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Importance of Weighting for Multi-Variable Habitat Suitability Index Model: A Case Study of Winter-Spring Cohort of *Ommastrephes bartramii* in the Northwestern Pacific Ocean

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Abstract Weighting values for different habitat variables used in multi-factor habitat suitability index (HSI) modeling reflect the relative influences of different variables on distribution of fish species. Using the winter-spring cohort of neon flying squid (*Ommastrephes bartramii*) in the Northwestern Pacific Ocean as an example, we evaluated the impact of different weighting schemes on the HSI models based on sea surface temperature, gradient of sea surface temperature and sea surface height. We compared differences in predicted fishing effort and HSI values resulting from different weighting. The weighting for different habitat variables could greatly influence HSI modeling and should be carefully done based on their relative importance in influencing the resource spatial distribution. Weighting in a multi-factor HSI model should be further studied and optimization methods should be developed to improve forecasting squid spatial distributions.

Key words weighting; multi-factors; habitat suitability index model; *Ommastrephes bartramii*; Northwestern Pacific Ocean

1 Introduction

Spatial distribution of fish populations are closely related to environmental variables (Block *et al*., 2003; Freeman and Rogers, 2003; Stoner *et al*., 2007; Anderson *et al.,* 2009). Various environmental variables play different roles in regulating the spatial dynamics of fish populations with some more important than others (Vincenzi *et al*., 2006; Li *et al*., 2009). The importance of a variable may also change with fish life history, reflecting different requirements of fish during various life history stages in natural habitats (U. S. Fish and Wildlife Service, 1984; 1986; Gore and Bryant, 1990; Manderson, 2005). Thus, integrating multi-factors in quantifying fish habitats can help understand and forecast the distribution of relevant fish species (Gillenwater *et al*., 2006; Van der Lee *et al*., 2006; Chen *et al*., 2010).

Habitat suitability index (HSI) models developed with environmental variables are often used to evaluate fish habitats (U. S. Fish and Wildlife Service, 1981; Vinagre *et al*., 2006; Vincenzi *et al*., 2006; Gómez *et al*., 2007; Tomsic *et al*., 2007). Two steps commonly used to establish an HSI model include: (1) calculating the suitability of index (SI) for each factor using literature models or appropriated statistical method; and (2) combining all SIs as an HSI using geometric mean model (GMM) or arithmetic mean model (AMM). Due to a lack of specific information, the same weights are often used in GMM and AMM for all environmental variables in an HSI model (Tomsic *et al*., 2007; Tian *et al*., 2009; Chen *et al*., 2010). A few studies used different weights for HSI model variables based on literature information and expert knowledge (Vincenzi *et al*., 2006; Li *et al*., 2009). However, limited research has been done to evaluate the impact of weighting on HSI modeling.

The distribution and abundance of *Ommastrephes bratramii*, a single year-class population and opportunistic species in the Northwestern Pacific Ocean, are greatly influenced by the biographical environment (Chen, 1997; Yatsu *et al*., 1997; Wang and Chen, 2005; Chen *et al*., 2008a, 2010). Many studies have shown that sea surface temperature (SST) strongly influences the distribution of fishing grounds (Sakurai *et al*., 2000; Bower and Ichii, 2005; Cao *et al*., 2009; Ichii *et al*., 2009). The composi-

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tion and structure of SST, which are affected by other environmental factors, such as the warm current of Brazil (Waluda *et al*., 1999), Kuroshio current (Cao *et al*., 2009) and El Niño/La Niña and climate change (Gonzalez *et al*., 1997; Waluda *et al*., 2006; Chen *et al*., 2007), have a direct impact on fish habitat and fishery resources (Cao *et al*., 2010). Horizontal gradient of SST (GSST) is considered to be related to the boundary of current and the fronts in oceans (Chen, 2004). Therefore, GSST data have been used to analyze the impact of marine environmental changes on fish distributions (Wang *et al*., 2003; Chen *et al*., 2009a). Sea surface height (SSH) is another important environmental factor. It is of interest to scientists because it reveals how much heat is stored in the ocean. Warm water is less dense than cold water, so higher SSH values indicate warmer water and are closely related to the distribution of fishing ground (Polovina *et al*., 1999; Chen *et al*., 2009b).

Therefore, we used the winter-spring cohort of *O. bartramii* in the Northwestern Pacific Ocean as an example to develop the HSI models by using ten different weighting schemes for SST, GSST and SSH, and then compared their differences to evaluate the influence of weights on established habitat models. The most suitable weighting scheme for these three environmental factors was identified for *O. bartramii* to illustrate the impor- tance of weighting for a multi-variable (HSI) modeling.

2 Materials and Methods

2.1 Fishery Data

The western stock of the winter-spring cohort of neon flying squid is mainly distributed in the west of 170°E in the Northwestern Pacific Ocean (Bower and Ichii, 2005). The area of 39°N–45°N latitude and 150°E–164°E longitude is an important traditional fishing ground of Chinese commercial squid-jigging vessels from August to October (Wang and Chen, 2005). The fishery data, including fishing dates, fishing locations with longitude and latitude, the number of fishing vessels and total catch each day from 2003 to 2008, were acquired from the Chinese Mainland Squid Jigging Technical Group located at Shanghai Ocean University. All the data were grouped in a temporal scale of week and spatial scale of 0.5° latitude and 0.5° longitude.

2.2 Environmental Data

Previous studies have shown that SST, GSST and SSH are key factors influencing the life history and spatial distribution of neon flying squid (Bower and Ichii, 2005; Chen and Tian, 2005; Chen *et al*., 2008b). Weekly SST data with a spatial resolution of 0.1° latitude and 0.1° longitude and weekly SSH data with a spatial resolution of 0.25° latitude and 0.25° longitude were obtained from the Goddard Space Flight Center on the NASA website (http://oceancolor.gsfc.nasa.gov, accessed November, 2010). The mean values of 25 original grids for SST and 4 original grids for SSH were calculated for the defined areas of 0.5° latitude and 0.5° longitude for SST and SSH data, respectively. Using SST data for the grid of 0.5° latitude and 0.5° longitude, the GSST data were calculated as:

$$GSST_{i,j}=\sqrt{\frac{(SST_{i,j-0.5}-SST_{i,j+0.5})^2+(SST_{i+0.5,j}-SST_{i-0.5,j})^2}{2}}, \tag{1}$$

where $GSST_{i,j}$ is the GSST in the latitude of i and longitude of j, $SST_{i,j-0.5}$, $SST_{i,j+0.5}$, $SST_{i+0.5,j}$, and $SST_{i-0.5,j}$ are the SSTs in the latitude of i, i, $i+0.5$ and $i-0.5$, respectively, and longitude of $j-0.5$, $j+0.5$, j and j, respectively.

2.3 HSI Modeling

The following three steps were used to construct the HSI models: (1) identifying key environmental variables to develop SI model; (2) determining weights for each variable; and (3) integrating HSI model over all the identified variables that are critically important in influencing fish distribution. In general, spatial dynamics of fishing effort reflects changes in the spatial distribution of targeted fish species, and thus can be considered as an indicator of targeted fish occurrence or availability (Andrade and Garcia, 1999; Chen *et al*., 2010). Tian *et al*. (2009) found that a fishing effort-based HSI model performs better than a CPUE-based HSI model in defining optimal habitats for neon flying squid. Therefore, this study defined the SI from the relationship between fishing effort and three environmental variables (SST, GSST and SSH) which were identified in previous studies as important in determining the distribution of *O. bartramii*.

SI values range from 0 to 1. The highest fishing effort is assigned an SI of 1, being associated with a range of the most favorable conditions (Brown *et al*., 2000). An SI of 0 implies that the environmental conditions are unfavorable and there is no fishing effort. In this study, we set 6 levels of SI values, *i.e.* 1, 0.75, 0.50, 0.25, 0.10 and 0, which are in accordance with the corresponding efforts for *O. bartramii* (Table 1). The SI values for three environmental variables were assumed from the first weeks to the thirteenth weeks of 2003–2008 (Tables 2, 3 and 4).

Table 1 Definitions of suitability index values for *Ommastrephes bartramii* based on the fishing effort of Chinese squid jigging fleets in the Northwest Pacific Ocean

Suitability index value	Description of habitat
1	The highest fishing effort
0.75	Usual occurrence or higher fishing effort (400 < F < highest fishing days)
0.5	Common occurrence or average fishing effort (250 < F ≤ 400)
0.25	A few occurrence or lower fishing effort (100 < F ≤ 250)
0.1	Rare occurrence or lower fishing effort (0 < F ≤ 100)
0	Zero fishing effort

Table 2 Suitability index (SI) values for SST from the first week (W1) to the thirteenth week (W13)

SST (℃)	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
11–12										0.1			0.1
12–13				0.25	0.1	0.1		0.1		0.5	0.5	0.1	0.5
13–14				0.1	0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.25
14–15				0.1	0.1	0.25	0.1	0.25	0.25	0.25	0.75	1	0.5
15–16			0.1	0.1	0.25	0.25	1	0.75	1	1	0.75	0.5	1
16–17	0.1	0.1	0.1	0.5	1	0.75	0.75	1	0.75	0.75	1	0.75	0.25
17–18	0.25	0.25	0.5	1	0.5	0.25	0.5	0.25	0.1	0.5	0.5	0.25	0.5
18–19	0.25	0.25	0.75	0.75	0.25	1	0.25	0.75	0.1	0.1	0.1	0.1	0.1
19–20	1	1	0.75	0.5	0.25	0.5	0.5	0.25		0.1	0.1	0.1	
20–21	0.75	0.25	1	0.25	0.5	0.5	0.25					0.1	
21–22	0.1	0.75	0.1	0.1	0.25								
22–23	0.25	0.5	0.25	0.1								0.1	
23–24	0.1	0.1											
24–25		0.25											

Table 3 Suitability index (SI) values for GSST from the first week (W1) to the thirteenth week (W13)

GSST (℃/0.5°)	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
0.0–0.5	0.5	0.25	0.25	0.5	0.25	0.25	0.75	0.75	0.25	0.25	0.5	0.5	0.25
0.5–1.0	0.5	1	1	0.75	1	1	1	0.75	0.75	0.5	1	1	0.25
1.0–1.5	1	0.75	0.75	1	0.75	0.75	0.5	1	0.75	1	0.25	0.5	0.75
1.5–2.0	0.25	0.25	0.75	0.5	0.5	0.5	0.25	0.25	0.5	0.5	0.75	0.5	1
2.0–2.5	0.5	0.25	0.25	0.75	0.25	0.25	0.25	0.25	1	0.75	0.25	0.5	0.5
2.5–3.0	0.1	0.1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.25	0.25	0.25
3.0–3.5		0.1	0.1	0.25	0.1	0.1	0.1	0.1	0.25	0.25	0.1	0.1	0.1
3.5–4.0		0.1		0.1	0.1		0.25	0.1	0.1	0.1	0.5	0.25	0.1
4.0–4.5				0.1				0.1				0.1	0.1
4.5–5.0													0.1

Table 4 Suitability index (SI) values for SSH from the first week (W1) to the thirteenth week (W13)

SSH (cm)	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
−30 – 25		0.1		0.1									
−25 – 20	0.1		0.1	0.25	0.1		0.1	0.1					
−20 – 15		0.1	0.1	0.1	0.25	0.1	0.25	0.25	0.1	0.1	0.1	0.1	0.1
−15 – 10		0.1	0.25	0.1	0.25	1	0.5	0.5	0.5	0.25	0.25	0.1	0.1
−10 – 5	0.1	0.25	0.25	0.25	0.25	0.25	0.75	0.5	0.5	0.75	0.5	0.25	0.25
−5 – 0	0.5	0.75	0.5	0.5	0.25	0.5	1	0.5	1	1	0.25	0.25	0.1
0 – 5	0.1	1	1	1	0.75	0.5	0.75	1	0.5	0.75	0.75	0.25	0.1
5 – 10	1	0.5	0.25	0.25	1	0.25	0.5	0.25	0.25	0.75	1	0.5	1
10 – 15	0.5	0.1	0.5	0.75	0.25	0.25	0.25	0.5	0.25	0.1	0.5	1	0.75
15 – 20	0.5	0.75	0.1	0.1	0.75	0.75	0.1	0.1	0.1	0.1	0.25	0.5	0.75
20 – 25	0.1	0.1	0.25	0.1	0.1	0.1		0.1		0.1	0.25	0.25	0.1
25 – 30	0.25	0.1		0.1		0.1	0.1	0.1		0.1	0.1	0.1	0.1
30 – 35			0.1									0.1	
35 – 40												0.1	

Table 5 The weighting scenarios considered for the weights of SST (w_{sst}), GSST (w_{gsst}) and SSH (w_{ssh}) in the HSI model

Scenario	w_{sst}	w_{gsst}	w_{ssh}
1	0.33	0.33	0.33
2	0.4	0.4	0.2
3	0.4	0.3	0.3
4	0.5	0.4	0.1
5	0.5	0.3	0.2
6	0.5	0.25	0.25
7	0.6	0.3	0.1
8	0.6	0.2	0.2
9	0.7	0.2	0.1
10	0.7	0.15	0.15

Previous studies suggested that SST is the most important factor, GSST is most closely related to SST, and SSH is the least important factor of the three selected environmental variables influencing the spatial distribution of *O. bartramii* (Chen *et al.*, 2007, 2009a, 2009b; Cao *et al.,* 2009, 2010; Ichii *et al.*, 2009). In this study, we proposed 10 different weighting scenarios to capture such differences in the importance of three environmental variables in influencing *O. bartramii* distributions (Table 5). SST was given the highest weight and the weights for GSST and SSH varied with the weight for SST.

The weighted HSI can thus be calculated as:

$$HSI = \sum_{i=1}^{n} SI_i w_i , \tag{2}$$

where SI_i is the SI value of environmental variable i, w_i is the weight of variable i, and n is the number of environmental variables.

2.4 Evaluating Weights of HSI Models

To evaluate the impact of different weighting schemes on the HSI model, the percentage of total fishing effort in each HSI interval (HSI=0.0–0.2; 0.2–0.4; 0.4–0.6; 0.6–0.8; 0.8–1.0) was calculated for 10 different weighting schemes as:

$$F_{i,j} = \frac{f_{i,j}}{f_i} \times 100 , \tag{3}$$

where $F_{i,j}$ is the percentage of fishing effort of the i_{th} scenario in the j_{th} HSI interval, $f_{i,j}$ is the fishing effort of the i_{th} scenario in the j_{th} HSI interval, and f_i is the total fishing effort of the i_{th} scenario.

The HSI values were compared among 10 weighting schemes using a relative difference index (RD) calculated as:

$$RD_{ij} = \frac{F_{ij} - \overline{F_{ij}}\,|_{i=1,2,3K}}{\overline{F_{ij}}\,|_{i=1,2,3K}} \times 100 , \tag{4}$$

where RD_{ij} is the relative difference of the i_{th} scenario in the j_{th} HSI interval, and $\overline{F_{ij}}\,|_{i=1,2,3K}$ is the average percentage of fishing effort of the j_{th} HSI interval for each scenario.

To select weights of HSI models for *O. bartramii*, we assumed that there was a positive linear relationship between the value of HSI and fishing effort (Chen *et al.*, 2010). The model can be written as:

$$F_{i,j} = a_i + b_i HSI_{i,j} , \tag{5}$$

where $HSI_{i,j}$ is the HSI value of the i_{th} scenario in the j_{th} HSI interval, and a_i and b_i are the two estimated parameters of the i_{th} scenario.

The performance of different HSI models with different weights for each of the three variables was evaluated and compared to identify the most suitable HSI model based on the residual standard error (RSR).

$$RSR_i = \frac{\sum_{j=1}^{n} (F_{i,j} - a_i - b_i HSI_{i,j})^2}{n-2} , \tag{6}$$

where RSR_i is the RSR of the i_{th} scenario, a_i and b_i are the two estimated parameters of the i_{th} scenario using equation 5, and n is the number of HSI intervals. The model that yielded the minimum RSR value was chosen as the best model.

3 Results

3.1 Comparing Fishing Efforts of Different Weighting Schemes

The percentage of fishing effort tended to increase with the HSI value from 0 to 0.8, but fluctuated as the HSI value was higher than 0.8 (Fig.1). The percentage of fishing effort differed with weighting schemes for a given interval of HSI values.

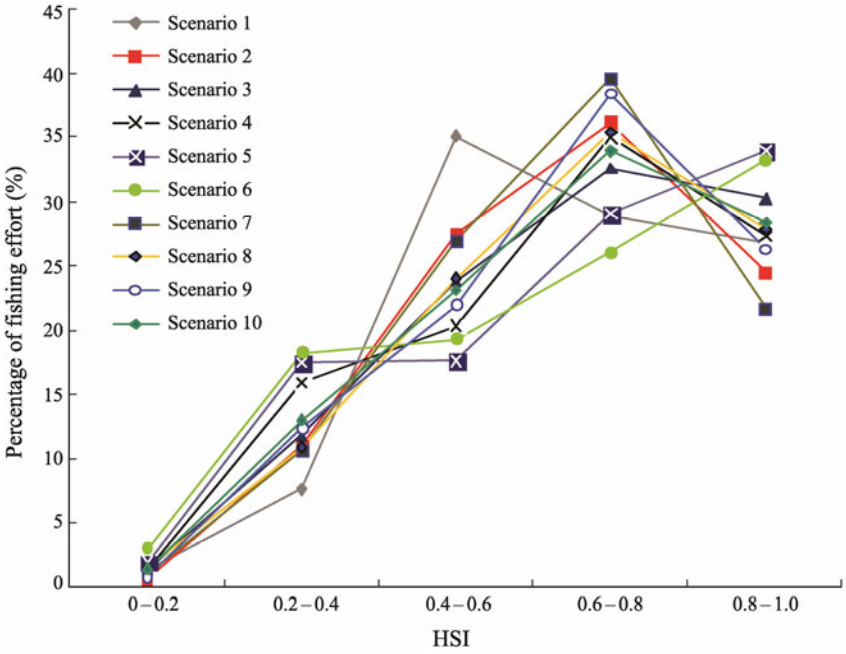

Fig.1 The relationship bewteen habitat suitability index (HSI) values and the percentage of fishing effort for 10 weighting scenarios for *Ommastrephes bartramii* from 2003 to 2008 in the Northwestern Pacific Ocean.

3.2 Comparing RDs

The largest range of RD values was found in the HSI interval of 0–0.2, for which the maximum and minimum values were 55.85% and −49.01%, respectively (Table 6). The least range of RD values occurred when HSI was between 0.6 and 0.8, for which the maximum value was 17.17% and the minimum value was −14.44% (Table 6).

Table 6 Relative difference (RD) calculated using equation (3) for the percentage of fishing effort in different intervals of HSI values for different weighting scenarios outlined in Table 5

Scenario	HSI				
	0−0.2	0.2−0.4	0.4−0.6	0.6−0.8	0.8−1.0
1	5.10	−40.26	45.93	−14.44	−4.03
2	−29.38	−16.35	12.27	17.17	−22.40
3	−49.01	−12.80	14.47	7.13	−12.79
4	9.41	−13.43	0.21	4.72	−0.27
5	−39.67	−2.46	−8.47	13.50	−5.92
6	4.86	−6.74	−0.91	−3.63	7.98
7	−0.89	2.37	−3.81	0.48	1.66
8	4.86	25.11	−15.50	3.49	−2.51
9	55.85	26.86	−17.30	−14.37	17.24
10	38.86	37.70	−26.89	−14.04	21.03

For all the HSI values, the largest range of RD values occurred in scenario 1 with the maximum and minimum values of 45.95% and −40.26%, respectively (Table 6). The range of RD values was larger than 50% for scenario 3, 5, 9 and 10. The smallest range of RD values occurred in scenario 7, for which the maximum and minimum values were 2.37% and −3.81%, respectively. The difference of RD values was smaller than 20% for scenario 6 (Table 6).

3.3 Selecting the Weighting of Variables for the HSI Model

The different HSI models with 10 weighting scenarios for the three environmental variables were evaluated. The HSI model under scenario 6 in which the weighting of SST, GSST and SSH was 0.5, 0.25 and 0.25, respectively, was the best for predicting the percentage of fishing effort (Table 7).

Table 7 Parameters of linear regression model between the percentage of fishing effort and habitat suitability index (HSI) and residual standard error (RSR) value for HSI models under 10 weighting scenarios for three environmental variables from Table 5

Scenario	a	b	RSR
1	1.96	36.01	10.52
2	1.85	36.31	9.40
3	0.41	39.15	5.01
4	2.30	35.41	6.78
5	1.12	37.73	3.80
6	2.92	34.15	3.58
7	2.37	35.27	11.41
8	0.69	38.62	6.92
9	0.74	38.52	8.46
10	1.21	37.59	6.00

4 Discussion

Weighting has a greater influence on low HSI values and less impact on high HSI values. Therefore, if the HSI value is low, which implies that the preferred habitat cannot be well defined, one must be careful to set the weight for each environmental variable. The largest variation in RD was found in scenario 1, for which the weights for all the three variables were the same. This indicates that it is not suitable to set equal weights for the three environmental variables in the HSI model to forecast the location of fishing ground and evaluate *O. bartramii* habitat.

The distribution and migration of *O. bartramii* in the Northwestern Pacific Ocean are greatly influenced by the environmental variables (Wang and Chen, 2005; Ichii *et al*., 2009; Chen *et al*., 2010). As a basic input factor, SST is commonly used in HSI modeling (Le Pape *et al*., 2003; Zagaglia *et al*., 2004; Zainuddin *et al*., 2006). In previous studies, SST was determined to be one of the most important variables or the single most important factor to explain the location of potential fishing grounds and optimal habitat of squid (Chen *et al*., 2005; Chen and Liu, 2006). Therefore, we assumed that SST was the primary variable used to forecast the fishing area in this study. The interaction of the warm Kuroshio Current and cold Oyashio Current, where the isotherm was intensive, provides a highly productive habitat for *O. bartramii* and most catch was obtained from this area (Wang and Chen, 2005; Cao *et al*., 2009; Chen *et al*., 2009a). Therefore, GSST was another potential important factor. The SSH, as an indicator of warm and cold waters, was closely related to the distribution of *O. bartramii* (Tian, 2006).

The setting of weights for different environmental variables can greatly influence HSI modeling. This is especially true for the environmental variable that is most important in determining the spatial distribution of fish. Of all the weighting scenarios considered in this study, the most suitable one would be scenario 6 for which the weights of SST, GSST and SSH were 0.5, 0.25 and 0.25, respectively. Compared with previous findings, our result has a higher weighting for SST (Tian *et al*., 2009; Chen *et al*., 2010). This suggested that the SST was more important than the other variables in influencing squid distribution. Other variables, such as wind and sea surface salinity, were not considered in the development of HSI model due to limited data. We speculate that the weights will vary when other variables are included.

The HSI models usually describe the relations between fish abundance and ecological variables, and then estimate the level of habitat suitability. Fishing efforts and CPUE are generally used as input parameters to estimate the SI value. Commercial fisheries CPUE is not always a reliable abundance index (Pedro, 2006). Fishermen tend to target areas where they know fish are distributed. This results in non-random distribution of fishing efforts with respect to fish distribution with fishing vessels being concentrated in the areas of high fish abundance but seldom in the areas of low abundance. Catchability is likely to improve over time due to the advancement in fishing technology. Thus, CPUE values might be a biased indicator of spatial and temporal variations of fish population (Hilborn and Walters, 1992). The spatio-temporal distribution of fishing effort usually reflects the level of concentration of fishing vessels and the fact that fishermen are satisfied with their catch rates in a commercial fishery (Pedro, 2006). Fishing vessels are likely to leave when the production is low. Thus, an area with more fishing vessels implies that the production is good, suggesting a high abundance in the area. In this case, fishing effort might be a better abundance index than CPUE (Gillis *et al.*, 1993; Swain and Wade, 2003). Under the same weights for different environmental variables, Tian *et al.* (2009) concluded that the CPUE-based HSI model tends to overestimate the ranges of optimal habitats and underestimate monthly variations in the spatial distribution of optimal habitats, and a fishing effort-based HSI model performs better in defining optimal habitats for neon flying squid.

We also found that the percentage of fishing effort declined or fluctuated when the HSI value was above 0.8 for all scenarios except for the scenarios 5 and 6 (Fig.1). This is not consistent with previous assumptions regarding a positive linear relationship between the value of HSI and fishing effort (Chen *et al.*, 2010). Our result shows that not only the weighting of multi-variable impact on the HSI model, but also the commercial fishery data influences the HSI model. Generally, the Chinese mainland squid jigger vessels have focused on the same fishing area. It is possible that the fishing vessels have failed to target the areas of high resources density. Moreover, in the Northwestern Pacific Ocean, *O. bartramii* is widely distributed and the formation of fishing ground is closely related to the distribution of the Kuroshio Current and Oyashio Current (Chen *et al.*, 2008b). Previous studies suggested that the vertical temperature structure played an important role in the formation of fishing ground of squid (Chen, 2004; Chen *et al.*, 2008b). The existence of plankton is a basic condition for the formation of squid fishing grounds (Chen, 2004; Chen *et al.*, 2008b). However, the vertical temperature structure and plankton are not considered in our study, which may lead to the research results obtained.

The objective of this study is to evaluate the impact of weighting for the three variables on an HSI model. It shows that the choice of weighting values for different variables can greatly influence fisheries habitat evaluation. We suggest that suitable weights for different environmental variables should be selected in developing HSI models. A sensitivity analysis similar to this study should be conducted to further evaluate the impact of weighting on HSI modeling, and optimization methods should be developed to improve the forecasting of squid spatial distributions.

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