Vol. 9: 347–360, 2017
https://doi.org/10.3354/aei00234

AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact

Published September 22

Assessing the carrying capacity of *Perinereis aibuhitensis* in a Chinese estuarine wetland using a GIS-based habitat suitability index model

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ABSTRACT: Increasing attention is being paid to estuarine benthic community conservation and restoration globally. In this study, a GIS-based habitat suitability index (HSI) model was utilized to estimate *Perinereis aibuhitensis* (Grube, 1878) carrying capacity in estuarine wetlands of the Zhimai River, eastern China. Eight parameters were investigated, including sand content, salinity, pH, and petroleum hydrocarbon. Each parameter was investigated by a non-linear suitability function for transition from transformed parameter values into a normalized quality index. The weight of each parameter factor was determined by an analytic hierarchy process. A functional relationship was established between habitat suitability and population abundance to assess the carrying capacity. Twelve observation stations, divided into central, eastern, and western regions, were selected to collect data on biogeochemical and environmental parameters. These data were interpolated by GIS. The HSI model was then applied to obtain thematic maps of suitable habitat areas for *P. aibuhitensis* and corresponding carrying capacities. Results showed that central and western regions (approximately 1.013 km^2, accounting for 66.38% of the total area) had a relatively high carrying capacity (130–150 ind. m^{-2}), whereas the carrying capacity of the eastern region was below average. The abundance of *P. aibuhitensis* did not reach the carrying capacity of the environment under present conditions, especially in the eastern region. Results of the present study indicate that the execution of *P. aibuhitensis* restoration is feasible in this region; the areas around Stn 7 and in the eastern region are recommended for restoration.

KEY WORDS: Carrying capacity · Habitat suitability index model · HSI · Geographical information system · GIS · *Perinereis aibuhitensis* · Zhimai River

INTRODUCTION

The polychaete *Perinereis aibuhitensis* (Grube, 1878) is widely distributed along Asian coastlines and estuaries, and is regarded as a good bio-indicator of metal and organic pollution (Sun et al. 2009, Yuan et al. 2010). Moreover, *P. aibuhitensis*, as a high-quality bait in aquaculture (fish, shrimps, and crabs), is a rich source of protein and provides some essential fatty acids. In China, it is often used as an important food source in fish farming (Zhang & Hu 2008). As an ecological keystone species, *P. aibuhitensis*, like other Polychaeta, can scavenge detritus and organic matter on the sediment surface, and plays a key role in nutrient recycling in water–sediment coupling (Davey & Watson 1995, Durou et al. 2005, 2007).

On the west coast of Laizhou Bay in northern China, estuarine wetlands of the Zhimai River com-

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prise important tidal flats (Shao et al. 2015) in which *P. aibuhitensis* is the dominant species. Due to rapid economic development, overfishing, and anthropogenic marine pollution, *P. aibuhitensis* habitats have been seriously degraded. The natural population of *P. aibuhitensis* has been declining on an annual basis and therefore requires urgent restoration and conservation (Zhang & Hu 2008).

Carrying capacity predictions are a necessary step in species conservation and restoration (McKeon et al. 2009, Guyondet et al. 2015). McKeon et al. (2009) and Steenweg et al. (2016) indicated that carrying capacity is significantly related to species habitat. If all suitable habitats in a particular location reach their carrying capacity, augmenting the population through species reintroduction will not facilitate population growth without habitat enhancement or restoration. Similarly, if a non-habitat factor is the main limitation of the population, habitat improvement or restoration will have no effect on population growth (Downs et al. 2008, McKeon et al. 2009, Steenweg et al. 2016). Estimates of the habitat carrying capacity can provide an effective and feasible measure of fish production for the sustainable development and management of aquaculture (Downs et al. 2008).

The habitat suitability index (HSI) model (USFWS 1981) is extensively used to predict habitat quality and species distributions, and to assess reserve and management priorities (Downs et al. 2008, Zajac et al. 2015). Vincenzi et al. (2006) estimated the annual potential yield of *Tapes philippinarum* using HSI values to provide important management decisions for sustainable development in a Mediterranean coastal lagoon (Sacca di Goro, Italy). Another HSI model was developed by Steenweg et al. (2016) to evaluate habitat quality and to assess whether there was sufficient habitat for a breeding population in the proposed reintroduction of plains bison *Bison bison bison* into Banff National Park (Canadian Rocky Mountains).

When evaluating habitat suitability, the need to use data from different sources and scales usually complicates the task and leads to increased data volumes (Store & Jokimäki 2003, Brach & Kaczmarowski 2014). GIS has been utilized in ecological modeling as a means of producing the required modeling data on different spatial and temporal scales (Carter et al. 2006, Mathys et al. 2006). GIS acts as a platform on which models are run and data are stored (Brown et al. 1994, Ripple et al. 1997), and can be used as a tool for extrapolating the results from a point basis to a spatial basis (Littleboy et al. 1996, Osborne et al. 2001).

The 2 aims of the present study were to (1) apply a GIS-based HSI model to evaluate habitat suitability and estimate *P. aibuhitensis* carrying capacity in the estuarine wetlands of the Zhimai River, China, and (2) compare estimated carrying capacity with that under present conditions to provide feasible suggestions for *P. aibuhitensis* conservation and restoration.

MATERIALS AND METHODS

Study area

The study area (1.5 km^2) was located in the southern region of the Zhimai River estuary tidal flat, adjacent to the Dongying Guangrao Nereis National Special Marine Reserve (Dongying City, Shandong Province, China), and to the east of Lai Zhou Bay (Bohai Sea, China). The study area is surrounded by salt fields and undeveloped land. Salinity ranges from 9 to 20‰, and pH fluctuations are small (8.15–8.53). The sediment type here comprises mainly muddy silt, and the main plant species include the common reed *Phragmites australis* and saline seepweed *Suaeda salsa*. The oil industry has always been a main industry in Dongying City. Therefore, petroleum exploration and production will likely impact the Zhimai River, with petroleum hydrocarbon and heavy metal (lead, copper, etc.) acting as potential environmental stressors in this area.

Sample collection and analysis

Eastern, central, and western regions of the study area were established to include a total of 4 sections and 12 observation stations (Fig. 1, eastern: Stns 1–3, central: Stns 4–9, western: Stns 10–12). Four field sampling campaigns were conducted in November 2010, March 2011, May 2011, and August 2011. Water quality and intertidal sediment characteristics were determined at these stations. Due to limitations in manpower, time, and funding, *Perinereis aibuhitensis* abundance was only determined at 6 stations (Stns 1–3 and 7–9). For each sampling campaign and station, 3 replicate soil samples were collected from 0 to 40 cm depth by a Van Veen grab (0.02 m^2), and 4 replicates for *P. aibuhitensis* abundance were determined in a 0.016 m^2 (40 × 40 cm) stainless steel sampling box (depth of 40 cm). All *P. aibuhitensis* samples were washed through a 1 mm mesh sieve, then counted and preserved in a 10% buffered formalin solution (Zhao et al. 1993). Species identification was assisted by marine taxonomy experts at the Marine Biology Institute of Shandong Province.

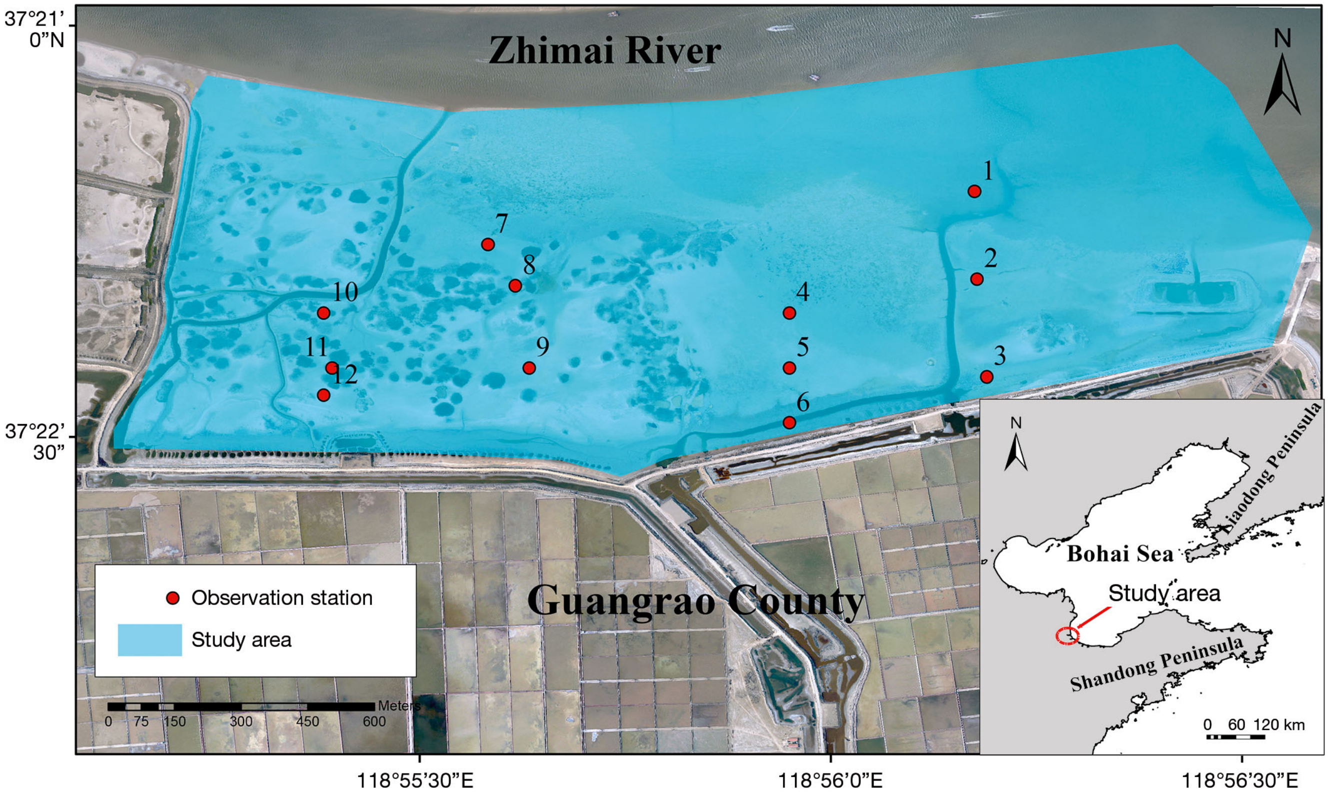

Fig. 1. Study area and monitoring stations in the estuarine wetlands of the Zhimai River, Laizhou Bay, northern China

All soil samples were air-dried by a vacuum refrigeration dryer (Marin Christ, Epsilon 2-6D), then powdered and sieved through a 0.149 mm nylon sieve to remove coarse debris. The concentrations of lead, copper, and cadmium in the soil were measured by inductively coupled plasma atomic emission spectrometry (JOBINYVON Company, ULTIMA 2) after digestion by an $HClO_4$-HNO_3-HF mixed solution described in Bai et al. (2011). Petroleum hydrocarbon was extracted from the soil with *n*-hexane and determined using an ultraviolet spectrophotometer (Shimadzu, UV-3600) (Yang et al. 2015). Sulfide was determined through methylene blue spectrophotometry according to the method of Alves et al. (2007). Quality assurance and control were assessed using duplicates, method blanks, and standard reference materials (GBW07401 and GBW080913) from the National Research Center for Standards in China with each batch of samples. The recovery rates for samples spiked with standards ranging from 95 to 105%. The measurement of pH, salinity, and sediment grain size was based on the method of Bai et al. (2011). Soil pH was determined by a Hach pH meter (Hach Company, LPV2500). A VWR scientific conductivity meter (VWR Scientific Products, 1410) was used to measure the electrical conductivity. The sediment grain size distribution was determined using a laser particle size analyzer (Malvern Instruments, MS2000).

Model methods

First, the parameter factors were screened. The parameter factor suitability functions were built and each parameter factor was determined by an analytic hierarchy process (AHP) and expert suggestions. Second, the HSI model was calculated using ArcGIS 10.0 software (ESRI) to obtain *P. aibuhitensis* habitat suitability values. Third, the function was constructed between the HSI value and carrying capacity. Finally, *P. aibuhitensis* carrying capacity was estimated using the HSI model (Fig. 2).

Model variables

Information on species–habitat relationships and life history are the basic requirements of the HSI model design (Vincenzi et al. 2006). Based on our data and previous studies (Miron & Kristensen 1993, Shi 1993, Ahn et al. 1995, Reish & Gerlinger 1997, Gu

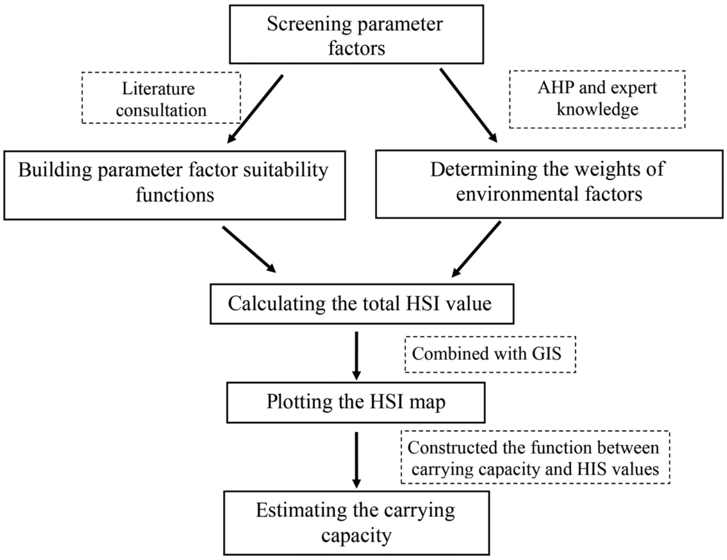

Fig. 2. Research method flow chart. AHP: analytic hierarchy process; GIS: global information system; HSI: habitat suitability index

& Jin 2002, Lv et al. 2009, Yuan et al. 2010, Cai & Yan 2014, Tian et al. 2014), environmental quality factors and environmental pollution factors were selected as input variables for the HSI model. The environmental quality factors included sand content (%), salinity (‰), and pH. The environmental pollution factors included petroleum hydrocarbon (µg l^{-1}), lead (mg l^{-1}), copper (µg l^{-1}), cadmium (µg l^{-1}), and sulfide (mg l^{-1}).

Parameter factor suitability functions

Parameter factor suitability functions (PFSFs) were defined to evaluate the suitability of particular locations relating to environmental parameters (Ortigosa et al. 2000, Vincenzi et al. 2006). For each variable, the suitability index (SI) was determined on an arbitrary scale between 0 and 1, where 0 was identified as a non-suitable habitat, and 1 was assigned to the most suitable condition. PFSFs are presented in Fig. 3. The PFSFs used in this study were compared with previous literature, as briefly illustrated hereafter.

Environmental quality factors

Sand content

Estuary substrate exerts a large influence on *P. aibuhitensis* distribution. Rocky (rock and gravel: >250 µm) sediments are unsuitable for *P. aibuhitensis* farming (Zhang & Hu 2008). Optimal substrate is characterized by a high proportion of silt and clay (slit and clay ≤125 µm), and a specific percentage of sand (25–50%; 125 µm < sand ≤ 250 µm) (Fauchald 1986, Ahn et al. 1995, Cai & Li 1995).

Salinity

Salinity affects the survival and growth of *P. aibuhitensis* during all of its life stages. *P. aibuhitensis* can grow and develop normally in a salinity range of 8–45‰; however, its optimal salinity range is 24–28‰ (Ushakova & Sarantchova 2004, Lv et al. 2009, Cai & Yan 2014).

pH

pH has a significant influence on the fertility and embryonic development of *P. aibuhitensis*. Optimal fertilization and hatching rates occur in pH 7.0–7.5, while *P. aibuhitensis* cannot fertilize <pH 6.0 (Shi 1993, Zhou et al. 2007, Zhang & Hu 2008).

Environmental pollution factors

Petroleum hydrocarbon

Petroleum hydrocarbon is highly toxic to Polychaeta (Sun et al. 2009). Previous studies showed that exposure to 3 µg l^{-1} of petroleum hydrocarbon did not result in mortality (Sun et al. 2006, Wang et al. 2007, 2008a); however, Wang et al. (2008a) reported that after an 8 d exposure to 30 µg l^{-1}, the mortality rate was 20%.

Copper

The accumulation of copper increases in body tissues under elevated concentrations (Won et al. 2013). Results of previous studies demonstrated that the activity of antioxidase and acetylcholinesterase changes when *P. aibuhitensis* is exposed to copper (Sun et al. 2006, Wang et al. 2007). After a 3 d exposure to copper, the value of lethal concentration 50 (LC_{50}) was shown to be 500 µg l^{-1}; the most suitable concentration recorded was <45 µg l^{-1} (Sun et al. 2006, 2009, Wang et al. 2007).

Cadmium

Cadmium is one of the most highly toxic heavy metals; it is widely distributed and can be accumulated *in vivo*. *P. aibuhitensis* has been shown to be sensitive to this heavy metal pollutant, especially Cd^{2+} (Ng et al. 2008, Wang et al. 2008a, Yuan et al. 2010). Ng et al. (2008) reported elevated metallothionein turnover (synthesis and breakdown) rates in *P. aibuhitensis* after Cd^{2+} pre-exposure. For *P. aibuhitensis*, the 96 h LC_{50} of cadmium has been shown to be 1000 µg l^{-1}, with the most suitable concentration being <80 µg l^{-1} (Wang et al. 2008a).

Lead

Lead-induced oxidative stress contributes to the pathogenesis of lead poisoning, resulting in the disruption of the delicate prooxidant/antioxidant balance in polychaetes (Chiba et al. 1996, Tian et al. 2014). The 96 h LC_{50} value of lead for adult *P. aibuhitensis* is 680 mg l^{-1}. When the concentration of lead is <50 mg l^{-1} (safe concentration in the chronic lead toxicity test), *P. aibuhitensis* can grow and develop normally (Tian et al. 2014).

Sulfide

Sulfide has a small effect on adult *Nereis* spp. (Fauchald 1986, Miron & Kristensen 1993). However, acute toxicity test results have demonstrated significant effects of sulfide on the survival rate of 3-setiger nectochaeta (Miron & Kristensen 1993). The safe sulfide concentration for 3-setiger nectochaeta (juvenile *P. aibuhitensis*) is <600 mg l^{-1}, with values <300 mg l^{-1} being the most suitable.

Weights of parameter factors

Although the effects of environmental factors vary among different organisms, identification of the relative factor weights is important in the development of an HSI model. The AHP is a method used for calculating the weights of parameter factors by qualitative and quantitative comparison of their relative importance (Saaty 1977, Saaty & Vargas 1991). In many sustainable habitat management models, AHP is widely used to create a methodology framework and reduce uncertainty (Store & Kangas 2001, Luan et al. 2011, Chen et al. 2013). For example, using AHP, Shen et al. (2008) identified the relative importance of habitat factors to determine the range of giant panda activity in the Minshan Mountains, China.

In the present study, considering the issues being addressed and the final objectives, hierarchy was used to change a complex unstructured problem into a simplified structured model. Each parameter factor was assigned a numerical value by comparing the relative importance (Saaty & Vargas 1991). Questionnaires were sent to appropriate experts to evaluate the relative importance of the 8 parameter factors. The results of the questionnaires were collected and averaged, and the AHP was then run; 'YAAHP' (Yet another AHP) software was applied to determine the weight of the variables using a matrix (Table 1).

The consistency ratio (CR) ratings of the matrices should be below 0.1; if they exceed this value, revisions to the matrix evaluations are required (Saaty 1977). In the present study, the CR of the environmental quality factors and environmental pollution factors was 0.0036 and 0.0115, respectively. Therefore, the results shown in Table 2 were considered reasonable and did not require revision. Weights of parameter factors are presented in Table 2, including sand content, salinity, pH, and petroleum hydrocarbon.

HSI calculation

With regard to the GIS spatial analysis module, the inverse distance weighted interpolation method was used for data interpolation. The HSI value of the study area was calculated by the score of each parameter factor. The HSI value represents the habitat's capacity to carry a particular species. An HSI model can quantitatively measure habitat quality and suitability using knowledge of the species' normal growth and reproduction habitat requirements (Hickey 2008, Knudson et al. 2015). In the present study, the HSI value is the sum of each parameter factor SI multiplied by the corresponding weight (Wang et al. 2008b, Acevedo & Cassinello 2009, Gumusay et al. 2016). The HSI model algorithm was as follows:

$$\mathrm{HSI} = \sum_{i=1}^{8} \mathrm{SI}_i \cdot W_i \qquad (1)$$

where SI_i is the suitability index value of a specific factor according to Fig. 3; W_i is the weight corresponding to a specific factor; and i (=1−8) is the index corresponding to the 8 input factors of the model.

Table 1. Index weight values of (A) habitat suitability index model variables, (B) environmental quality factors, and (C) environmental pollution factors. Fractions indicate relative weighting of variables — numerator: row variable; denominator: column variable

(A) Model variables	Environmental quality factors	Environmental pollution factors
Environmental quality factors	1/1	3/1
Environmental pollution factors	1/3	1/1

(B) Environmental quality factors	Sediment composition	Salinity	pH
Sediment composition	1/1	3/1	5/1
Salinity	1/3	1/1	2/1
pH	1/5	1/2	1/1

(C) Environmental pollution factors	Petroleum hydrocarbon	Lead	Copper	Cadmium	Sulfide
Petroleum hydrocarbon	1/1	3/1	4/1	4/1	5/1
Lead	1/3	1/1	2/1	2/1	3/1
Copper	1/4	1/2	1/1	1/1	2/1
Cadmium	1/4	1/2	1/1	1/1	2/1
Sulfide	1/5	1/3	1/2	1/2	1/1

Table 2. Defined weights of parameter factors calculated by the analytical hierarchy process method

Sediment composition	Salinity	pH	Petroleum hydrocarbon	Lead	Cadmium	Copper	Sulfide
0.4860	0.1724	0.0196	0.1190	0.0526	0.0303	0.0303	0.0178

Map plotting

To make the assessment results more intuitive, the HSI values were reclassified to create habitat suitability maps with gradient colors. Following this, map projection transformation was performed and the value of each class of HSI area was calculated by raster statistics. Both reclassification and projection transformation were implemented using ArcGIS 10.0 software.

Estimating carrying capacity

The HSI model identifies suitable regions for *P. aibuhitensis* using habitat information, but it does not quantify the availability of the study area. With expert evaluation (H. Liu pers. obs.) and field observations, the function between *P. aibuhitensis* carrying capacity and HSI values was constructed through modification of the method by Vincenzi et al. (2011). The maximum carrying capacity of the most suitable habitats (those with HSI ≥ 0.9) was 148 ind. m^{-2} (the average of the pre-survey). When the HSI was <0.2, theoretically, normal growth could not occur; therefore, it was assumed that *P. aibuhitensis* abundance would be negligible. Consequently, the carrying capacity can be determined by linearly scaling the HSI between 0.2 and 0.9, as follows:

$$CC = \begin{cases} 0 & \text{if } 0 \leq HSI \leq 0.2 \\ 211\,HSI - 42.2 & \text{if } 0.2 < HSI < 0.9 \\ 148 & \text{if } 0.9 \leq HSI \leq 1 \end{cases} \quad (2)$$

where CC is the *P. aibuhitensis* carrying capacity.

RESULTS

Overall, this region contained a suitable level of habitat for *Perinereis aibuhitensis*; the HSI value ranged from 0.64 to 0.92 (Fig. 4). Approximately 70% (1.062 km^2) of the study area exhibited HSI values >0.80, with the most suitable habitats found around Stn 5 (HSI > 0.90; Table 3). In contrast, the HSI values of the eastern region (Stns 1–3) were relatively low (0.64–0.80), especially at Stn 3 (only 0.64). Moreover, a small area near Stn 7 also exhibited an HSI value <0.80 (Fig. 4).

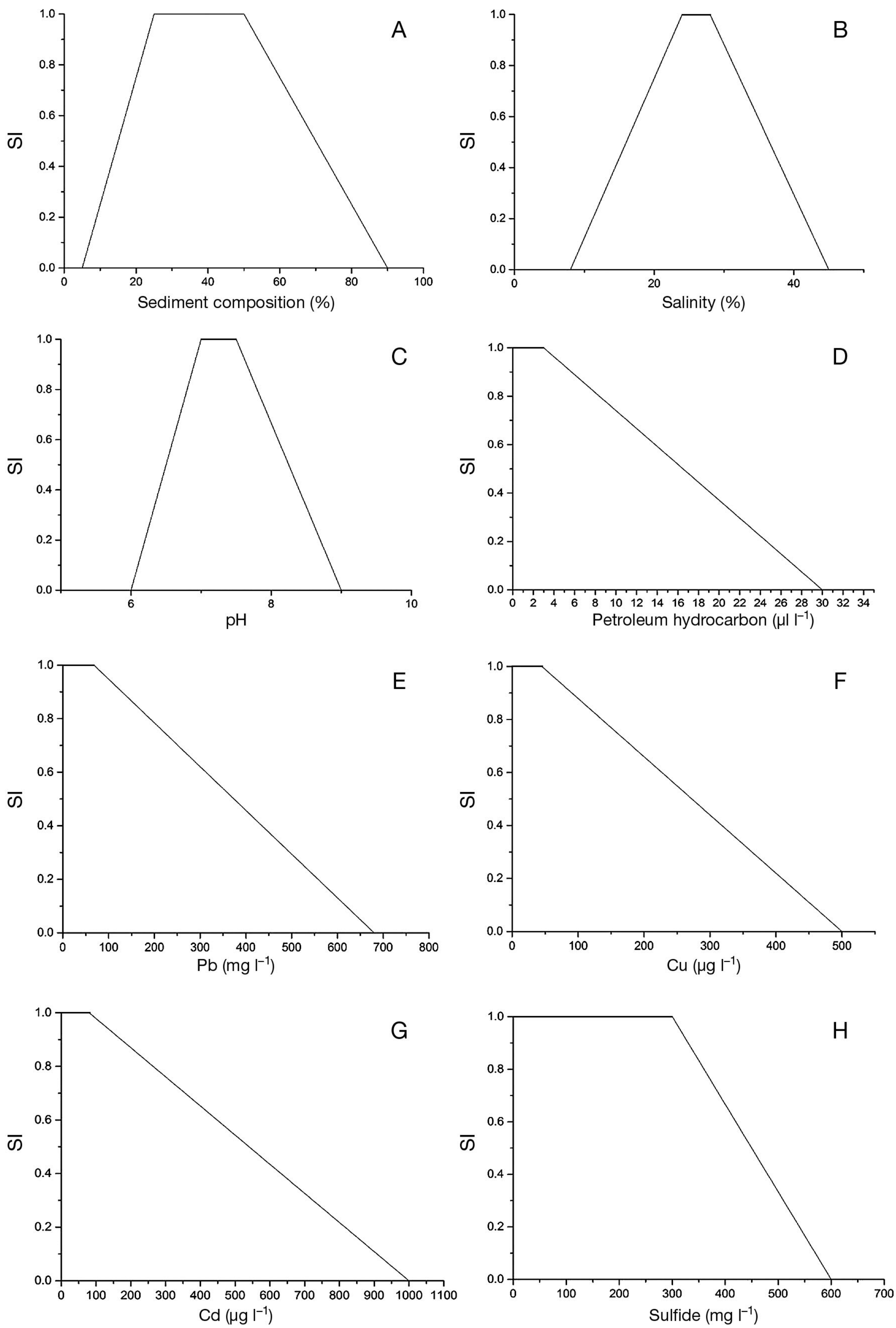

Fig. 3. Parameter factor suitability functions for: (A) sand content; (B) salinity; (C) pH; (D) petroleum hydrocarbon; (E) lead; (F) copper; (G) cadmium; and (H) sulfide. SI, suitability index

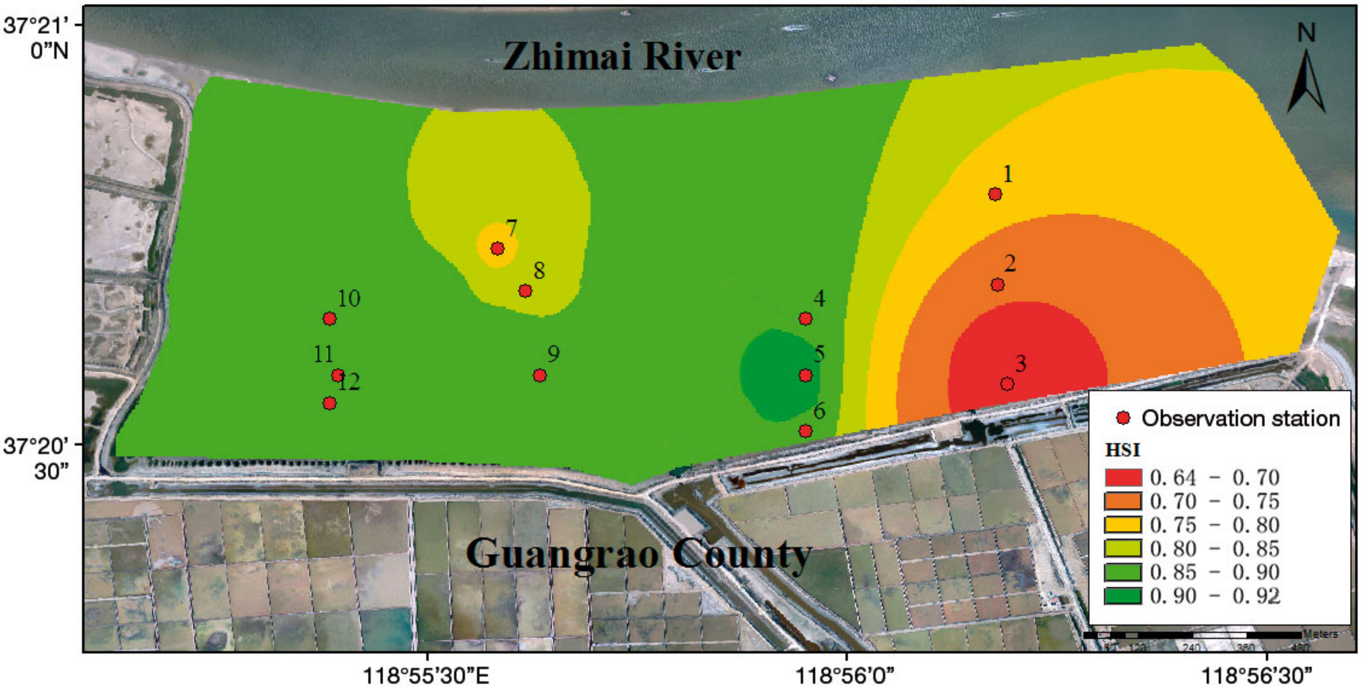

Fig. 4. Habitat suitability map for *Perinereis aibuhitensis* in the estuarine wetlands of the Zhimai River. HSI: habitat suitability index

The area of 6 different carrying capacity classes was calculated by GIS, and then the carrying capacity of each class was estimated using the average value (Table 4). The total abundance of *P. aibuhitensis* was approximately 2.03 × 10^8 individuals and the average carrying capacity was 130 ind. m^{-2}. These calculations are comparable with those of other studies in some estuarine wetlands of northern China (Fauchald 1986, Zhao et al. 1993).

The carrying capacity of *P. aibuhitensis* ranged from 94 to 148 ind. m^{-2} (Fig. 5). Higher carrying capacity (130–150 ind. m^{-2}), accounting for 66.38% of the total area, was mainly distributed in the central and western regions (around Stns 4–6, 8, 10–12) of the study area. Only a few spot-like regions exhibited a carrying capacity <130 ind. m^{-2}. The carrying capacity of the eastern region (Stns 1–3) was less than the average, especially at Stn 3 (90 ind. m^{-2}).

Table 3. Suitable habitat area (km^2 and % of total area) of 6 different classes of habitat suitability index for *Perinereis aibuhitensis* in the estuarine wetlands of the Zhimai River

	HSI					
	0.64–0.7	0.7–0.75	0.75–0.8	0.8–0.85	0.85–0.9	0.9–0.95
Area (km^2)	0.060	0.141	0.263	0.218	0.819	0.025
Percent (%)	3.93	9.24	17.23	14.29	53.67	1.64

Table 4. Area covered (km^2) and *Perinereis aibuhitensis* abundance (×10^6 ind. per class) in 6 different classes of carrying capacity for *P. aibuhitensis* in the estuarine wetlands of the Zhimai River

	Carrying capacity (ind. m^{-2})						
	90–100	100–110	110–120	120–130	130–140	140–150	Total
Area (km^2)	0.018	0.094	0.178	0.197	0.325	0.688	1.500
Abundance (×10^6 ind.)	1.71	9.87	20.47	24.63	43.88	99.76	203.12

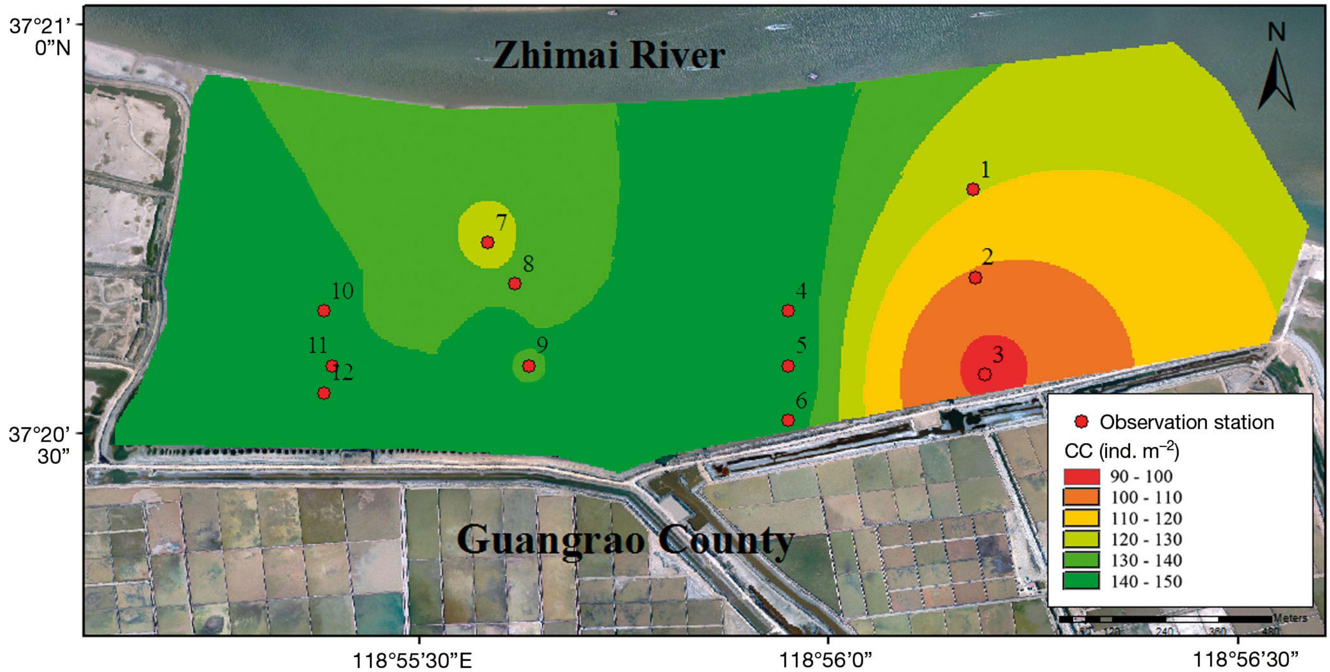

Fig. 5. Carrying capacity (CC) map for *Perinereis aibuhitensis* carrying capacity in the estuarine wetlands of the Zhimai River

The areas with a carrying capacity <100 ind. m^{-2} only comprised 0.018 km^2, accounting for 1.2% of the total area.

DISCUSSION

Analysis of *Perinereis aibuhitensis* carrying capacity: implications for restoration

In general, the total estimated *P. aibuhitensis* carrying capacities in estuarine wetlands of northern China are comparable with those reported in other studies (Fauchald 1986, Zhao et al. 1993). Mobile species have strong selection preferences for various habitats that determine their relative abundance (Steenweg et al. 2016). There were 2 main areas with a relatively low carrying capacity (<130 ind. m^{-2}) in the study area, namely the eastern region and Stn 7. The SI map of each parameter factor can help determine the reasons for the differences in carrying capacity in this region.

The SI value of sand content was low at Stns 1–3 (Fig. 6A). This is because the sand content of these stations (59.28, 64.91, and 69.95%, respectively) exceeded the upper limitation of the most suitable sand content (range: 25–50%). Moreover, around Stn 3, the SI value of pH was relatively low (Fig. 6C). These factors may be responsible for the low carrying capacity in the eastern region. This is comparable with the findings from Cai & Li (1995) and Zhang & Hu (2008). Zhang & Hu (2008) found that a higher sand factor could significantly influence the feeding rate of *P. aibuhitensis* based on the relationship between sediment and feeding in this species. Cai & Li (1995) compared distributions of Polychaeta in the Minnan-Taiwan Shoal and reported that the optimal sediment composition for Polychaeta is a high proportion of silt and clay, and a specific percentage of sand (25–50%).

Another low carrying capacity area was identified around Stn 7. Although the SI value of pH at Stn 7 was the highest, the salinity was very low (for SI values, see Fig. 6B,C). The low salinity is due to the low terrain in this area, which results in rainwater accumulation. Moreover, the salinity weight (0.1724) was higher than that for pH (0.0194). These effects most likely resulted in the low HSI value and carrying capacity at this station. Zhou et al. (2007) also highlighted that a specific suitable salinity and pH are necessary for all life stages of *P. aibuhitensis*, but especially during fertilization and hatching.

All SI values of environmental pollution factors (petroleum hydrocarbon, copper, cadmium, lead, and sulfide) were 1, indicating that their effect on *P. aibuhitensis* growth and reproduction was negligible in the study area. The difference in environmental quality factors (sand content, salinity, and pH) there-

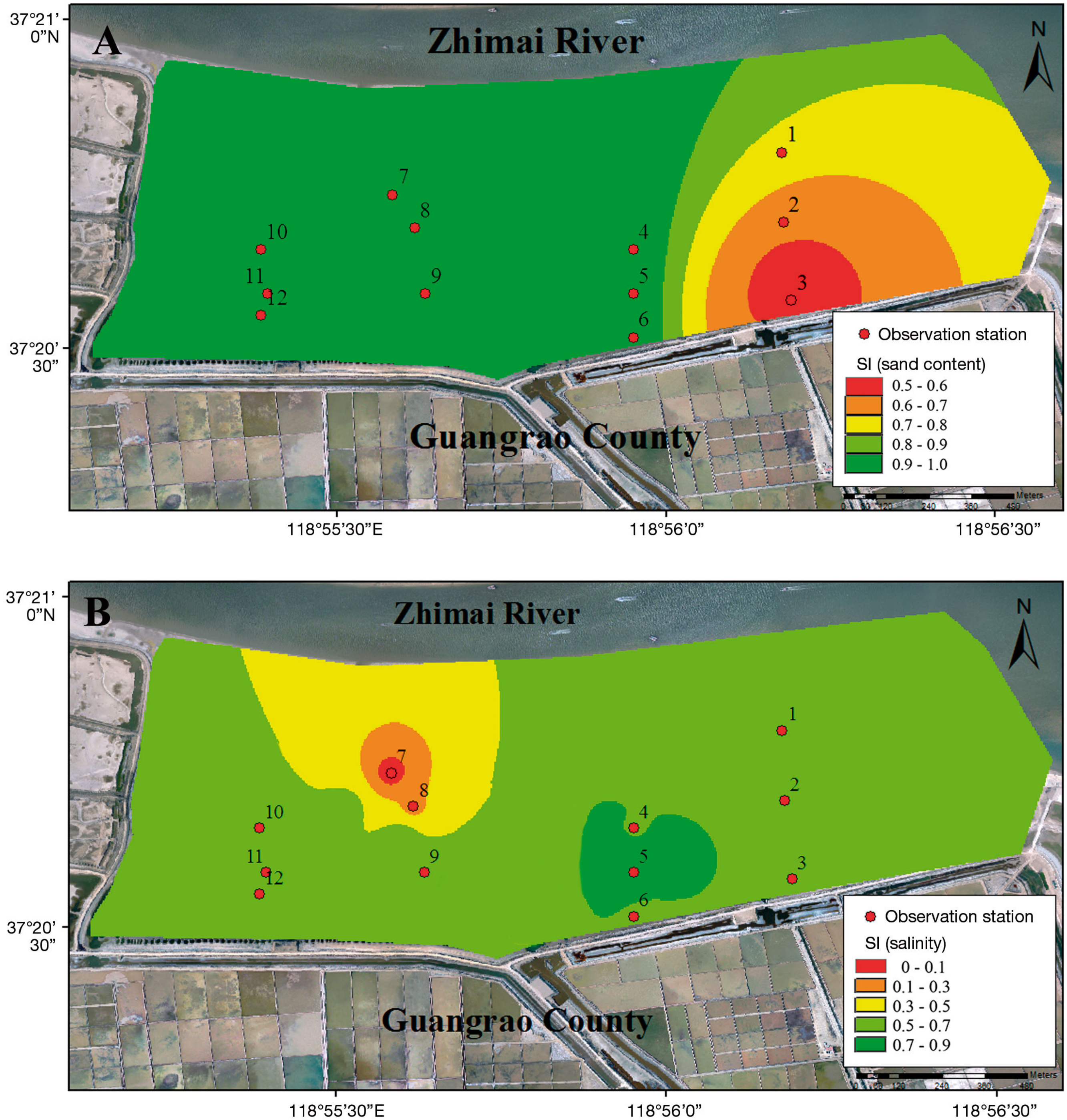

Fig. 6 (continued on next page). Suitability index maps of the environmental quality factors (A) sand content, (B) salinity, and (C) pH for *Perinereis aibuhitensis* in the estuarine wetlands of the Zhimai River

fore appears to be the main reason for the diversity in the carrying capacity of this region.

To provide a reasonable and feasible proposal for *P. aibuhitensis* conservation and restoration in the estuarine wetlands of the Zhimai River, carrying capacity from field surveys was compared with estimated carrying capacity. Generally, the 6 stations' (Stns 1, 2, 3, 7, 8, and 9) field survey carrying capacities were lower than the estimated carrying capacities, particularly at Stns 2 (61 versus 108 ind. m^{-2}, respectively), 3 (27 versus 90 ind. m^{-2}), and 7 (88 versus 125 ind. m^{-2}) (Table 5). The abundances of *P. aibuhitensis*

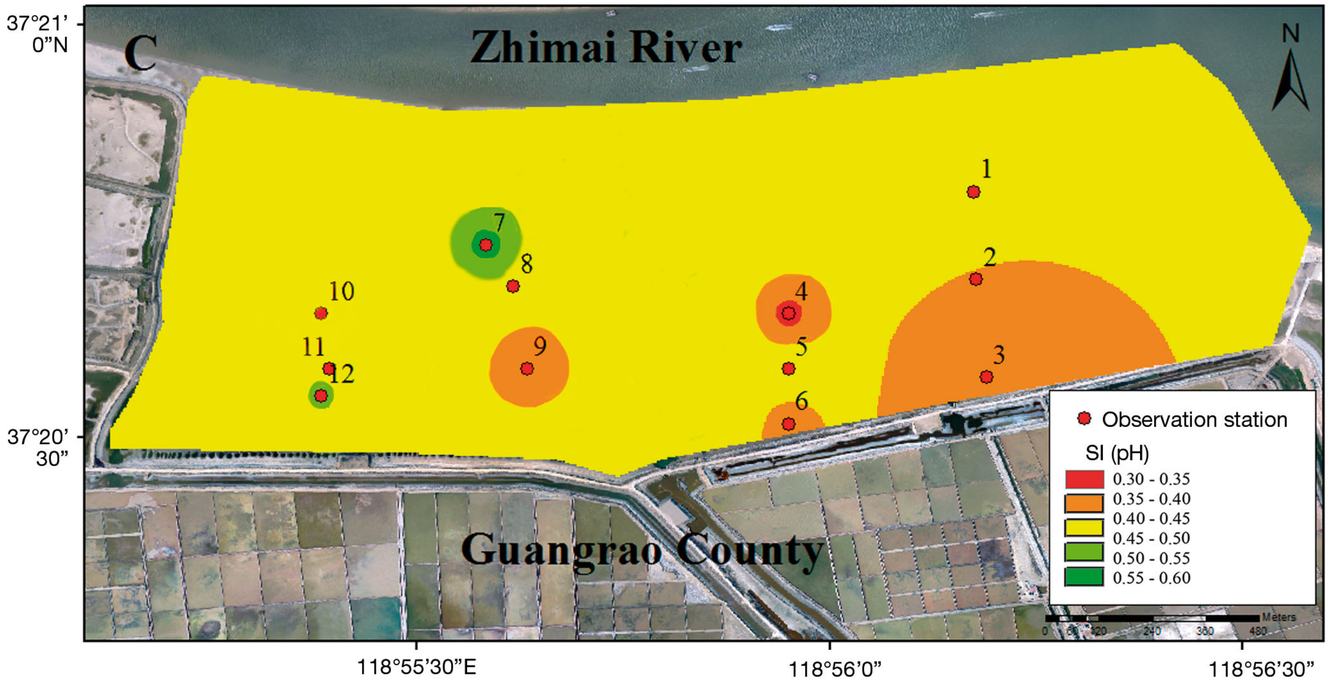

Fig. 6 (continued)

did not reach the environmental carrying capacity, especially around Stn 7 and in the eastern region. These areas should therefore be considered as recovery areas; an appropriate density of *P. aibuhitensis* should be allocated in these areas. Moreover, as a cave-dwelling benthic organism, *P. aibuhitensis* can significantly improve the environmental parameters of the sediment (increase dissolved oxygen, reduce heavy metal, and recycle organic matter) due to their continuous movement (Fauchald 1986, Zhou et al. 2007). Consequently, this will increase the HSI for other fauna and flora in this region. This highlights the importance of *P. aibuhitensis* restoration in the estuarine wetlands of the Zhimai River.

Assessment of the HSI model

With the purpose of restoring ecological environments and sustainable development, increasing amounts of attention have been paid to habitat suitability and species carrying capacity (Hirzel et al. 2006). Different approaches have been adopted in the estimation of benthic carrying capacity (Edgar 1993, Vincenzi et al. 2006, Byron et al. 2011).

Table 5. *Perinereis aibuhitensis* carrying capacity assessments, based on field surveys and model estimates

	Station					
	1	2	3	7	8	9
Field survey (ind. m^{-2})	100	61	27	88	92	148
Model estimate (ind. m^{-2})	121	108	90	125	133	148

Considering the aspect of food flux, Edgar (1993) proposed a metabolic rate-based index model to calculate the epifaunal carrying capacity in island and estuarine habitats. Habitat carrying capacity levels were expressed as an index of total community consumption by summing the body masses of individual animals. Food production and consumption within habitats were directly determined in the study by Edgar (1993); therefore, the methodology was convenient and simple. However, the precondition of the model requires that environmental factors, such as predator abundance, water temperature, and salinity, have little influence on research species. Therefore, the metabolic rate-based index model cannot be applied to estimate the carrying capacity of most estuarine wetland species. In our study, parameter factors were selected for comprehensive assessment of the habitat suitability of the study area, and the carrying capacity was estimated based on the relationships in an HSI model. This methodology can be easily transferred to other coastal and estuary habitats.

Ecopath is a static, mass-balance, ecosystem-based modeling software that focuses on energy transfer between trophic levels; it is widely used in ecological studies (Vasconcellos et al. 1997). It encompasses the full trophic spectrum, making it an appropriate ecosystem modeling tool for determining ecological carrying capacity (Monaco & Ulanowicz 1998, Jiang & Gibbs 2005). Byron et al. (2011) estimated the ecological oyster carrying capacity of Narragansett Bay with the Ecopath model. Compared with Byron et al. (2011), the method used in the present study is simple and lacks complex mass-balance models. A more carefully calibrated, complex trophic/dynamical model would provide more useful information on nutrient cycling and allow for a more detailed analysis of species' ecological carrying capacity. However, little is known about the Zhimai River estuary, limiting the utilization of such a model. Overall, the approach adopted in the present study was a reasonable compromise between simplicity and the complexity of other ecosystem models.

The HSI model, like any other model, has advantages and disadvantages. Increasing the accuracy of the results and other improvements are needed to optimize the model in the future. Other internal or external factors may also influence the growth of *P. aibuhitensis*, such as pathogens, predators and competition, water temperature, and other forms of natural or anthropogenic disturbance. Moreover, the carrying capacity formulation for *P. aibuhitensis* should be more accurately constructed in order to minimize the differences between predicted and observed yield.

CONCLUSIONS

An HSI model was applied to quantitatively and qualitatively analyze *P. aibuhitensis* carrying capacity in the estuarine wetlands of the Zhimai River. Results showed that the central and western region have a relatively high carrying capacity, whereas that of the eastern region is below average. Under the present conditions, *P. aibuhitensis* abundances did not reach the carrying capacity of the environment, particularly in the eastern region. Initiation of species restoration in this area is feasible and urgent; the area around Stn 7 and the eastern region are recommended as the main recovery areas. Despite lack of scientific validation, it is believed that this approach (HSI model with GIS) can provide feasible and effective management for other aquaculture species (such as fish, shrimps, and crabs).

Acknowledgements. This study was jointly funded by the National Natural Science Foundation of China (NSFC) (no. 41206102), the National Marine Public Welfare Research of China (no. 201305009), and the Major Agricultural Application Technology Innovation Project of Shandong Province.

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Editorial responsibility: Catriona MacLeod, Hobart, Tasmania, Australia

Submitted: November 2, 2016; Accepted: June 19, 2017
Proofs received from author(s): August 23, 2017