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Application of the Gini Index on the Evaluation of the Environmental Heterogeneity and Habitat Suitability Index for Larval Gobies

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Abstract: Spatial environmental heterogeneity in the Yangtze River Estuary (YRE) is always mentioned but rarely quantified and included in the evaluation process. This study introduced the habitat suitability index evaluation model based on the Gini index (HSI_{gini}) to evaluate the optimal ranges of suitable environmental factors for three typical estuarine gobies, i.e., *Rhinogobius giurinus*, *Acentrogobius pflaumii*, *Odontamblyopus rubicundus*, and their habitat quality. The evaluation was carried out based on field surveys conducted in the spring and summer of 2018–2020. The Lorentz curve and Gini index were used to evaluate the spatial environmental heterogeneities in the YRE. The spatial heterogeneity of environmental factors in the Yangtze Estuary ranged from 0.62 to 0.05, with the highest Gini index for salinity and the lowest for temperature. The combination of environmental factors had significant spatial effects on habitat, with temperature showing mainly seasonal effects. The study indicated that the YRE is a good habitat for gobies and that there is spatial and seasonal differentiation in the habitats of different species, greatly reducing interspecific competition. Environmental heterogeneity is important for biological processes and should be incorporated into the modeling of bio–environmental relationships in future research to provide a basis for environmental and biological conservation and management.

Keywords: estuarine environmental variation; ichthyoplankton; habitat suitability index; the Lorentz curve; bio–environmental relationship

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1. Introduction

Over 90% of economically important species, including fish, have been depleted due to overexploitation and habitat loss [1]. The habitat of fish has a significant effect on marine biodiversity and fishing production. With the execution of ecological restoration and fishery management programs, evaluating habitat quality has become a vital task [2]. The habitat suitability models (HSMs) based on habitat selection theory and niche theory, which investigate the interaction between organisms and environmental variables by measuring biological abundance or the possibility of occurrence, are useful management tools for marine life and habitat [3,4].

In general, HSM consists of habitat suitability models [5], species distribution models (SDMs) [6], resource selection functions [7], niche models [8], etc. Although these studies used a variety of algorithms and models, including regression analysis, envelope analysis, Bayesian models, neural networks, and other classical and machine learning techniques, they all addressed comparable issues [3]. The habitat suitability index (HSI) model was first proposed to quantify the effect of land management plans on wildlife habitats [9], and it is the most utilized tool for assessing habitat quality. Currently, the HSM is widely used in fish spawning and nursery habitat studies in rivers, estuaries, and oceanic ecosystems [10,11], and is regarded as a powerful tool for identifying priority protection areas [12], predicting habitat changes under climate change [13,14], forecasting potential fishing grounds, and managing biological resources [15].

Larval fish are regarded as the foundation for understanding fish recruitment, species diversity, marine food webs, and sustainable fisheries [16,17]. They are more sensitive to external environmental changes than adult fish, and more than 99% of fish die during this period [18]. Due to their poor swimming ability, physical and biological variables influence the selection of habitats for larval fish. Physical factors such as current patterns, water velocity, and water direction determine the dispersal of larval fish [19]. The survival rate of larval fish is mostly affected by the environmental and biological parameters of the habitat, such as sea temperature [20]. Optimal habitats are regions with high survival rates under the impact of multiple environmental conditions [21].

Estuaries are regions of land–sea interaction where the complex and variable coupling of physical, chemical, biological, and sedimentary processes results in a greater degree of heterogeneity in the marine environment [22,23]. The Yangtze River Estuary (YRE) is the largest estuary in the Southwest Pacific and serves as the spawning ground, nursing ground, feeding ground, and migratory corridor for a wide variety of marine organisms. It has an extremely high level of biodiversity, with over 300 species of fish recorded [24]. Numerous studies show that biological processes in the YRE are linked to environmental heterogeneity [25,26], but no quantitative analysis has been conducted on the topic. Geographically, the Yangtze River Estuary is split into three branches and four outlets. It is influenced by the Yangtze River Diluted Water, the Yellow Sea Cold Water Mass, and the Kuroshio Current [27]. The salinity, dissolved oxygen, and other environmental factors are highly varied in the southern and northern branches [26,28]. This study uses the YRE as a case study to conduct research that is typical and representative and therefore can serve as a foundation for the conservation of ecology and biodiversity.

Gobies are abundant and diverse in estuaries, and the sensitivity of their larvae and juveniles to environmental changes makes them the chosen indicator species for environmental changes in estuaries [29]. However, the direct economic value of goby is generally low, and researchers have paid less attention to gobies in the YRE, resulting in a lack of knowledge about them. In this study, three typical dominant gobies in the estuary, i.e., *Rhinogobius giurinus*, *Acentrogobius pflaumii*, and *Odontamblyopus rubicundus*, were selected as case studies to examine the optimal requirements of the environment and the effects of environmental heterogeneity on the distributions of habitat. On the basis of the HSI, we introduced the habitat suitability evaluation model based on the Gini index (HSI_{gini}) [30]. The Gini index indicates the heterogeneity of environmental factors, which refers to the environment's complexity, diversity, structure, or temporal and spatial variability [31]. It is a crucial regulator of biodiversity, genetic consequences, and species coexistence [31–34]. This contribution provides an analysis of coupled-causal relationships between the environment and organisms, which is predictive for studying ecological issues such as survival mechanisms, population replenishment, and changes in the marine food webs of larval fish in their habitats [21].

2. Materials and Methods

2.1. Data Collection

In 2018, 2019, and 2020, seven cruises were conducted in the YRE to gather the biological and environmental data analyzed here (Figure 1a). The surveys were carried out in the spring (May) and summer (August; June and July in 2018) during the peak of fish breeding. The entire survey area was divided into four subareas (A, B, C, and D, shown in Figure 1b) based on geographical factors such as water depth and salinity. The subareas were further subdivided into 159 grids of equal size ($3' \times 3'$; $1' = 1.85$ km) over the entire study area. Using the random stratified sample method, around 55 stations were set up for each survey [35]. To collect larval fish, a plankton net with an opening width of 80 cm and a mesh size of 505 μm was used. Ten minutes were spent horizontally dragging the net at a speed of 2 to 3 knots. The volume of water was recorded using a calibrated flow meter installed at the entrance to the net.

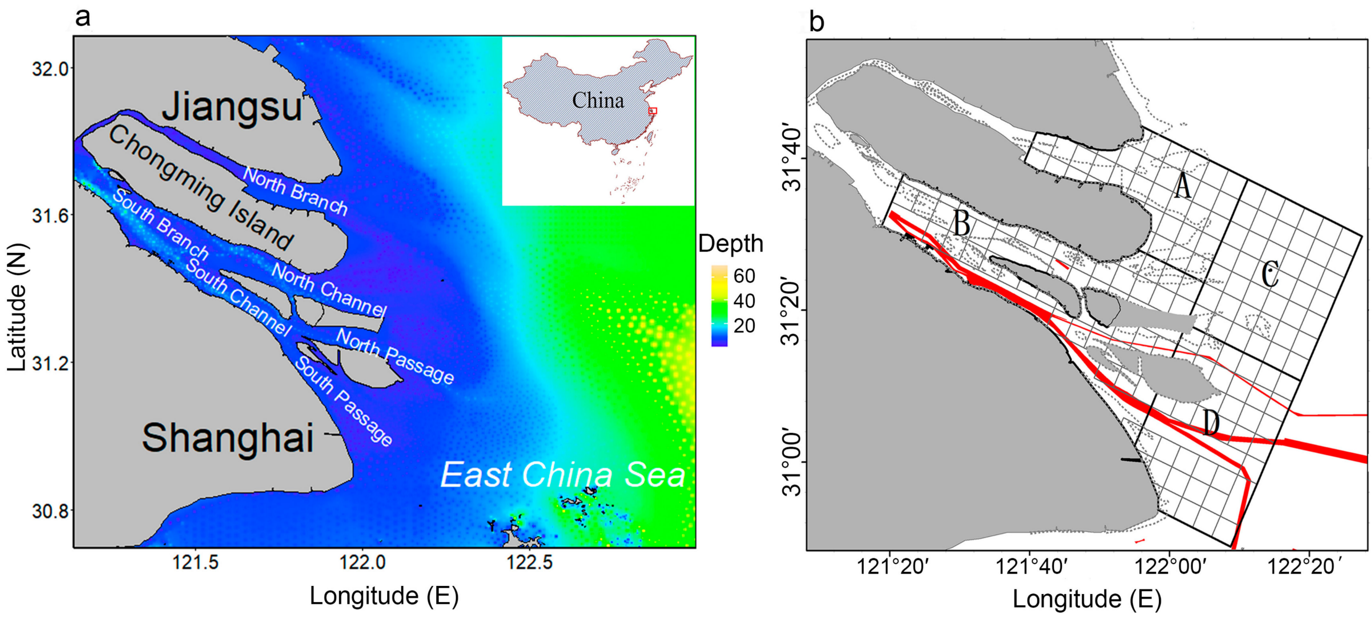

Figure 1. Study area and sampling stations (**a**) Area map and water depth; (**b**) Subareas of the survey, the red area is a deep-water channel).

The samples were immediately fixed in a formalin-buffered saltwater solution containing 5% formalin after collection. The larval fish species were identified in the laboratory using the morphological approach and classified as pre-larva, post-larva, and juvenile. The environmental parameters were recorded using the SBE-19plus V2 SeaCAT conductivity–temperature–depth system (CTD). The mean values for temperature (SST, °C), salinity (SSS), dissolved oxygen concentration (sdo, ml/L), and chlorophyll-a concentration (schl, mg/m^3) at three meters below the sea's surface were determined. Figure 1a depicts the sea depth extracted from the electronic chart.

The geography of the YRE is trumpet-shaped, and it is a delta estuary with several branches. Chongming Island divides the interior of the estuary into two branches, the southern branch and the northern branch. The southern branch is divided into the southern and northern channels by Changxing and Hengsha islands (Figure 1). The southern branch is the main flood discharge channel, and more than 80% of the total net flow of the southern and northern branches comes from freshwater runoff [36]. August is a dry season on the Yangtze River, and the effects of runoff are smaller than the tide-induced rise in seawater. The northern branch becomes the main upstream channel for seawater, even reversing flow into the southern branch [37]. The salinity of the northern branch is approximately 10 to 25 times more than that of the southern branch all year-round [28].

2.2. Data Analysis

Three dominant gobies were identified using the index of relative importance:

$$\mathrm{IRI} = N\% \times F\% \tag{1}$$

where N is the density of fish (individual(ind)/m^3), which is normalized by dividing the number of individuals counted in the laboratory by the volume of water sampled during the survey; $N\%$ is the ratio of a species' density to the total density of all species, F is the number of stations where it occurs, and $F\%$ is the ratio of stations where it occurs to all surveyed stations.

The suitability index (SI) was determined by the envelope method. SIs range from 0 to 1 and were used to characterize the habitat suitability [38]. When SI = 1, the environmental conditions are deemed optimal for biological survival. When SI = 0, the habitat environment is completely unsuitable for biological survival. The optimum range of environmental conditions for each goby was calculated using the SI. SI was calculated using the following formula:

$$\mathrm{SI}_{i,k} = \frac{DI_{i,k} - DI_{i,min}}{DI_{i,max} - DI_{i,min}} \tag{2}$$

where i is the i-th environmental variable, k is the k-th level of the environmental variable, DI is the density index (ind/m^3) of species, DI_{max} and DI_{min} represent the maximum and minimum density. When SI > 0.8, the environment is optimal for biological survival, and the interval corresponding to that environment is the optimal interval.

The generalized additive model (GAM) was used to examine the relationship between the SI of the environment and each species [39] as follows:

$$\mathrm{g}(\mu) = \alpha + \sum_{i=1}^{n} f_i(x_i) + \varepsilon \tag{3}$$

The Spearman correlation test was used to determine the importance of environmental factors. Using the Gini index, the spatial heterogeneity of environmental factors was measured. The cumulative percentage of environmental factors and stations was calculated to draw the Lorentz curve. The more heterogeneous the spatial distribution of environmental factors, the greater the curvature of the Lorentz curve. The Gini index is the ratio of the area enclosed by the real Lorentz curve and the 45° diagonal line of equality to the area of the lower right triangle.

The modeling steps of the Gini index-based habitat suitability index evaluation model are as follows: first, the $\mathrm{HSI_{gini}}$ model explores the spatial heterogeneity of each environmental factor using the Lorentz curve and Gini index; second, it draws the environmental factor suitability index curve (SIC) based on biological and environmental information and defines the optimum range of environmental factors for a habitat; and finally, construct the model using the fundamental principle that the distance between the measured and the optimal environmental factor represents habitat quality.

The model assumes: (1) The spatial heterogeneity level of the environment should be properly accounted for when determining the weight of environmental factors. The more environmental instability, the greater the effect on biological distribution; (2) the optimal environmental range is derived from the biological density, and the closer the habitat environment is to the optimal range, the greater the habitat quality.

The Gini index ranges from [0, 1], 0 represents absolute equality and 1 represents absolute inequality. On the basis of the distance between the actual environment and the optimal interval, the $\mathrm{HSI_{gini}}$ model was developed:

$$\mathrm{HSI_{gini}} = \frac{1}{W} \times \sum\nolimits_i^n (1 - |C_i - P_i|/M_i) \times G_i \times W_i \tag{4}$$

$$\mathrm{W} = \sum\nolimits_i^n G_i \times W_i (i = 1,\ 2,\ 3,\ \ldots\ \ldots, n) \tag{5}$$

$\mathrm{HSI_{gini}}$ is the habitat suitability index of each goby based on the Gini index, P_i is the observed value of environmental factor i, C_i is the most comfortable state endpoint value closest to P_i, and M_i is the most comfortable state endpoint value farthest from P_i. The weight of environmental factor i is the product of G_i (Gini index) and W_i. When the environmental factor i falls between P_i and M_i, the location is considered to be the optimal habitat. At this point, $\mathrm{HSI_{gini\_i}} = 1 \times G_i \times W_i$ (i = 1, 2, 3, ...), and $\mathrm{HSI_{gini}}$ = 1. The farther the $\mathrm{HSI_{gini}}$ departs from 1, the less suitable it is for the habitat.

The model was verified by cross-validation, 80% of the samples were used as the training set and 20% as the test set. This process was repeated 100 times for each model. The

Akaike Information Criterion (AIC) was used to select the model with the best performance. The AIC is calculated as the following formula:

$$\mathrm{AIC} = 2\mathrm{K} - 2\ln L \tag{6}$$

The determination coefficient R^2 and the root mean squared error (RMSE) were used to examine the fit of the observed and predicted values and the accuracy of the model prediction, i.e.,

$$\mathrm{R}^2 = 1 - \frac{RSS}{TSS} \tag{7}$$

and

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{8}$$

where *RSS* is the residual sum of squares, and *TSS* is the total squared sum of deviations, k is the number of parameters, L is the likelihood function, N is the sample size, y_i is the observed value, and $\hat{y}_i$ is the predicted value.

All calculations and visualizations were performed using the R packages 'mgcv', "ineq", "ggplot2", "plyr", "classInt", and "Hmisc".

3. Results

3.1. Environmental Heterogeneity

The spatial heterogeneity of each environmental factor in the YRE was quite different (Figures 2 and 3; Figure S1 and Table S1 in Supplementary Materials). In spring and summer, the SST Lorentz curve was closest to the line of equality, with a Gini index of 0.05–0.06, suggesting that the spatial variation in SST was uniform. The SSS Lorentz curve had the greatest degree of curvature, with a Gini index between 0.59 to 0.66, indicating that the spatial variation in salinity was very uneven. The spatial heterogeneity of depth, sdo, and schl was greater than SST but less than SSS (Table 1).

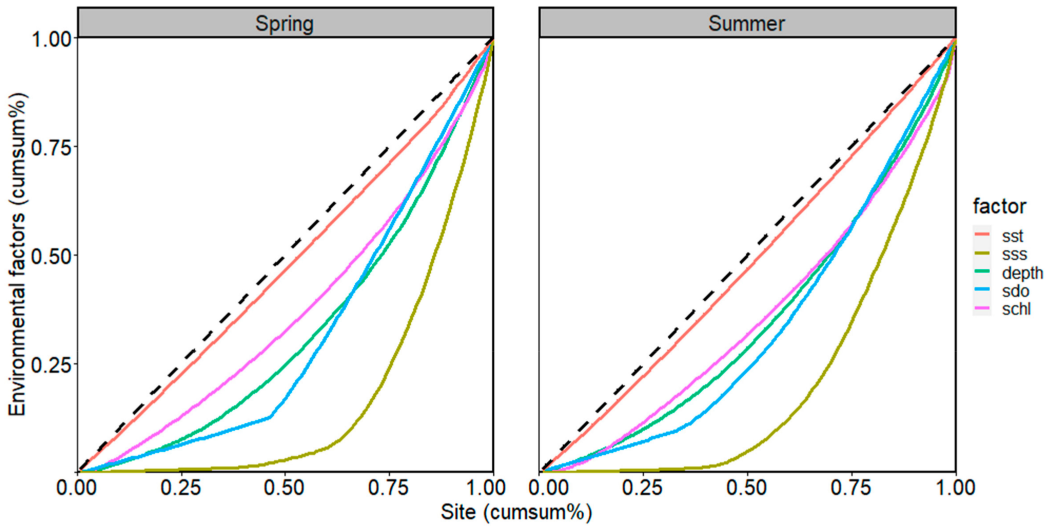

Figure 2. The Lorentz curve of environmental factors in the Yangtze Estuary in the spring and summer (2018–2020; the black dashed line represents the line of equality; the colorful lines are the Lorentz curves, the greater the curvature of the curve, the more heterogeneous the environmental factors are distributed spatially).

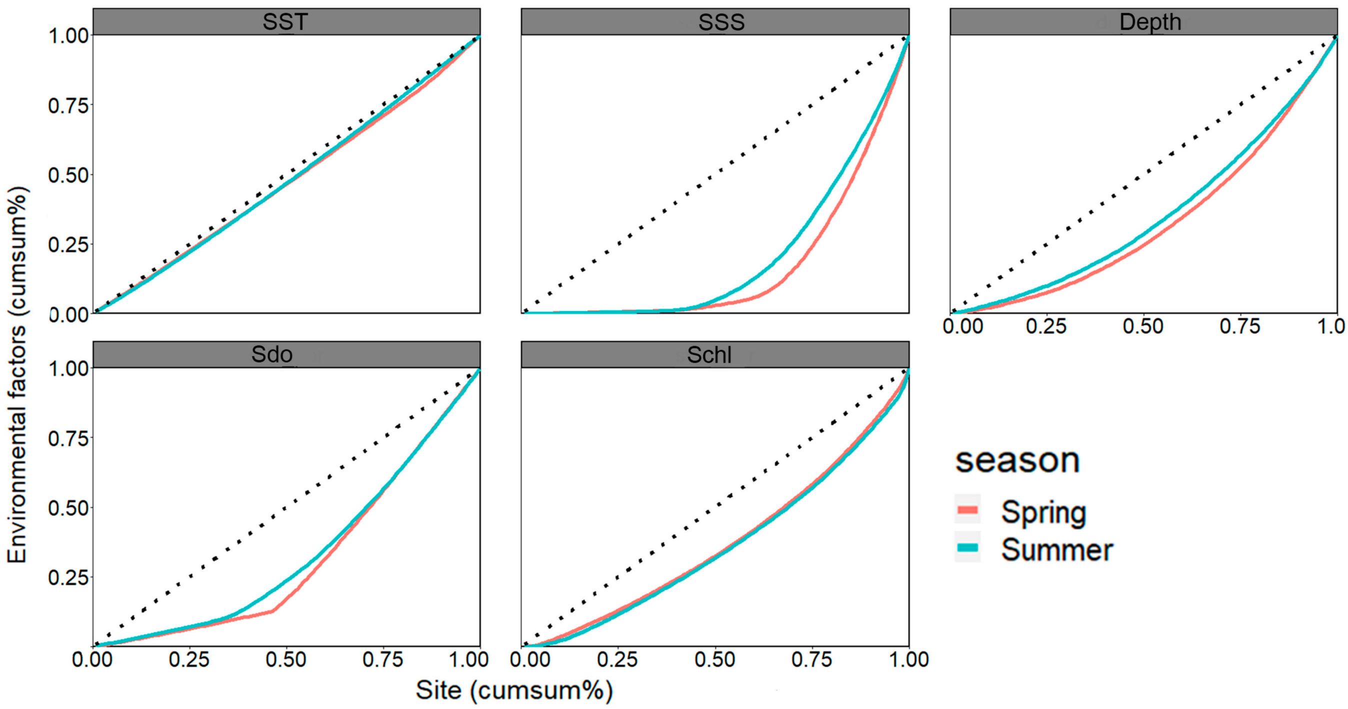

Figure 3. Lorenz curves of environmental factors in the Yangtze Estuary (2018–2020; the black dashed line represents the line of equality; the colorful lines are the Lorentz curves, the greater the curvature of the curve, the more heterogeneous the environmental factors are distributed spatially).

Table 1. Spatial heterogeneity of environmental factors in the Yangtze Estuary in spring and summer (2018–2020).

		SST	SSS	Depth	Sdo	Schl
Gini Coefficient Range	Spring	0.06	0.66	0.35	0.36	0.26
	Summer	0.05	0.59	0.29	0.33	0.28
0~0.2	very low heterogeneity	√				
0.2~0.3	low heterogeneity			*		√
0.3~0.4	medium heterogeneity			**	√	
0.4~0.5	high heterogeneity					
0.5 < Gini < 1	very high heterogeneity		√			

* Representing the level of heterogeneity in summer, ** representing the level of heterogeneity in spring, and √ representing it has the same level of heterogeneity in spring and summer.

3.2. The SIC and the Optimal Environmental Conditions

When SI > 0.8, the SIC showed a sharp peak, and the density of gobies in this range reached the peak. *R. giurinus* had two temperature peaks, around 18 and 22 °C, respectively (Figure 4A). In addition, *A. pflaumii* and *O. rubicundus* showed two and three salinity peaks, respectively (Figure 4E,F). The water with a salinity of around 0 and 20 was optimal for the former, whereas 0, 12, and 20, were optimal for the latter. Two points on the SIC for schl of *O. rubicundus* had values around 0.3 and 1 (Figure 4O). The optimal range of environmental factors is listed in Table 2.

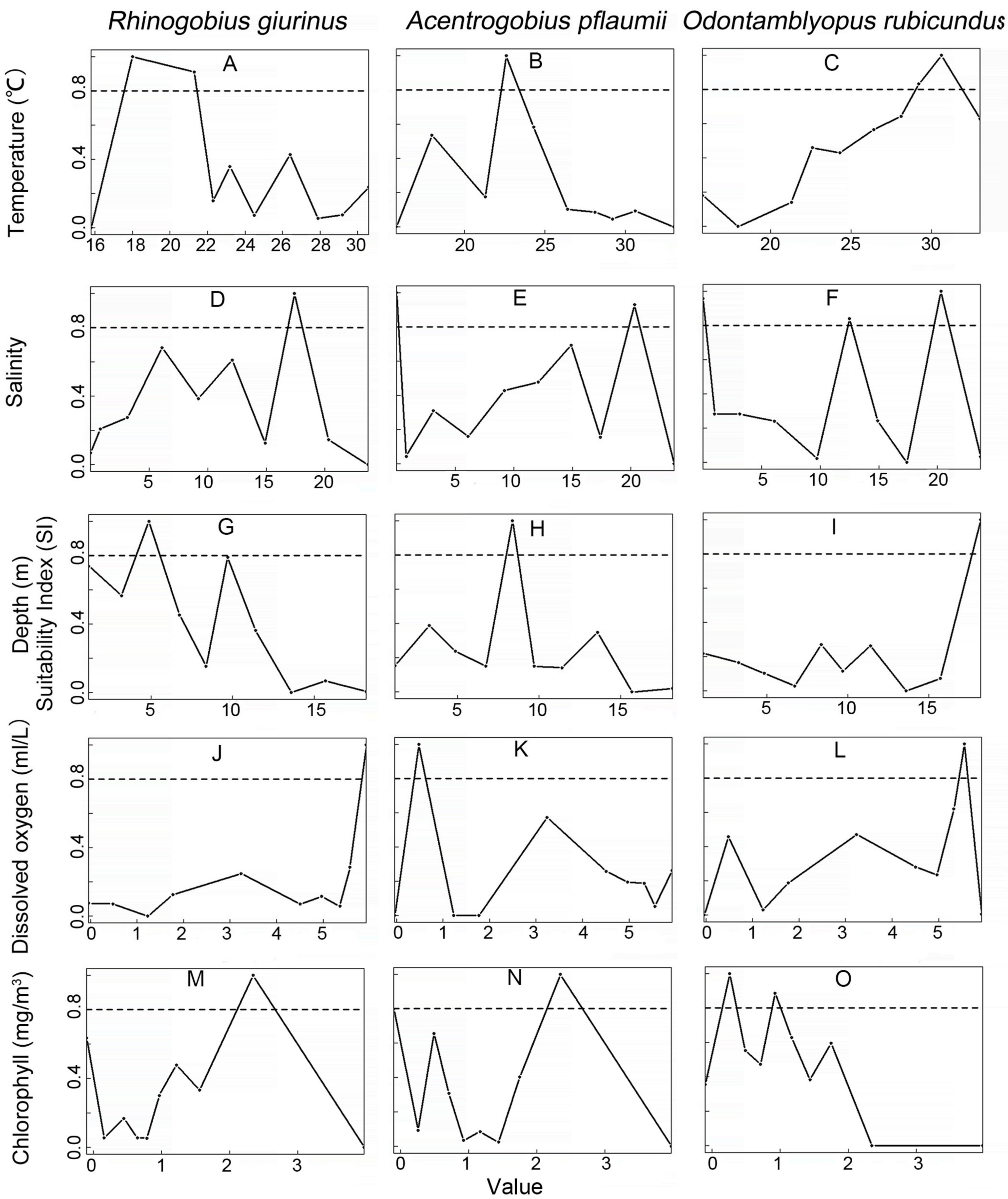

Figure 4. Suitability index curve (SIC) of three gobies with respect to environmental factors in the Yangtze Estuary (the inflection point of the line is the outer envelope point of the suitability index (SI); (**A**) SIC of temperature for *R. giurinus*; (**B**) SIC of temperature for *A. pflaumii*; (**C**) SIC of temperature for *O. rubicundus*; (**D**) SIC of salinity for *R. giurinus*; (**E**) SIC of salinity for *A. pflaumii*; (**F**) SIC of salinity for *O. rubicundus*; (**G**) SIC of depth for *R. giurinus*; (**H**) SIC of depth for *A. pflaumii*; (**I**) SIC of depth for *O. rubicundus*; (**J**) SIC of dissolved oxygen for *R. giurinus*; (**K**) SIC of dissolved oxygen for *A. pflaumii*; (**L**) SIC of dissolved oxygen for *O. rubicundus*; (**M**) SIC of chlorophyll for *R. giurinus*; (**N**) SIC of chlorophyll for *A. pflaumii*; (**O**) SIC of chlorophyll for *O. rubicundus*).

The GAM regression analysis showed that the SI of a single environmental factor had no significant correlation with the observed density of gobies, while various combinations of environmental factors significantly increased the model's deviance explanation and adjusted R^2 (Table 3, Figures S4–S7 in Supplementary Materials).

Table 2. Environmental factor ranges corresponding to the peak suitability index exceeding 0.8 for larval gobies in the Yangtze Estuary (values corresponding to more than one peak are shown in brackets; SST in °C, Depth in m, sdo in ml/L, schl in mg/m^3).

Species	Environmental Factor	$Optimal_{min}$	$Optimal_{max}$
Rhinogobius giurinus	SST	17.6	19.0
	SSS	16.8	18.1
	Depth	4.1	5.5
	Sdo	5.8	6.4
	Schl	0.5	2.1
Acentrogobius pflaumii	SST	22.3	23.4
	SSS	19.8 (0)	20.8 (0.5)
	Depth	8.0	8.7
	Sdo	0.4	0.6
	Schl	2.1	2.1
Odontamblyopus rubicundus	SST	28.9	31.9
	SSS	0.7 (0/12.2)	15.5 (0.5/12.7)
	Depth	17.7	20.4
	Sdo	5.4	5.6
	Schl	0.1 (0.9)	0.4 (1.1)

Table 3. The regression of SI and observed density of gobies in the Yangtze Estuary.

Species	Season	*Tweedie variance power*	Adj-R^2	Deviance Explained	AIC	Factors with Significant Effects
Rhinogobius giurinus	Spring	1.50	0.61	0.66	−62.39	sst **, sss **, sdo **, schl *
Rhinogobius giurinus	Summer	1.51	0.30	0.43	−43.70	depth **, schl **
Acentrogobius pflaumii	Spring	1.37	0.30	0.58	44.04	depth **, schl *
Acentrogobius pflaumii	Summer	1.37	0.33	0.45	36.46	sst **, sss **, depth **, sdo **, schl **
Odontamblyopus rubicundus	Spring	1.56	0.02	0.73	23.43	sdo **
Odontamblyopus rubicundus	Summer	1.53	0.10	0.14	29.31	depth *, sdo **, schl *

Significance: * $p < 0.05$; extremely significance: ** $p < 0.01$.

3.3. Model Validation and HSI_{gini} Evaluation

The model with the lowest AIC and RMSE was selected as the best (Table 4). The HSI_{gini} of each goby was obtained and interpolated using ordinary Kriging interpolation based on the best model (Figure 5). The predicted range of the habitat for each goby matched the survey range. The optimal habitats for the three gobies showed significant spatial and seasonal differences. The optimal habitats for *R. giurinus* and *O. rubicundus* had obvious spatial differences in the southern and northern branches. The main distinction of *A. pflaumii*'s habitats was the seasonal variation.

Table 4. Optimal model parameters and their formulas obtained from cross-validation.

Species	AIC	R^2	RMSE	Formula
Rhinogobius giurinus	−164	87.3%	0.06	y = 1.03x + 0.002
Acentrogobius pflaumii	−165	52.0%	0.75	y = −0.16x + 0.72
Odontamblyopus rubicundus	−216	94.1%	0.03	y = −0.94x + 0.03

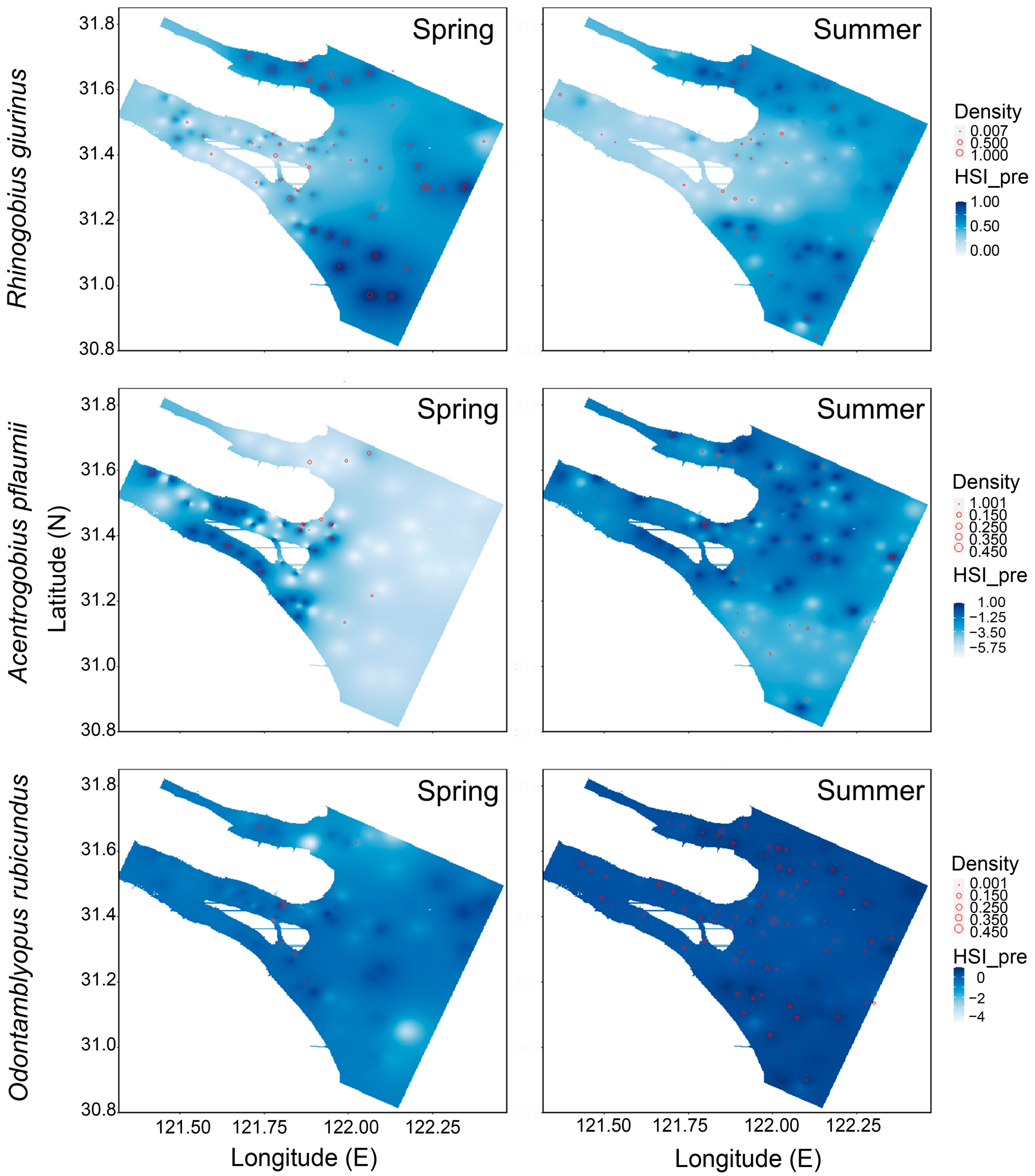

Figure 5. The distributions of HSI_{gini} and the surveyed density of larval gobies in the Yangtze Estuary in spring and summer.

4. Discussion

The requirements and adaptations of different fish species to environmental factors are reflected in the differences in the environmental factor values corresponding to the peak SI. The SICs of three gobies examined in this study had multiple peaks, with the highest peak above 0.8 generally being one. A few SICs, such as temperature for *R. giurinus*, salinity for *A. pflaumii* and *O. rubicundus,* and chlorophyll for *O. rubicundus*, having 2–3 peaks, reflecting the particularly wide range of adaptations of gobies to environmental factors. The larval *A. pflaumii* and *O. rubicundus* may adapt to both freshwater with lower salinity and brackish water with higher salinity (about 20), as indicated by the salinity difference at the salinity maximum. This allows larval gobies to have a high survival rate in estuaries with a high degree of heterogeneity and in the face of climate change-induced habitat alterations. We also examined the distribution of larval *Coilia mystus* in the YRE surveyed during the same period. Its habitat distribution showed a distinct aggregation pattern with a small area, as well as a preference for specific environmental conditions [35].

Each life history stage of a fish shows a specific pattern of SIC for the environment, which can be taken as a sign of habitat selection and adaptation. Larval fish are poor or nonexistent swimmers; thus, their habitat selection is mainly subject to current dispersal [21]. Eggs are usually distributed in aggregations with a single-peaked SIC pattern, which is related to the spawning behavior of the broodstocks and the characteristics of the eggs [40]. In contrast, the larval fish are influenced by both their own weak active selective ability in addition to the passive transport by water currents [41], resulting in a SIC shape with multi-peaks and a more dispersed distribution compared to eggs [10].

The SICs of most adult fish or invertebrate populations are unimodal, with monotonically increasing and decreasing shapes on both sides of the peak [5,13]. Some species have two or more peaks, with a distinct distinction between the higher and lower peaks [42]. Adult fish have a high capacity for swimming and autonomous selection of the environment, and according to habitat selection theory, organisms preferentially live in habitats with the highest reproductive and survival rates, and gradually spread to suboptimal habitats as competition increases [43,44], resulting in the single-peaked SIC morphology.

The spatial and temporal variations of environmental factors are the primary external driver of heterogeneity within the ecosystems [32]). They influence the circulation of matter and energy, the distribution and migration of organisms, and the coexistence patterns of species [45]. Spatial heterogeneity can be utilized as a predictor of temporal heterogeneity in both terrestrial and aquatic ecosystems [46]. The heterogeneity–diversity relationship (HDR) is complex, and a positive HDR is commonly accepted [47]. In some situations, HDR does have a negative relationship. For instance, heterogeneity causes the fragmentation of ecosystems, which reduces the size of acceptable habitats for organisms, hence lowering biodiversity [33]. In future decades, marine organisms will be exposed to more environmental heterogeneity as a result of climate change superimposed on natural environmental variability [48]. Modeling the mechanisms by which organisms respond to environmental variability would provide a basis for predicting biological responses under future climate change in order to enhance risk assessment and conservation strategy [49]. This study focused on the link between spatial heterogeneity and habitat due to the lack of longer time series data.

Environmental variability in estuaries is usually influenced by topography and current factors, such as freshwater flow and tidal rhythm. The salinity in the YRE had a high level of spatial heterogeneity in both spring and summer (the average Gini index was 0.62). Salinity is important to the growth and distribution pattern of larval gobies [50], and there was a positive HDR between the spatial heterogeneity of salinity and the diversity of larval gobies in the YRE as it provided diverse habitats for different species. The lower salinity in the southern branch was not conducive to the survival of larval *R. giurinus*, but it was favorable for the survival of the other two gobies examined. The spatial heterogeneity of SST was fairly low, as measured by an average Gini index of 0.055, and had a substantial impact on the habitat distribution only in the spring of 2018. Nonetheless, its SST seasonal fluctuation was substantial. The SST in spring was suitable for larval *R. ginrinus* and *A. pflaumii*, while summer was optimal for *O. rubicundus*. Thus, future research should focus more on the consequences of the temporal heterogeneity of SST on marine organisms.

Furthermore, depth, dissolved oxygen, and chlorophyll a have been identified as the primary factors influencing the physiological processes of marine organisms [51]. The spatial heterogeneity of depth, sdo, and schl in the YRE was medium, and had significant and/or extremely significant effects on the habitat distributions of gobies in different seasons, respectively. The deep-water channel (maximum depth of around 20 m) dug in the southern branch, the southern channel, and the northern passage may account for the majority of this. The schl is considered to indicate the food supply for larval fish and was therefore incorporated into the study [52]. Notwithstanding the abundance and diversity of larval gobies, as well as their significance as prey and predators in food webs and micro food webs, little is known about their feeding ecology in the YRE [53,54]. This study showed that the three investigated larval gobies' habitats had an association with chlorophyll a, which could be attributed to a diet containing phytoplankton, or other zooplankton food sources indirectly related to chlorophyll a. The latter might be more likely, given most gobies are confirmed to prefer feeding on zooplankton, etc. [55].

There were considerable differences in the spatial and temporal utilization of the habitat by the three gobies in the YRE. *R. giurinus* occupied a larger area of optimal habitat in the spring, while *O. rubicundus* and *A. pflaumii* had a larger area of optimal habitat in summer. The optimal habitats for *R. giurinus* were located mainly in waters other than the southern branch, but *A. pflaumii* habitats were distributed throughout the entire YRE. In spring and summer, the habitat distribution of *O. rubicundus* was highly variable, with the area located mainly in the southern branch in spring and expanding to the waters close to the eastern and southern parts of the Jiudansha in summer. The spatial and temporal separation of fish habitats during the early stages of their life cycle will decrease interspecific competition and increase the population survival rate, thereby boosting biodiversity [56].

The ecological and biological impacts of hydrological projects are well documented [57]. In recent decades, the development of a variety of hydraulic projects and estuarine improvement projects in the upstream Yangtze River and estuary has had an impact on the YRE's regional environmental stability. The effect of the projects on environmental heterogeneity and the distribution of biological habitats should be compared to historical data in order to generate reliable conclusions. The interrelationship between marine organisms in terms of competition and coexistence is extremely complex [58,59], and further analysis of intra- and inter-specific relationships in larval fish communities is required. Particularly, inter-specific relationships, such as predator–prey relationships, which influence the quality of habitats [60], should be considered in future research. By using the Lorentz curve and Gini index, the spatial heterogeneity of environmental factors can be assessed and compared directly. Environmental heterogeneity is closely correlated to ecological and biodiversity issues, and it is recommended that future studies delve deeply into this topic. As more HSMs are developed, the HSI ratings delineate the habitat range of fish with varying values or magnitudes. Yangtze River fisheries' management can be informed by HSI evaluation in order to promote stock- and ecosystem-based fisheries management.

5. Conclusions

The Lorenz curve and Gini index were used in this study to highlight the heterogeneity characteristics of various environmental factors in the YRE. This allows the quantification of the spatial heterogeneity of various environmental factors. The approach was brief and straightforward, allowing for the inclusion of environmental heterogeneity in the study of bio–ecological processes, and providing ideas and examples for future environmental factor weighting and bio–environmental relationship exploration.

The research indicated that the salinity of the YRE had high spatial heterogeneity, with a Gini index of 0.62; the temperature had the lowest spatial heterogeneity, with a Gini index of 0.05, and there were significant seasonal changes. The habitat suitability of *R. ginurinus* and *A. pflaumii* differed between the southern and northern branches, with the southern branch being unsuitable for *R. ginurinus* and the major habitat for *A. pflaumii* in spring. Suitable habitats for *O. rubicundus* were found across the survey area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11020381/s1, Figure S1: Histogram of environmental factors in the spring and summer in the Yangtze Estuary (2018–2020). Figure S2: The correlation coefficient (ρ) of gobies and each environmental factor in the spring and summer in the Yangtze Estuary (2018–2020). Figure S3: The spatial distribution of the sea temperature and salinity in the spring and summer in the Yangtze Estuary (2018–2020). Figure S4: The spatial distribution of SI of environmental factors for three larval gobies in the Yangtze Estuary. Figure S5: Results for *R. giurinus* derived by GAM (left two panels: spring; right two panels: summer). Figure S6: Results for *A. pflaumii* derived by GAM (left two panels: spring; right two panels: summer). Figure S7: Results for *O. rubicundus* derived by GAM (left two panels: spring; right two panels: summer). Table S1: Summary of environmental factors in the spring and summer in the Yangtze Estuary (2018–2020).

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