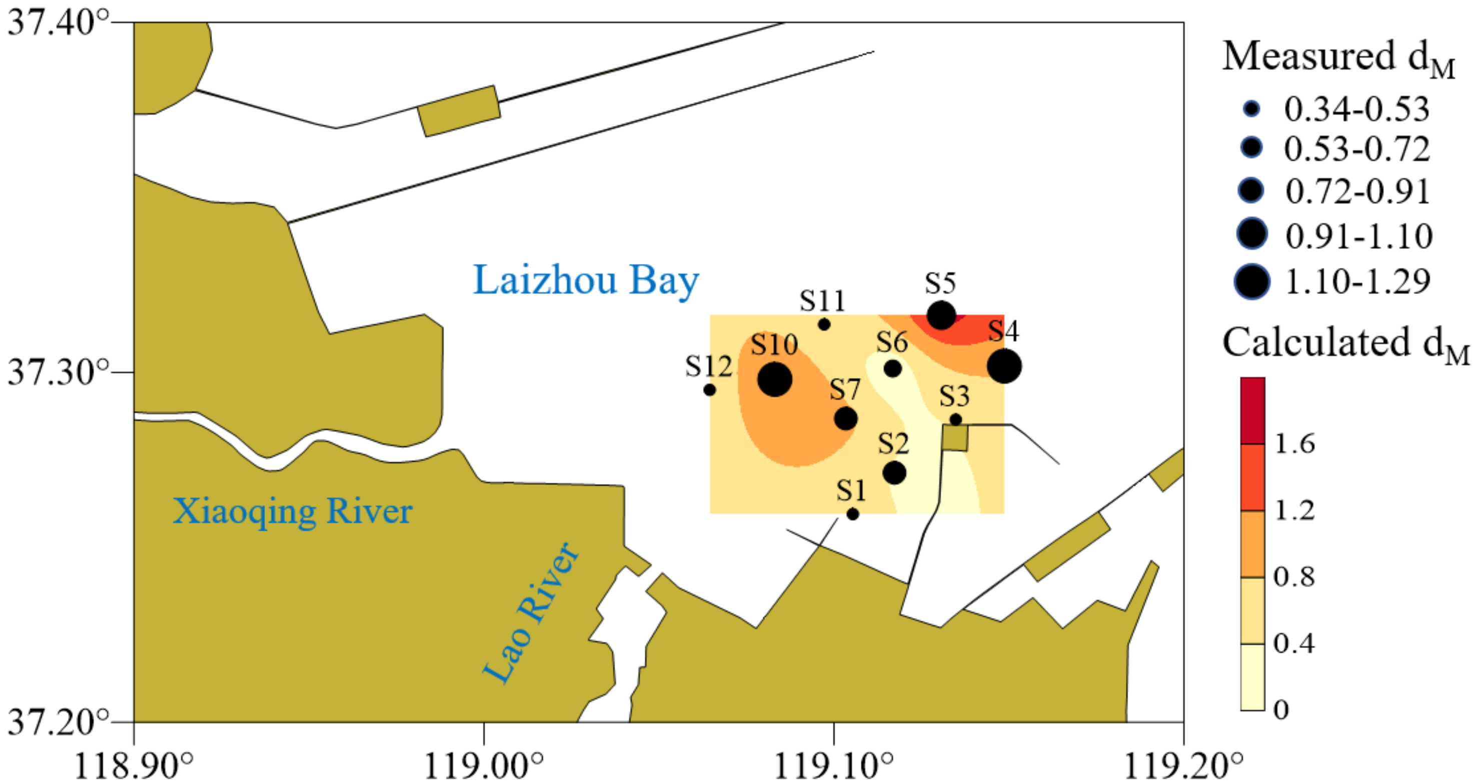

Figure 10

The spatial distributions of the measured and predicted Margalef diversity index (d_M)