Modeling potential distribution of Indo-Pacific humpback dolphins (*Sousa chinensis*) in the Beibu Gulf, China

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Abstract

Background. Mapping key habitats of marine mega-vertebrates with high mobility is crucial for species conservation. Due to difficulties in obtaining sound data in the field, Species Distribution Modeling (SDM) provides an effective alternative to identify habitats. As a keystone and flagship species in inshore waters in southern China, Indo-Pacific humpback dolphins (*Sousa chinensis*) play an important role in coastal ecosystems. However, our knowledge on their key habitats remained unclear in some waters including the Beibu Gulf of South China Sea.

Methods. We used a maximum entropy (Maxent) modeling approach to predict potential habitats for *Sousa chinensis* in the Beibu Gulf of China. Models were based on eight independent oceanographic variables derived from Google Earth Digital Elevation Model (DEM) and Landsat images, and presence-only sighting data from boat-based surveys and literatures during 2003-2013.

Results. Three variables, distance to major river mouths, to coast and to 10-m isobaths, were the strongest predictors, consistent with other studies on the dolphin habitat selection. Furthermore, we confirmed that influence of estuaries was the most important and irreplaceable. Besides two known distribution areas as well as data sources, a new area close to the boundary of China and Vietnam, Beilunhe Estuary (BE), was predicted as a potential habitat.

Discussion. Influence of estuaries is likely to indicate feeding preference of the humpback dolphins. The "new" habitat BE should be a key area connecting China and Vietnam dolphins,

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and deserved to be examined and preserved.

Keywords

SDM; Maxent modeling; the Beibu Gulf; Indo-Pacific humpback dolphins (*Sousa chinensis*)

Introduction

Marine mega-vertebrates, including sharks, sea turtles and marine mammals, represent ecologically important parts of marine biodiversity (Block et al. 2011; Bowen 1997; Estes et al. 2011; Pendoley et al. 2014; Schipper et al. 2008). However, most populations are now severely threatened by the anthropogenic activities (Jackson et al. 2001). Species that inhabit coastal waters and estuaries are particularly threatened (Lotze et al. 2006). Suitable MPA networks urgently need to be designed to protect these mobile animals (Baum et al. 2003; Edgar et al. 2014; Hooker et al. 1999; Pendoley et al. 2014). There is an increasingly need to identify key habitats (Guisan et al. 2013; James et al. 2005), usually including areas that are important to their prey and offspring (Evans 2008; Pendoley et al. 2014).

Like most marine vertebrates, marine mammals are difficult to observe in the wild due to their mobility, which results in the acquisition of fragmentary data in the field (Moura et al. 2012; Pauly et al. 1998). SDM approaches provide an effective alternative to map species distribution by linking species location information with environmental variables (Franklin 2009). A machine learning model, maximum entropy method works efficiently, and has the highest predictive performance consistency (Elith et al. 2006). It has been applied to

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predicting distributions of small cetaceans (Edren et al. 2010; Moura et al. 2012; Thorne et al. 2012) .

The Indo-Pacific humpback dolphin (*Sousa chinensis*), a small cetacean, has an extensive range in shallow coastal waters from northern Australia and central China to South Africa, including at least 32 countries and territories (Jefferson & Hung 2004; Jefferson & Karczmarski 2001). Due to inhabiting close to coasts, most stocks are threatened by range-wide incidental mortality in fishing gear, and habitat degradation and loss (Jefferson & Karczmarski 2001; Ross et al. 1994). The dolphin population is decreasing, and its status was defined as Near Threatened (NT) (IUCN 2015). In Chinese waters, the dolphin was historically found in nearshore waters from the Vietnam border north to the mouth of the Yangtze River until 1960s (Jefferson & Hung 2004; Xu et al. 2015). Now only five stocks exist in discontinuous areas, including Xiamen, western Taiwan, Pearl River Estuary, Zhanjiang, and the Beibu Gulf (BG) (Wang & Han 2007), Most of the areas were identified to have the highest human impact (Halpern et al. 2008). Hung et al. suggested that the Chinese populations should be listed in the IUCN Red List of Threatened Species because the areas they inhabit have the fastest economic growth (Huang et al. 2012). Among the five stocks, it is limited knowledge about the southwest population in BG. Besides some fragmented records and local surveys (Chen et al. 2016; Deng & Lian 2004; Pan et al. 2006; Smith et al. 2003; Yang & Deng 2006), we cannot outline the dolphin distributions yet in BG or only in BG of China. Meanwhile, the coastal zone in BG of China has been undergoing increasing development since 2008. Key habitats are needed to be identified and protected

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from human impact during coastal development.

Objectives of this study was to use the available presence-only data obtained from local areas to predict potential distribution of the humpback dolphins in the BG of China by using Maxent modeling approach. In addition, important environmental variables that contributed to modeling habitats were identified and their relationship to dolphin occurrence was discussed.

Materials and Methods

Ethic Statement

Our field work was permitted and supported by the Sanniang Bay Management Committee, which is part of the local government. GPS coordinate range of the survey area is 108°33′3″-109°3′10″E, 21°45′28″-21°21′7″N (Fig 1). Because we adopted no-touch survey methods, we needed no approval from animal ethics committees under Chinese Law.

Study area

The study area is located in north of the Beibu Gulf (BG, also named the Gulf of Tonkin), South China Seas (Fig. 1). BG is a semi-enclosed sea surrounded by the land territories of China, Vietnam, and the Hainan Island of China. The seafloor is basically plain, slowly descending from the coastline to the middle (Liu & Yu 1980). Our analysis was restricted to inshore waters with a boundary of 10-m isobaths because of anecdotal information indicating that distribution of the dolphins was confined to 10-m isobaths in BG. Above 200 rivers flow into this area, including several major rivers, the Beilunhe (BLH), the Fangchengjiang (FCJ), the Maolingjiang (MLJ), the Qinjiang (QJ), the Dafengjiang (DFJ), the Nanliujiang (NLJ),

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and the Jiuzhoujiang (JZJ) river. The total area is about 5,985 km^2 with a coastline about 2,000 km. With the rapid industrialization and urbanization of coastal areas, there is increasing human impact to the north, which belongs to the Guangxi Province of China. Three main cities (Fangchenggang [FCG], Qiznhou [QZ], and Beihai [BH]) and four great harbors (Fangchenggang [FCG], Qiznhougang [QZG], Beihaigang [BHG] and Tieshangang [TSG]) are situated along the Guangxi coastal area.

Our survey area, Sanniang Bay and its adjacent waters (SBs) (Fig. 1), is located in the mid-north part of BG, where some residents and seasonal migrants of humpback dolphins are inhabited (Pan et al. 2006). SBs has now become a dolphin-watching tourism hotspot. Tourists are encouraged to watch wild dolphins by boats while swimming with and feeding dolphins are forbidden.

Sighting data and bias elimination

Dolphin occurrence datasets used in this study were all collected from boat-based sightings during 2003-2013. Two sources were included, from literatures (Wang 2006; Xu et al. 2012b) and from opportunistically boat-based surveys (Fig. 1, Table 1).

Sampling bias, as a general problem during Maxent modeling (Phillips et al. 2009; Yackulic et al. 2013), if not been eliminated, often resulted in spatial omission and commission errors (Kramer-Schadt et al. 2013; Kremen et al. 2008; Sastre & Lobo 2009). Because spatial filtering methods could effectively minimize these errors (Kramer-Schadt et al. 2013), we adopted a spatial filtering to mitigate bias. For occurrence data within every 1-km2 environmental grid, we randomly kept only one record. As a result, 204 records were used for

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predictive modeling over the whole study area (Table 1).

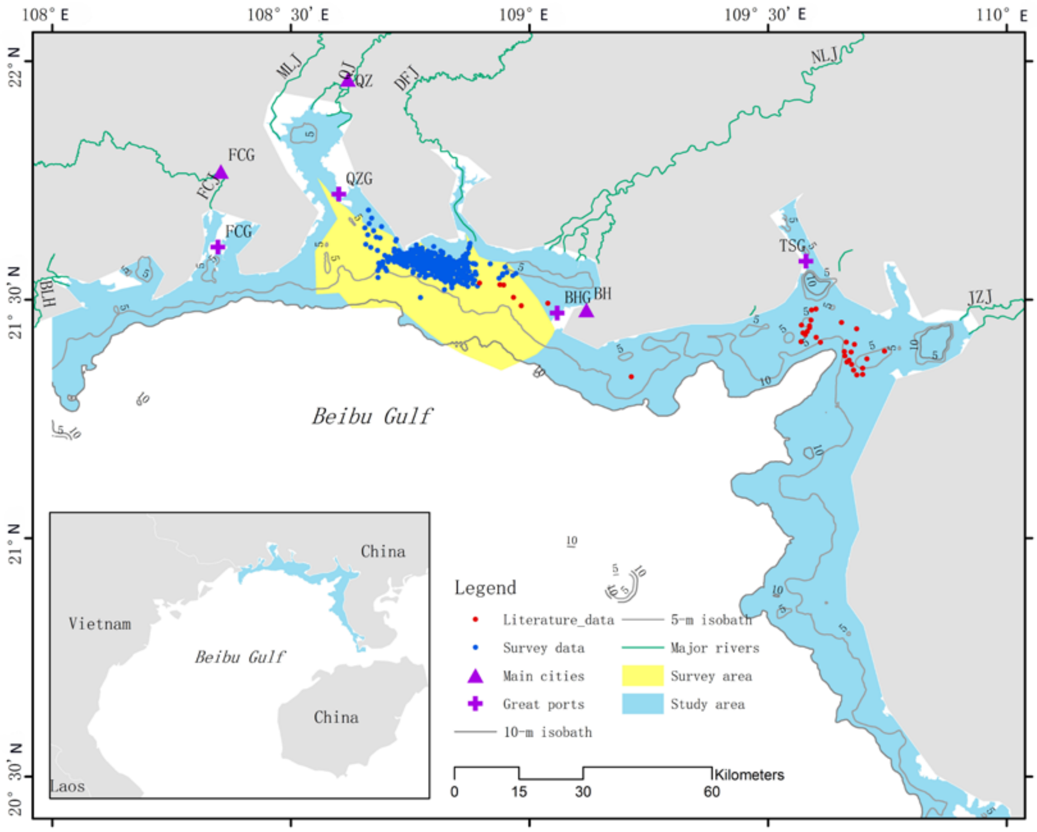

Fig. 1 Study area, survey area and sighting records of *S. chinesis* as shown. The blue study area represented inshore waters of the Beibu Gulf (BG) of China with a boundary of 10-m isobaths. And 5-m isobaths were also drawn. The yellow area displayed our survey range, Sanniang Bay and its adjacent waters (SBs). The dolphin occurrence records were collected from our surveys (celestine blue dots) and literatures (red dots) (Wang 2006; Xu et al. 2012b).

Table 1 Numbers of the dolphin sighting data from different sources during 2003-2013 and used for predictive models. Totally 503 sighting records, 36 from literatures (Wang 2006; Xu et al. 2012b) , 467 from opportunistic surveys, and finally 204 used for modeling after spatial filtering.

From surveys	From literatures	Total records	For modeling
467	36	503	204

Environmental variables and reducing multicollinearity

Water depth, distance to coast and existence of estuaries were examined as important environmental factors that influence habitat selection of humpback dolphins in Chinese waters (Chen et al. 2007; Liu 2007). We developed eleven variables to describe the

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oceanographic and hydrological characteristics of the dolphin habitats: water depth (depth), distance to 0-, 5-, and 10-m isobaths (dis_iso0, dis_iso5 and dis_iso10), distance to land (islands included) (dis_land), coast (mainland-only) (dis_coast), river mouths (dis_rm), and major river mouths (dis_m_rm), which were described in "Study area", and three variables indicative of seafloor topography (slope, aspect, and rugosity). Rugosity, which describes ruggedness of seafloor, was defined as the ratio of surface area to planimetric area (surf_ratio) (Thorne et al. 2012). A base dataset for water depth was extracted from a free resource, Google Earth DEM (Google 2013), with a resolution of 300-m. Isobaths were generated from the base depth layer. Slope, aspect, and rugosity variables were also calculated by using a four-cell method of DEM Surface Tools based on the depth layer (Jenness 2013). The coastline, islands and river mouths layers were extracted from Landsat images in 2005-2007 (USGS 2010). Distance variables were calculated using the Euclidean distance toolkit of the spatial analyst extension in ArcGIS 10.1. All variables were continuous with a resolution of 1-km.

To reduce multicollinearity of environmental layers, correlation coefficients were calculated using the multi-analysis function of the spatial analyst extension in ArcGIS 10.1 (Table 2). By eliminating correlating variables where Pearson's $| r | > 0.75$, we retained independent variables for modeling (Kramer-Schadt et al. 2013; Kumar & Stohlgren 2009). Finally, eight variables were used for predicting (Table 2, Fig. 2): aspect, depth, dis_coast, dis_iso10, dis_iso5, dis_m_rm, slope, and surf_ratio.

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Table 2 Pearson's correlation coefficients for model variables. Coefficients shown in red and with "*" represent significant correlations (| *r* |>0.75). Eight independent variables were retained for modeling: aspect, depth, dis_coast, dis_iso10, dis_iso5, dis_m_rm, slope, and surf_ratio .

	Aspect	Depth	Dis_ coast	Dis_ rm	Dis_ iso0	Dis_ iso10	Dis_ iso5	Dis_ land	Dis_ m_rm	Slope	Surf_ ratio
Aspect	−	0.011	0.040	0.15	0.036	−0.019	0.043	0.058	0.15	0.013	0.0014
Depth		−	−0.57	−0.078	−0.53	0.41	0.24	−0.56	−0.08	0.12	-0.10
Dis_coast			−	0.026	0.97*	−0.49	0.0028	0.99*	0.025	−0.059	0.092
Dis_rm				−	0.043	−0.30	−0.13	0.047	1.0*	0.011	-0.0021
Dis_iso0					−	−0.48	0.029	0.98*	0.042	−0.031	0.045
Dis_iso10						−	0.27	−0.49	−0.30	0.046	-0.087
Dis_iso5							−	−0.010	−0.13	0.11	-0.17
Dis_land								−	0.045	−0.058	0.090
Dis_m_rm									−	0.012	-0.0038
Slope										−	-0.66
Surf_ratio											-

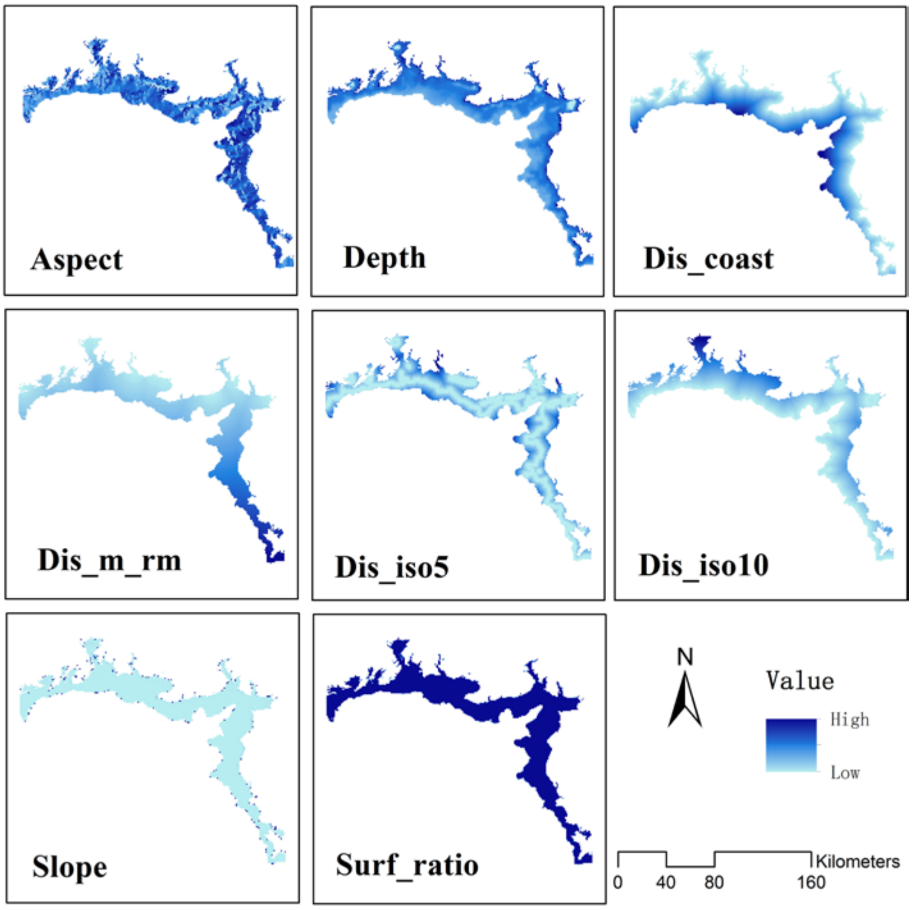

Fig. 2 Environmental layers for modeling. Eight independent variables , aspect, depth, dis_m_rm, dis_coast, dis_iso5, dis_iso10, slope and surf_ratio, were included.

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Maxent modeling

Maxent software version 3.3.3k was applied for modeling dolphin distribution (Phillips et al. 2006; Phillips et al. 2004; Phillips & Dudik 2008). Based on 205 dolphin sighting records and eight environmental layers, we built a BG model to explore suitable habitats of the humpback dolphins in BG of China. Cross-validation was used to assess the model fit, and 10 replications were performed. Auto-features for environmental variables were chosen (Phillips & Dudik 2008). Logistic outputs were interpreted as probability of species presence , or suitability of predictive habitats (Phillips & Dudik 2008). We used two measurements to evaluate the model. One was a binomial test (threshold-dependent) on omission and predicted area, another was AUC value (threshold-independent) both on training and test data (Liu et al. 2005; Phillips et al. 2006). The relative contributions of environmental variables to the models were estimated. The importance of different variables was examined using jackknife analyses. Response curves were plotted to assess how each environmental variable affected our prediction.

Identification of potential habitats

A binary map consisting of suitable habitats and non-habitats was generated according to selective thresholds. The output probabilities of the presence of dolphins were reclassified into two suitability levels: 0 = unsuitable, 1= suitable. Then areas with suitable levels was defined as suitable habitats. We chose two conservatively logistic thresholds to differentiate habitats and non-habitats, equal training sensitivity and specificity (ESS), and maximum training sensitivity plus specificity (MSS) (Liu et al. 2005; Thorne et al. 2012). Fragmental

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patches were erased, continuous patches were regarded as potential habitats, and the patch area were calculated. Mappings were performed in ArcMap 10.1 (ESRI, USA).

Results

Model evaluation

The average AUC values, including training datasets (173 or 174 records) and test datasets (19 or 20 records) from 10 reduplications, were all more than 0.9 (Table 3), illustrated that the BG model had excellent discriminatory ability (Table 3). Threshold-dependent tests also indicated that the predictive results significantly better than random prediction with p-values << 0.01 (Table 3).

Table 3 Summary of Maxent modeling outputs. Number of occurrence records used, AUC values and the two selected thresholds and corresponding omission rates et. al. were as follows.

Samples	Number of records	AUC values (Avg.±S.D.)
Training	173/174	0.947±0.001
Test	19/20	0.92±0.02
	ESS (Avg.±S.D.)	**MSS (Avg.±S.D.)**
Logistic thresholds	0.26±0.01	0.22±0.02
Fractional predicted area	0.118±0.006	0.14±0.02
Training omission rate	0.118±0.006	0.08±0.2
Test omission rate	0.18±0.09	0.17±0.08
P-value	1.8×10^{-9}	9.5×10^{-10}

Potential habitats

The BG model produced a patchy distribution output along the northern coastline of BG, the median logistic probability from 5.9×10^{-9} to 0.85 (Fig. 3a). It can be explained as the maximum habitat suitability of the dolphins in BG up to 0.85 (Phillips & Dudik 2008).

Owing to better performance in fractional predicted area, training and test omission rate

(Table 3), we took the binary map based on the MSS threshold as suitable habitat output (Fig. 3b). 14% area were identified as suitable habitats (Table 3). Three continuous patches were defined as potential habitats of the humpback dolphins in BG of China, Sbs (~ 478.3km^2), Beihai Shatian waters (BSs, ~189.5km^2) and Beilunhe Estuary (BE, ~74.0km^2) (Fig. 3c).

For omission error of sighting data, 2.3% (4/175) sighting records were omitted from predicted distribution in Sbs (Fig. 3d) while the omission rate was up to 35.7% (10/28) in BSs (Fig. 3e) .

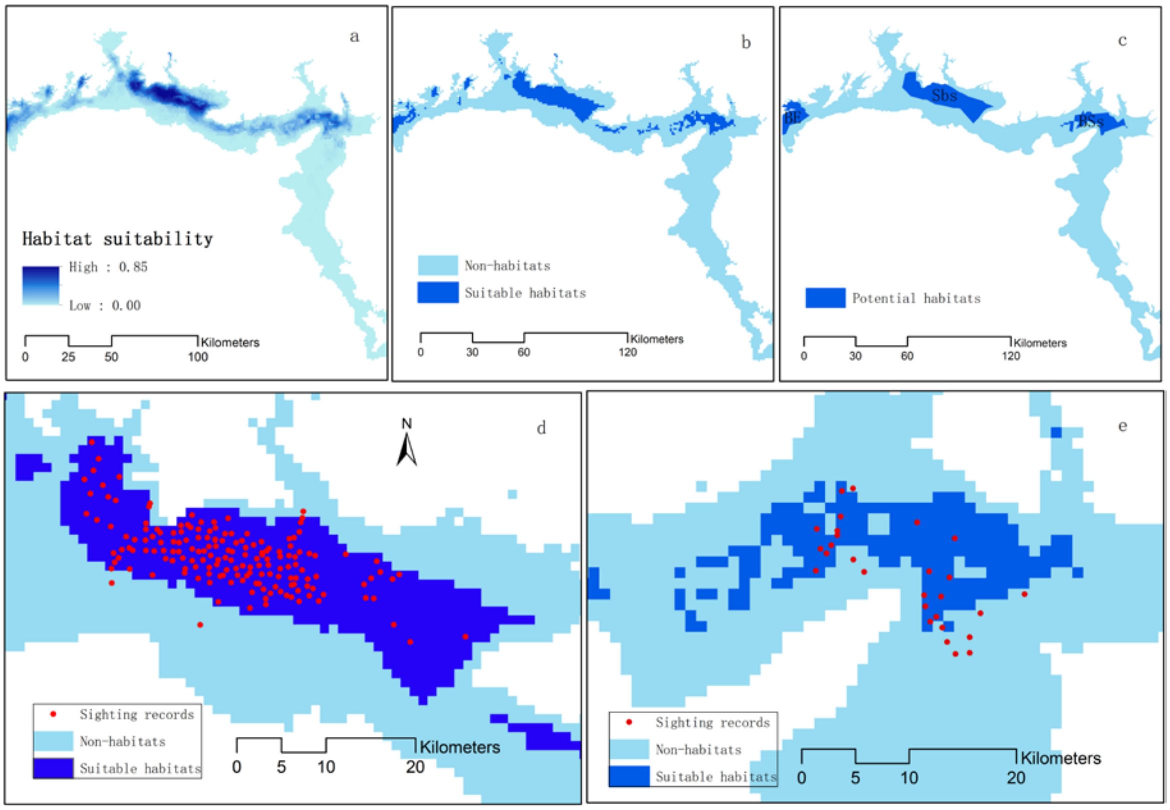

Fig. 3 Predicted distribution (a), suitable habitats (b), potential habitats (c) of *Sousa chinensis* in BG; omission error of sighting data in suitable habitats of Sbs (d) and BSs (e). The median of habitat suitability ranged from 5.9 $\times 10^{-9}$ to 0.85 (a). Suitable habitats reclassified by the MSS threshold were mainly distributed in northern part of BG as the binary map shown (b). Three continuous areas, BE, SBs and BSs, were identified as potential habitats (c). There were 2.3% (4/175) sighting records omitted from suitable habitats in Sbs (d). Omission rate was 35.7% (10/28) in BSs (e).

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Important variables

The distances to major river mouths, 10-m isobaths and coast were the three strongest predictors for the presence probabilities of the humpback dolphins in BG. Sum of percent contribution of the three variables was up to 73.4% when averaged over replicate runs (Fig. 4). The jackknife test of variable importance demonstrated that the distances to major river mouths was the most useful information whether used in isolation or being omitted, and regardless of using training gain, test gain or AUC on test data. The three topographic variables, aspect, slope and rugosity (described as surf_ratio), appeared to be little importance for the dolphin distribution (Fig. 4).

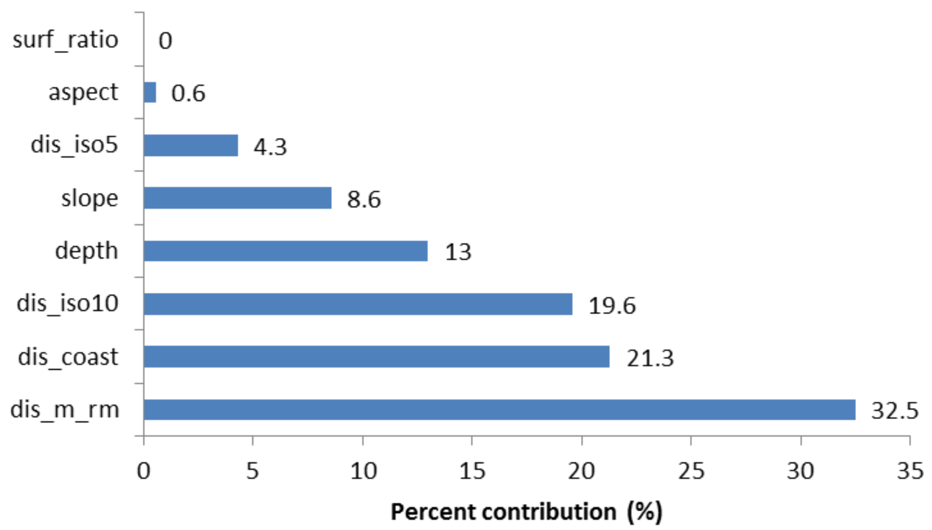

Fig. 4 The percent contributions of the environmental factors to *S. chinensis* habitat suitability. The distances to major river mouths (dis_m_rm), 10-m isobaths (dis_iso10) and coast (dis_coast) were the three strongest predictors. The topographic variables of sea floors, aspect, slope and surf_ratio, displayed little importance for the dolphin presence.

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Discussion

Habitat preference

The variables, distances to major river mouths, 10-m isobaths and coast, were identified as the three strongest predictors for the dolphin presence. Response curves revealed where were the suitable habitats for *Sousa chinensis* : 5-10 km to coast, 5-20 km to10-m isobaths, and <20 km to major river mouths (Fig. 5). It means that the humpback dolphins preferred the major estuaries environment along the north of BG. Other researchers had also discovered the dolphins prefer to inhabiting in estuaries and nearby shallow waters (Chen et al. 2007; Chen et al. 2010; J. Parra et al. 2006; Karczmarski et al. 2000; Liu 2007). Furthermore, our analysis confirmed the first importance of estuaries for the dolphins. The dolphin distribution feature, similar to other cetaceans, mostly results from their foraging for prey (Davis et al. 2002; Moura et al. 2012; Thorne et al. 2012). Studies of the humpback dolphin feeding habits demonstrated that above 20 kinds of demersal and shoaling fish found in productive estuaries were inclusive in their diet (Barros & Cockcroft 1991; Barros et al. 2004; Jefferson & Karczmarski 2001; Pan et al. 2013; Parra 2006; Parra & Jedensjö 2009; Ross et al. 1994; Wang 1965; Wang 1995). That's why the humpback dolphins preferred to estuaries, for feeding on diverse and abundant fish. As a result, the east of BG was excluded from suitable habitats because of no great rivers flowing. We deduced that suitable habitats could be found in the west coast belongs to Vietnam for the same reason. Consistent with this, Smith et al. (Smith et al. 2003) reported several sightings of humpback dolphins in the Nam Trieu River mouth, Vietnam during 1999- 2000.

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Estuaries, however, are not always food sources for the dolphins. River-associated and coastal pollution is the other side of the coin (Jenssen 2003; Sun et al. 2012). Accumulation of organochlorine compounds (DDTs, PCBs and HCB) , polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Hg, Pb et al.) in humpback dolphins was discovered in many distribution areas (Cagnazzi et al. 2013; Hung et al. 2006a; Hung et al. 2006b; Wu et al. 2013) , that challenges conservation of the estuary-type dolphins.

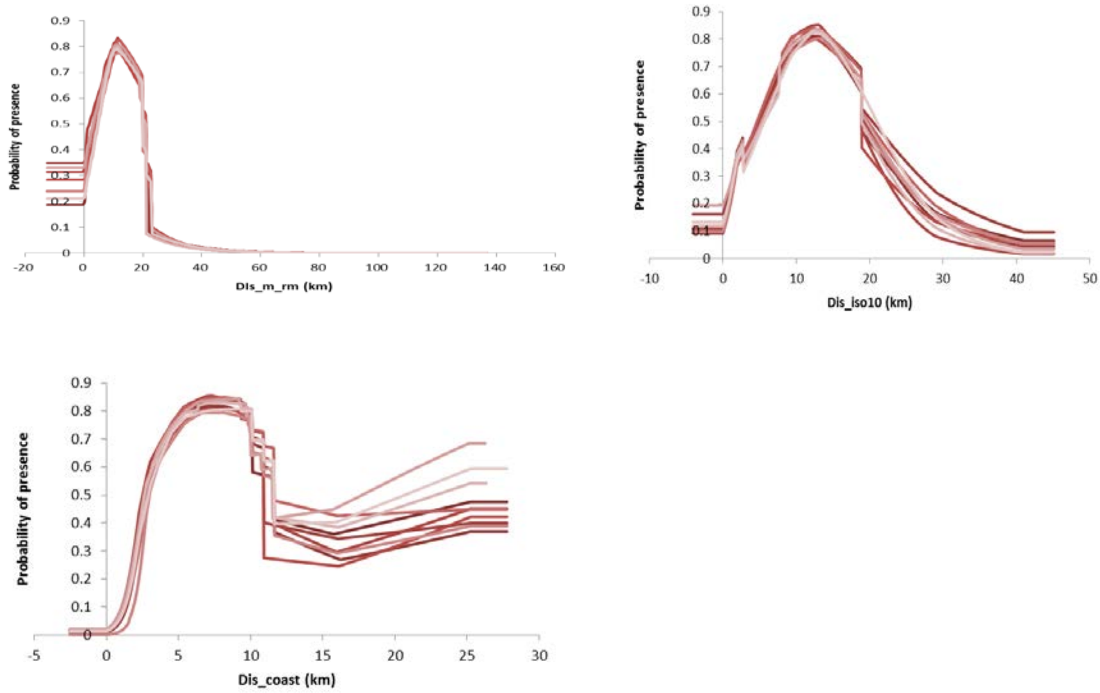

Fig. 5 Reduplicated response curves of the three strongest predictors showing how each influences model prediction. Probability of the dolphin presence reaches their peaks when the dolphins are <20 km to major river mouths, 5-20 km to10-m isobaths and 5-10 km to coast.

Variables describing topological features of the seafloor such as slope, aspect and surf_ratio were not good predictors for the dolphin habitats. This seemed inconsistent with the results of spinner dolphin distribution modeling in Hawaii', which revealed rugosity was one of the most important factors (Thorne et al. 2012). However, this might similarly demonstrate that

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dolphins prefer a flat seafloor for efficient echolocation (Thorne et al. 2012). The relatively weak predicting power might be explained by the fact that BG is fairly flat (Fig. 2-Aspect, Slope and Surf_ratio). Sandy and muddy floors are common in shallow waters of BG (Liu & Yu 1980). Different from the spinner dolphins avoiding enemies in Hawaii', the humpback dolphins could focus on seeking food in BG.

"New" habitats

Areas with high habitat suitability could be thought as potential habitats (Chivers et al. 2013). Among the three identified areas, Sbs and BSs were sources of sighting records, which could also be confirmed by previous publications (Deng & Lian 2004; Pan et al. 2006; Xu et al. 2012a; Yang & Deng 2006). BE, however, was a "new" area identified as a potential habitat of the dolphins. Although no published field data supporting our finding, it was still a result valuable to be examined further. In fact, according to our informal interviews with local fishermen, the dolphins could occasionally be sighted in the Beilunhe river mouth, which maybe a hint of the dolphin presence nearby. Home range of the humpback dolphins was believed up to ~100 km^2 (Hung & Jefferson 2004) or above (Xu et al. 2012b). We deduced that predicted area of BE should be larger than 78 km^2 and extent to Vietnam waters. BE would be an important area connecting Vietnam and China habitats which needed to be surveyed further.

Humpback dolphins displayed varying degrees of fidelity to inshore habitats, "resident" and "transient" included (Karczmarski 1999; Parra et al. 2006; Xu et al. 2012c). For the dolphins in BG, although residence pattern was still little known by far, some individuals may use multiple habitats throughout the year (by field observation). As a result, every distribution patch is important for conservation.

Similar to other highly mobile or migratory marine species, MPA networks might be more efficient than isolated MPAs (Evans 2008; Hoyt 2012). It is also the case with the humpback dolphins. Based on our finding for the "new" habitat, we recommended a regional MPA network of *Sousa chinensis* in BG. BE should be put more attention. We also suggested a cooperative survey with Vietnam in BE and its adjacent waters.

Using Google Earth DEM and Landsat images to predict the distribution of marine species

SDMs have been widely applied to many terrestrial species (Franklin 2009; Robinson et al. 2011). However, their application for marine species remains relatively scarce (Reiss et al. 2011; Robinson et al. 2011). One of reasons for this was lacking of available environmental data. Our study provided an example of applying open data sources to generating environmental layers. The data obtained from Google Earth DEM were overlapped with the sea maps of BG in China, particularly in the 0, 5, and 10 m isobaths. The Landsat images outlined the coast and river mouths, which could be real-time and more accurate than the sea maps. We believed that this type of open data could be beneficial to SDM applying to marine species.

Conclusions

In summary, the present study used presence-only sighting data from local areas together with the environmental layers extracted from Google Earth DEM and satellite images to perform maximum entropy modeling of the potential distribution of Indo-Pacific humpback

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dolphins in BG of China. Our outputs had excellent discrimination for the dolphin habitat suitability. Our results predicted a “new” potential habitat BE apart from known Sbs and BSs, which was regarded as an important area connecting China and Vietnam dolphin stocks.

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