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

Mei Chen[1,2], Yuqin Song[1], and Dagong Qin[2]

[1] Department of Environmental Management, College of Environmental Sciences and Engineering, Peking University, Beijing, P. R. CHINA

[2] Center for Nature and Society, School of Life Sciences, Peking University, Beijing, P. R. CHINA

Corresponding Author:

Mei Chen

No.5 Yiheyuan Road, Haidian District, Beijing 100871, P.R.China

Email address: meichen_pku@hotmail.com

Abstract

Mapping key habitats of marine mega-vertebrates with high mobility is crucial for establishing Marine Protected Area (MPA) networks. Due to difficulties in achieving sound data in the field, Species Distribution Modeling (SDM) provide an efficient alternative. 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. We used a maximum entropy (Maxent) modeling approach to predict potential habitats for the dolphins in the Beibu Gulf of China. Models was based on eight independent oceanographic parameters derived from Google Earth Digital Elevation Model (DEM) and Landsat images, and presence-only data from boat-based surveys between 2003 and 2013. Three variables, distance from major estuaries, from coast and from 10-m isobaths, were the strongest predictors, consistent with previous studies. Apart from known areas, a new area, Beilunhe Estuary (BE) close to the boundary of China and Vietnam was predicted. Based on our findings, we proposed a regional MPA network for humpback dolphins in the Beibu Gulf of China.

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 efficient alternative by projecting over larger spatial areas (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 predictively modeling of distributions of several 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)[1]. In Chinese waters, the dolphin historically distributed 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 locales, including Xiamen, western Taiwan, Pearl River Estuary, Zhanjiang, and the Beibu Gulf (Wang & Han 2007). Most of them are situated in the marine areas that are identified to have the highest human impact (Halpern et al. 2008). Hung et al. suggested that the population in China should be listed in the IUCN Red List of Threatened Species because it inhabits the area with the fastest economic growth (Huang et al. 2012). Among the five stocks, little is known about the southwest population in the beibu Gulf. Apart from some fragmented records and local surveys (Chen et al. 2016; Deng & Lian 2004; Pan et al. 2006; Smith et al. 2003; Yang & Deng 2006), there is no systematic

[1] IUCN 2013, www.iucnredlist.org

surveys in the whole area that encompasses both China and Vietnam. Meanwhile, coastal zone in the Beibu Gulf of China has been undergoing increasing development since 2008. The dolphins are needed to be protected via MPAs from human impact during coastal development (Evans 2008).

Aim 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 Beibu Gulf of China using Maxent modeling approach. In addition, important environmental predictors that contribute to dolphin key habitats were examined and their relationships to dolphin occurrence were 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. We conducted boat-based survey approach. When we surveying, trained observers looked for the dolphins with the naked eye. We maintained at least 50-meter distance from the animals unless they swam close to us initiatively, for both observation and following them. There is no touching, feeding, and other improper behaviors with the dolphins. Therefore, approval from animal ethics committees are not required 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 sea floor is basically plain, slowly descending from the coastline to the middle (Liu & Yu 1980). Our analyses were restricted to inshore waters with a boundary of 10-m isobaths because anecdotal information indicating 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), and the Jiuzhoujiang (JZJ) river. The total area is ~5,985 km^2 with a coastline of ~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 ports (Fangchenggang [FCG], Qiznhougang [QZG], Beihaigang [BHG] and Tieshangang [TSG]) are situated along the Guangxi coastal area. BG represents the most western distribution of humpback dolphins in China.

Our survey area, Sanniang Bay and its adjacent waters (SBs) (Fig. 1), is located in the mid-north 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.

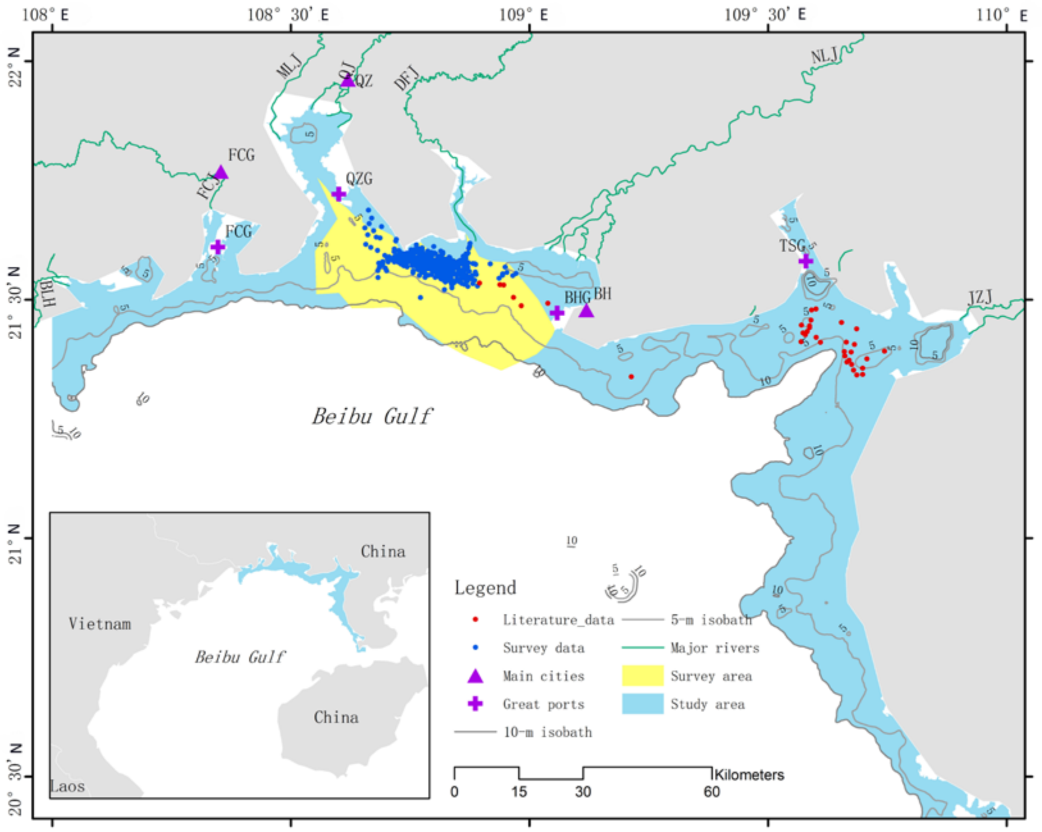

Fig. 1 Sighting records of *S. chinesis* from surveys shown as celestine blue dots in the survey area (Sanniang Bay and its adjacent waters, SBs) in yellow color, data shown as red dots from literatures (Wang 2006; Xu et al. 2012b). Study area in blue color represents inshore waters of the Beibu Gulf of China with a boundary of 10-m isobaths.

Sighting data and bias elimination

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

Sampling biasˋ as a general problem during Maxent modeling (Phillips et al. 2009; Yackulic et al. 2013)ˋ 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-km^2 environmental grid, we random kept only one record. At last, 204 records were used for predictive modeling in our study area (Table 1).

Table 1 Sighting numbers of *S. chinensis* 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 and its relationship with estuaries are the most important parameters that influence the habitat selection of humpback dolphins in Chinese waters (Chen et al. 2007; Chen et al. 2010; Jefferson & Hung 2004; Jefferson & Karczmarski 2001; Ross et al. 1994). We developed eleven variables to describe the oceanographic characteristics of the dolphin habitats: water depth (depth), distance from 0-, 5-, and 10-m isobaths (dis_iso0, dis_iso5 and dis_iso10), distance from land (islands included) (dis_land), coast (mainland-only) (dis_coast), estuaries (dis_estu), and major estuaries (as described in “Study area”) (dis_m_estu), and three parameters indicative of sea floor topography (slope, aspect, and rugosity). Rugosity, which describes ruggedness of sea floor, 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 Inc. USA, 2013), at a 300-meter resolution. Isobaths were generated from the base depth layer. Slope, aspect, and rugosity variables were also based on the depth layer, and were calculated using ArcGIS extension, DEM Surface Tools v.2.1.375, and a four-cell method[2]. The coastline, islands and estuary layers were extracted from Landsat images in 2005–2007[3]. Distance variables were calculated using the Euclidean distance toolkit of the spatial analyst extension in ArcGIS 10.1. All variables were continuous, and resolved to 1 km × 1 km grids.

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

[2] Jenness Ent. USA, 2013; available at: http://www.jennessent.com/arcgis/surface_area.htm
[3] USGS USA, 2010; available at: http://landsat.usgs.gov

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_estu, slope, and surf_ratio.

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

	Aspect	Depth	Dis_ coast	Dis_ estu	Dis_ iso0	Dis_ iso10	Dis_ iso5	Dis_ land	Dis_ m_estu	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_estu				–	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_estu									–	0.012	-0.0038
Slope										–	-0.66
Surf_ratio											-

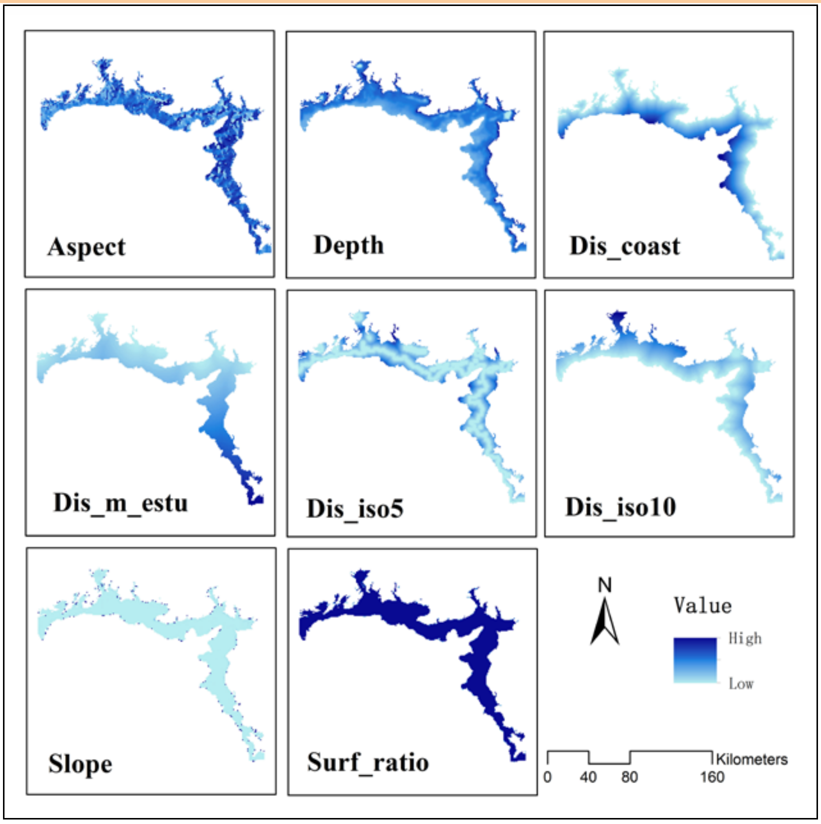

Fig. 2 Environmental layers for modeling. Eight independent variables , aspect, depth, dis_m_estu, dis_coast, dis_iso5, dis_iso10, slope and surf_ratio, were included.

Maxent modeling

Maxent[4] 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 oceanographic 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 granted for suitability of predictive habitats (Phillips & Dudik 2008). A threshold-independent

[4] version 3.3.3k, available at: http://www.cs.princeton.edu/~schapire/maxent/

measurement, Area Under the Curve (AUC) value of Receiver Operating Characteristic (ROC) curve, was adopted to evaluate the discriminatory ability of the model using both the training and test datasets (Liu et al. 2005). 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 encompassing potential habitats and non-habitats was generated. 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 patches were erased, continuous patches were granted for potential habitats and patch area were calculated. Mappings were performed in ArcMap 10.1 (ESRI, USA).

Results

Model evaluation

The average AUC values, including training sets (173 or 174 records) and test sets (19 or 20 records) from 10 reduplications, were more than 0.9 (Table 3), suggesting 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 , predicting distribution of *S. chinensis*.

Samples	**Number of records**	**AUC values (Avg.±S.D.)**
Training	173/174	0.947±0.001
Test	19/20	0.92±0.02
	ESS	**MSS**
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^{-09}	9.5×10^{-10}

Potential habitats

The BG model produced a patchy distribution output along the northern coastline of BG, the median logistic probability output from 5.9×10^{-9} to 0.85 (Fig. 3-a). 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 a binary map based on the MSS threshold as suitable habitat outputs (Fig. 3-b). 14% area were identified as suitable habitats (Table 3). Three large patches were defined as dolphin potential habitats, Sbs (~ 478.3km^2), Beihai Shatian waters (BSs, ~189.5km^2) and Beilunhe Estuary (BE, ~74.0km^2) (Fig. 3-c).

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

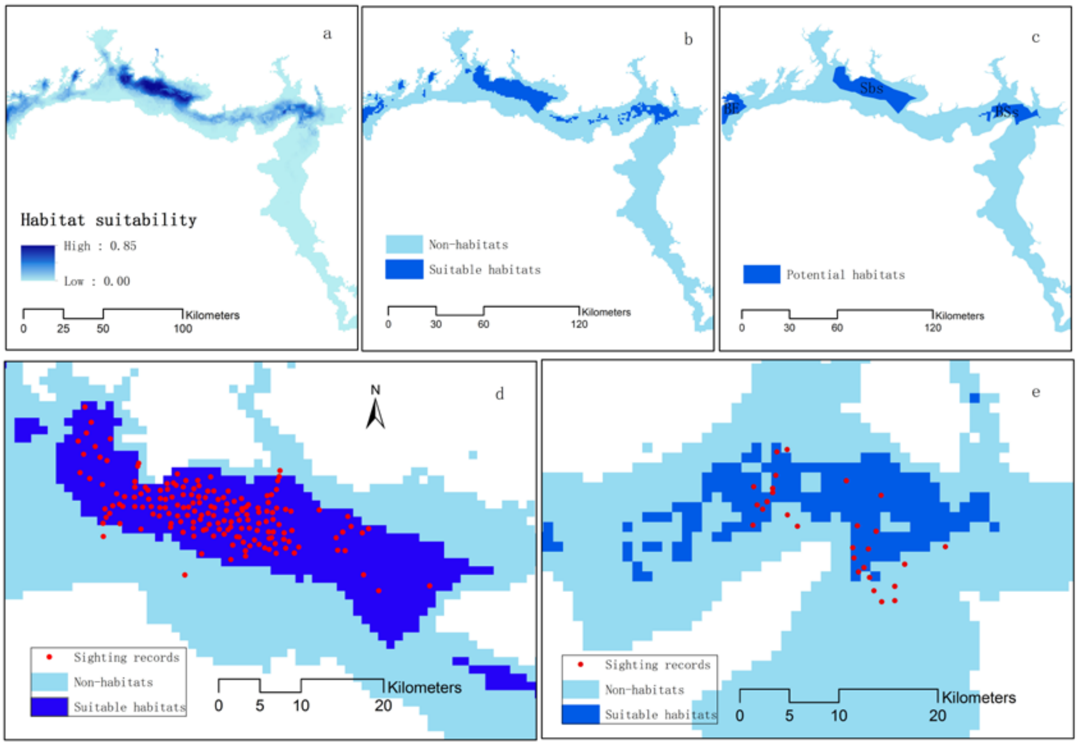

Fig. 3 Predicted distribution (a), suitable habitats (b) ,potential habitats (c) of *Sousa chinensis* in BG; omission error of sighting data in suitable habitats of Sbs (d) and in BSs (e). The median of habitat suitability ranged from 5.9 ×10^{-9} to 0.85 (a). Suitable habitats by the MSS threshold mainly distributed in northern part of BG in China as the binary map shown (b). Three large 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).

Important predictors

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

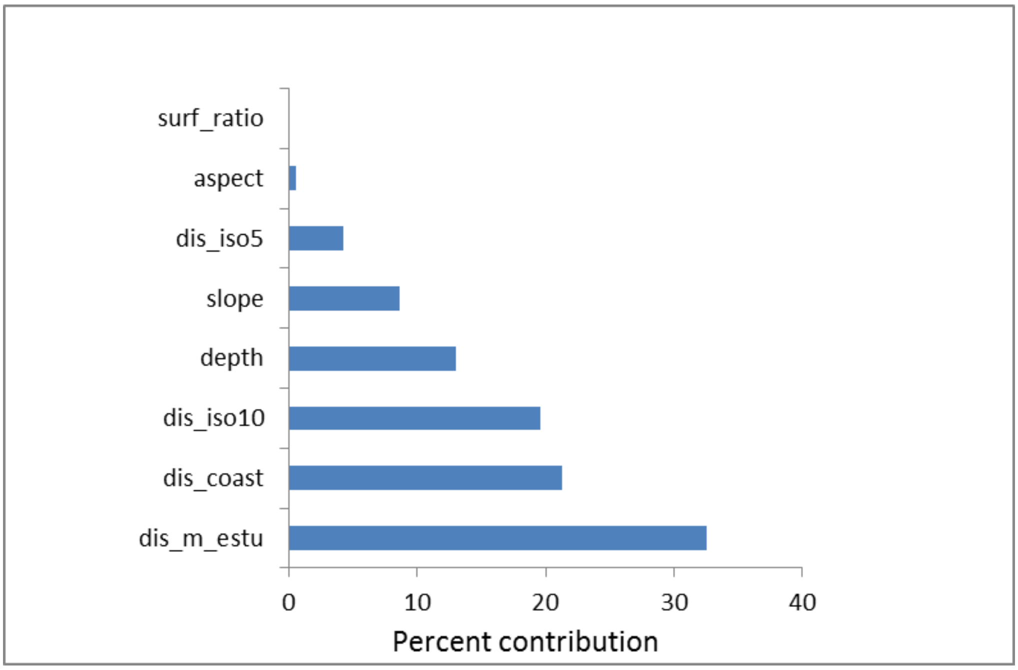

Fig. 4 The percent contributions of the environmental factors to *S. chinensis* habitat suitability. The distances from major estuaries (dis_m_estu), from 10-m isobaths (dis_iso10) and from coast (dis_coast) were the three strongest predictors.

Discussion

Habitat preference to estuaries

Distance from major estuaries, from 10-m isobaths and from coast were identified as the three strongest predictors, which defined suitable habitats for the dolphins. Response curves revealed spatial space of the habitats : 5-10 km from coast, 5-20 km from 10-m isobaths, and <20 km from major estuaries (Fig. 5). It means that the humpback dolphins preferred estuaries in inshore waters along the north of BG which was consistent with previous studies on habitat preferences of humpback dolphins (Chen et al. 2007; Chen et al. 2010; Jefferson & Hung 2004; Jefferson & Karczmarski 2001; Karczmarski et al. 2000; Parra 2006; Ross et al. 1994). Moreover, our analysis confirmed further the importance of estuaries for the dolphins. This distribution feature, similar to other small cetaceans, mostly reflected the species hunting their prey (Moura et al. 2012; Thorne et al. 2012). Research demonstrated that humpback dolphins have a broad-spectrum diet, and that most prey were demersal and shoaling fish found in productive estuaries of South Africa, Australia, and China, including Hong Kong, Xiamen, and BG (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). As a result, the east of BG was excluded because of no great rivers flowing. We deduced that suitable habitats could be found in the west coast of 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 between 1999 and 2000.

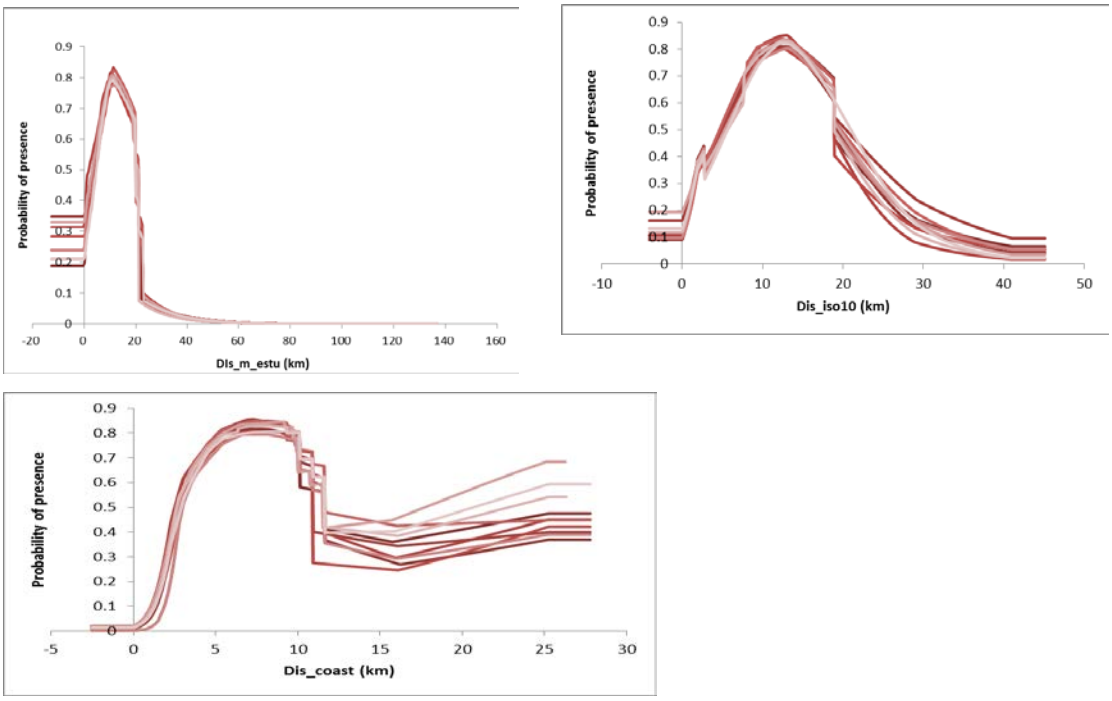

Fig. 5 Reduplicated response curves of the three strongest predictors, , from 10-m isobaths and from coast, showing how each influences model prediction. Probability of the dolphin presence reaches their peaks when the dolphins are <20 km from major estuaries, 5-20 km from 10-m isobaths and 5-10 km from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

Variables describing topological features of the sea floor such as slope, aspect, and rugosity were not good predictors of the dolphin habitat. This seemed inconsistent with the results of spinner dolphin distribution modeling in Hawaii', which revealed rugosity as one of the most important factors (Thorne et al. 2012). However, this might similarly demonstrate that dolphins prefer a flat sea floor 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 examination for conservation

Areas with high suitability could be thought as potential habitats (Chivers et al. 2013). Among the three 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 link between 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 and 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 on "new" habitats, we recommended a regional MPA network of *Sousa chinensis* in BG. And BE should be put more attention as the link conservation from China and Vietnam. 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 confirmed the sea maps of BG of China, particularly in the 0, 5, and 10 m isobaths. The Landsat images outlined the coast and river mouths, which were even 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 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 link between China and Vietnam populations. We suggested a regional MPA network including the three large potential habitats.

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