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RESEARCH ARTICLE

Long-term habitat loss in a lightly-disturbed population of the Indo-Pacific humpback dolphin, *Sousa chinensis*

Haiping Wu[1,2†] | **Yuhou Xu**[1,2†] | **Chongwei Peng**[1,2] | **Yongyan Liao**[2] | **Xianyan Wang**[3] | **Thomas A. Jefferson**[4] | **Hu Huang**[1] | **Shiang-Lin Huang**[5]

[1] Guangxi Key Laboratory of Beibu Gulf Marine Biodiversity Conservation, Guangxi, China

[2] Department of Marine Science, Qinzhou University, Guangxi, China

[3] Laboratory of Marine Biology and Ecology, Third Institute of Oceanography, Xiamen, China

[4] Clymene Enterprises, Lakeside, CA, USA

[5] College of Science, Shantou University, Shantou, China

Correspondence
Shiang-Lin Huang, Marine Biology Institute, College of Science, Shantou University, 243, Daxue Road, Shantou, Guangdong, 515063, China
Email: shianglinhuang@gmail.com

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Abstract

1. Coastal and estuarine waters are important ecosystems with high primary and secondary productivity, but they are prone to the impacts of habitat loss caused by anthropogenic activities. For species exclusively inhabiting coastal and estuarine waters, such as the Indo-Pacific humpback dolphin, *Sousa chinensis*, irreversible habitat loss can have dramatic implications for population viability.
2. A Landsat image database was used to determine the extent of coastal changes along the northern Beibu Gulf, where a large humpback dolphin population is found. The results were compared with the standardized sighting gradient (SPUF) determined from a questionnaire survey of fishermen and likely core habitats identified by application of a global digital elevation model.
3. Both SPUF and likely core habitat results indicated a continuous distribution of the humpback dolphin along the northern Beibu Gulf. Landsat images revealed that 129.6 km^2 of coastal waters were permanently lost in the past 40 years, 60 km^2 within the likely core habitats. Although this may be considered small, the impact of such habitat loss could be substantial in some local habitats.
4. The humpback dolphin population in the northern Beibu Gulf should be regarded as one management unit, with two or more social subunits. Immediate systematic surveys are needed to fill information gaps on true distribution range and habitat-use patterns.
5. Habitat protection actions for dolphins in the northern Beibu Gulf should include both core and linking habitats, including enacting protected areas in core habitats, mitigating anthropogenic impacts in likely habitats, restoring both coastal waters and surrounding landscape quality, effective treatment of industrial sewage discharge, and comprehensive environmental impact assessments for the planning of coastal development projects.

KEYWORDS
distribution, habitat loss, information gap, Landsat, likely habitats, local ecological knowledge, *Sousa chinensis*

1 | INTRODUCTION

Coastal and estuarine waters are important ecozones that connect aquatic and terrestrial ecosystems (Barendregt, Whigham, Meire, Baldwin, & Van Damme, 2006; McLusky & Elliot, 2004; Ray, 2005). High primary and secondary productivity and biodiversity in this environment facilitate reproduction and growth of numerous aquatic organisms (Barbier et al., 2011; Ramos, Amorim, Elliott, Cabral, & Bordalo, 2012; Ray, 2005), which further nourishes neighbouring ecosystems (Deegan, 1993). These coastal and estuarine ecosystems, however, are also some of the most intensely

†Both authors contributed equally.

degraded ecosystems in the world (Barbier et al., 2011; França et al., 2012; Jickells, Andrews, & Parkes, 2016; Lotze et al., 2006; MacKinnon, Verkuil, & Murray, 2012). This has diminished the long-term survival prospects of many aquatic organisms (Chen, Huang, & Han, 2014; Worm et al., 2006). For species exclusively inhabiting coastal and estuarine waters, this habitat-quality deterioration and ecosystem degradation can have major implications for their long-term population viability.

The Indo-Pacific humpback dolphin, *Sousa chinensis*, is one of the species that is most vulnerable to the degradation and deterioration of coastal and estuarine waters (Huang, Chang, & Karczmarski, 2014; Huang & Karczmarski, 2015; Jefferson & Karczmarski, 2001; Jutapruet et al., 2015; Ross et al., 2010). Unlike most other marine species, the humpback dolphin exclusively uses coastal and estuarine waters (Jefferson & Karczmarski, 2001; Jefferson & Rosenbaum, 2014; Jutapruet et al., 2015) for virtually all life functions (Würsig, Parsons, Piwetz, & Porter, 2016). Human-induced changes in habitat structure and status in some coastal waters have shifted the distribution patterns, habitat use and social structure of humpback dolphins (Dungan, Hung, Wang, & White, 2012; Huang & Karczmarski, 2015; Karczmarski et al., 2017; Wang et al., 2015; Wang, Wu, Zhu, & Huang, 2017). In countries where coastal and estuarine waters have been massively altered to accommodate land reclamation or port facilities along with rapid urbanization and industrialization in the past decades, such as in China (Chen et al., 2014; Huang & Karczmarski, 2015; MacKinnon et al., 2012), the baseline shift can be substantial.

In Chinese waters, distribution and ranging patterns of humpback dolphins have been reported at several discontinuous sites (Chen et al., 2011, 2016; Hung & Jefferson, 2004; Wang, Wu, Chang et al., 2016; Wang, Yang et al., 2016; Würsig et al., 2016; Xu et al., 2015) and it is believed that several discrete populations inhabit the Chinese coastline. Between these sites, confirmed reports of humpback dolphin sightings or occurrences are rare or none. Current information cannot distinguish whether these are less important habitats that the dolphins seldom visit, or if there are some other likely habitats which represent information gaps due to insufficient survey effort (as in Li et al., 2016). In Chinese waters, many of the humpback dolphin habitats have been damaged or destroyed to accommodate artificial landscapes such as land reclamation, embankments or harbours, often without implementation of adequate mitigation and compensation measures (Chen et al., 2014; Huang & Karczmarski, 2015; Karczmarski et al., 2017; Rao, Lin, Kong, Jin, & Peng, 2014; Wang et al., 2017), while the likely impact of these anthropogenic activities on humpback dolphin habitat status is often not fully addressed in current environmental impact assessment programmes. The actual risk to population viability due to habitat degradation and deterioration can easily be underestimated (Huang et al., 2014), especially in some of the larger 'populations'.

One of the challenges to measure the likely impact of habitat degradation and deterioration on humpback dolphin viability may come from insufficient spatial coverage that current survey efforts provide. Many of the field surveys are primarily restricted to specific 'hot-areas' where the humpback dolphins are frequently sighted (as in Chen et al., 2011, 2016; Xu et al., 2015), but leave other potential habitat areas un-investigated. Current reports on the extent of occurrence of 'home-range' of the humpback dolphin, may cover only a part of the distribution range of the population (Hung & Jefferson, 2004; Jutapruet et al., 2015; Wang, Wu, Chang et al., 2016). Cross-matching of the photo-ID catalogues between different studies can help to answer the question of inter-site movements (Jutapruet et al., 2015; Wang, Wu, Chang et al., 2016); however, this has rarely been done and usually requires long-term survey effort to accumulate sufficient data to minimize the chance of incorrect conclusions. In many developing countries, such as China, the implementation of field surveys has fallen behind environmental development activities (Huang & Karczmarski, 2015; Karczmarski et al., 2017; Wang, Yang, Hung, & Jefferson, 2007), which may fail to recognize proper baselines.

Application of questionnaire surveys and long-term satellite-based remote-sensing data may help to fill these information gaps over a broad spatial scale. Information from questionnaire surveys has proved valuable in revealing the occurrence and distribution of animals over a broad geographic range (Logan, Gerber, Karpanty, Justin, & Rabenahy, 2015; Turvey et al., 2010; Wang, Yang et al., 2016; Wu, Wang, Ding, Miao, & Zhu, 2014), and to facilitate conservation-action planning and protected-area design (Sánchez-Carnero, Rodríguez-Pérez, Couñago, Barzik, & Freire, 2016; Turvey et al., 2013). The legacy of Landsat missions (http://landsat.usgs.gov/about_mission_history.php) provides satellite-borne monitoring of environmental characteristics on a fine spatial (30–60 m) and spectral resolution over a mesoscopic region. By contrasting current satellite data with earlier satellite images, Landsat imagery studies can map the locations and sizes of habitat change and loss in humpback dolphin habitats over the past four decades (Chander, Markham, & Helde, 2009; Huang & Karczmarski, 2015; Karczmarski et al., 2017; Wang et al., 2017).

In the northern Beibu Gulf, occurrence of the humpback dolphins has been systematically investigated at two neighbouring locations, the Hepu Dugong Reserve (HDR) and Dafengjiang River Estuary (DRE) habitats (Chen, Zheng, Yang, Xu, & Zhou, 2009; Chen et al., 2016; Wu et al., 2017) and interpreted as possible evidence of two social communities (Chen et al., 2016). Outside these two habitats, opportunistic sightings of the humpback dolphin were reported at Red River Estuary in Vietnamese waters based on two cetacean surveys (Smith et al., 2003). Wide information gaps occur between the investigated habitats owing to the lack of field surveys, even opportunistic ones. Preliminary analyses have revealed significant habitat change in the coastal and estuarine waters in the northern Beibu Gulf (Huang & Karczmarski, 2015). Baselines relevant to the distribution of humpback dolphins, however, are still incomplete in this region. In this study, distribution gradients and likely habitats of humpback dolphins in the northern Beibu Gulf were described, based on results of a questionnaire survey and by applying current knowledge of the humpback dolphin habitat preference to a global digital elevation (DEM) model. Based on a four-decades-long Landsat database, the extent of habitat loss in the coastal waters in the northern Beibu Gulf was measured. The urgent need to incorporate more active measures to restore habitat quality and population connectivity, and to identify the likely habitats that should be preserved with highest priority were addressed.

2 | METHODS

2.1 | Study site, questionnaire surveys and data analyses

The study area encompassed the coast of northern Beibu Gulf in Guanxi Province, China (from 108.051°E to 109.704°E), which was further divided into 12 sectors from A to L (Figure 1). primarily based on the locations of fishing villages. Questionnaire surveys were conducted in the 14 fishing villages in December 2013. The interviewees were exclusively local fishermen with experience of fishing in past decades. Local guides helped facilitate communication between questionnaire teams and interviewees. Photos of humpback dolphins were used to help the interviewees to recognize the species correctly.

In the questionnaire form the first and last (or the age of interviewee if the fisherman was still fishing) years of fishing ($Tf_{s,i}$ and $Tl_{s,i}$, s: sector, i: the ith interviewee), the sector(s) where the interviewee sighted humpback dolphins (s_i) and the earliest and latest ($Ye_{s,i}$, $Yl_{s,i}$) years they sighted the animals were recorded. Local ecological knowledge on the humpback dolphin (L) was measured by the percentage of interviewees that have experience encountering humpback dolphins in the field during their fishing career:

$$L_s = \frac{Ie_s}{I_0 s} \tag{1}$$

where Ie_s and I_0s are the number of interviewees who sighted humpback dolphins in the field and total number of questionnaires received in the sector s.

For each interviewee (i) his/her relative sighting history matrix (H) was prepared by

$$H_{s,i} = \left[h_{s,i}\left(Ye_{s,ii}\right), \ldots, h_{s,i}\left(Yl_{s,i}\right)\right], h_{s,i}(t) = 1 \tag{2}$$

where s is the sector in which the interviewee encountered humpback dolphins. If dolphins were encountered at more than one sector, the calculation was applied to all sectors equally. Then the probabilities of sighting per fisherman per year (SPUF) in decade t was calculated by

$$SPUF_{s,t} = \frac{\sum_{t}^{t+9} h_{s,i}(t)}{\sum_{s=A}^{L} \sum_{t}^{t+9} h_{s,i}(t)}, \quad (t = 1960, \ 1970, \ 1980, \ 1990, \ 2000 \text{ and } 2010) \tag{3}$$

which indicates the tendency of the humpback dolphin to occur at sector s in decade t.

2.2 | Satellite imagery and habitat loss measurements

Landsat images of the study site, path 124 and 125 row 045, in the early 1970s, 1990s, 2000s and 2014 were downloaded from the United States Geological Survey (USGS) website (http://glovis.usgs.gov/). The images from the early 1980s were not used as the image quality did not meet the standard for analysis: cloud coverage lower than 20% for the entire image or 0% cloud coverage over the study area. Landsat 7 data after 2003 were not used, because of the scan line corrector failure problem (http://landsat.usgs.gov/products_slcoffbackground.php).

All downloaded Landsat scenes were processed into false-colour images by ArcMap 9.3 (ESRI, 2008), using the RGB231 (R: red, G: green, B: blue) band composite for the Landsat 1–4 Multispectral Scanner (MSS) data, the RGB742 band composite for the Landsat 5 Thematic Mapper (TM) data and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data, or the RGB753 band composite for the Landsat 8 Operational Land Imager (OLI) data (Chander et al., 2009; Merem & Twumasi, 2008). These band composite images allowed clear contrasts between aquatic and terrestrial objects and between urban and vegetated landscapes (Chen et al., 2014; Karczmarski et al., 2017; Kerr & Ostrovsky, 2003; Wang et al., 2017). The earliest Landsat image over the study site dated back to 1973 (Landsat 1 MSS) and hence was referenced as the baseline image for identifying habitat loss.

The following processes were used to identify the change or loss of coastal waters. Landsat images from later than 1973 were first superimposed on the baseline image (Landsat 1 1973). Then the sites

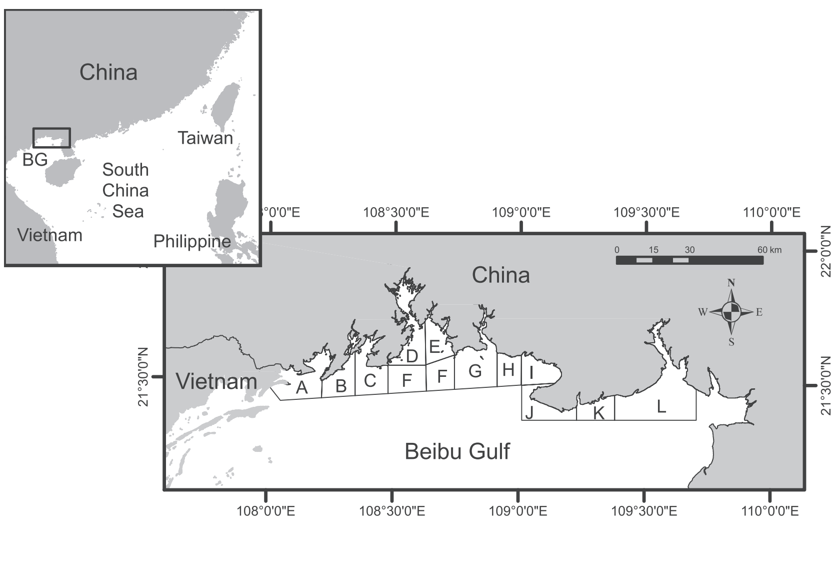

FIGURE 1 Study site and sectors delineation in the northern Beibu Gulf, Guanxi Province, China

where original coastal waters were replaced or enclosed by artificial structures, including long-banks, harbours or land reclamations, were highlighted and outlined by polygons, which were identified as losses of coastal waters.

To identify the likely habitat of the humpback dolphin in the northern Beibu Gulf, three isobath contours (−1 m, −5 m and −15 m) were applied to the global digital elevation model (DEM) overlaying the study area from ETOPO 1 Global Relief Model, National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration (NOAA) (Amante & Eakins, 2009; https://www.ngdc.noaa.gov/mgg/global/global.html). Waters between −1 m and −5 m isobaths were assigned as likely core habitats (Hc), and between −1 m and −15 m were assigned as likely habitat-maximum (Hm), based on current knowledge of the distribution patterns and habitat preferences of the humpback dolphin (Chen et al., 2016; Jefferson & Karczmarski, 2001; Jutapruet et al., 2015; Wang, Wu, Turvey, Rosso, & Zhu, 2016; Wu et al., 2017). Then, areas for which habitat loss occurred inside Hc_s were extracted and calculated as the primary habitat loss at sector s, Hl_s. Thus, the extent of habitat loss at sector s (E_s) was measured by:

$$E_s = \frac{Hl_s}{Hc_s} \times 100\% \tag{4}$$

Finally, the significance of correlations of $SPUF_s$ with Hc_s, Hl_s and E_s were tested using general linear models.

3 | RESULTS

3.1 | Local ecological knowledge and SPUF

During the questionnaire-survey trip, 300 questionnaires were completed from 14 fishing villages in the 12 sectors (Table 1). No questionnaires were received from sectors D and F. Average age of the interviewees was 54.8 (SD±15.9) years old and 81.67% of interviewees were older than 40 years (Table 1). The average length of fishing career of the interviewees was 37 (SD±16.7) years (Table 1).

In total, 82.67% (SD±3.19%) of interviewees had experienced sighting humpback dolphins during their fishing careers (Figure 2a). Humpback dolphins can be found in all sectors. Most of the sightings of humpback dolphin dated back to the 1950s, except sector C, and the earliest sighting was recorded in the early 1930s in sector J. Through 2013, humpback dolphins were still sighted in most sectors (Figure 2b). From the 1960s to the 2010s, the SPUF of dolphin in different sectors did not change significantly (Kolmogorov–Smirnov tests ≤ 0.3, P > 0.664), although temporal decreases in sectors E, I, J and L, and increases in sectors A, B, C, G, H and K were observed (Figure 2 c). Sector G always had the highest SPUF, ranging from 20.55% in the 1960s to 26.84% in the early 2010s and averaging 22.65% (±SD

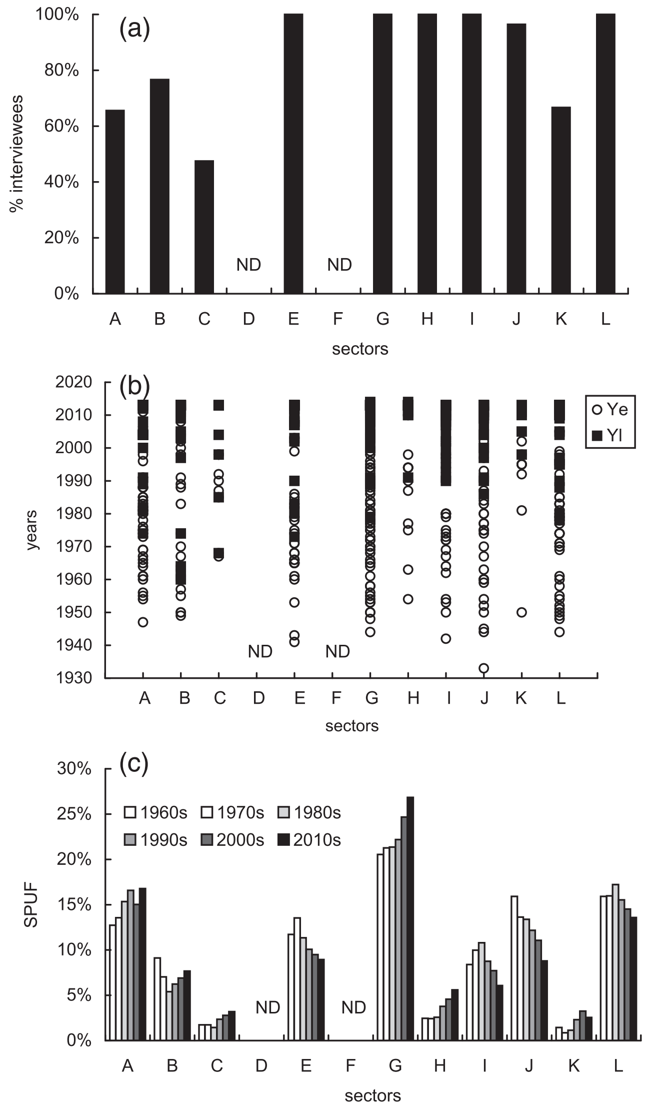

FIGURE 2 Local ecological knowledge presented by (a) percentage of fishermen with experience of encountering humpback dolphins, (b) histories of sightings per fisherman (ye: The earliest sighting, Yl: The latest sighting), and (c) standardized sighting rate (SPUF, % probabilities of sighting per fisherman per year), of humpback dolphins at different sectors across the northern Beibu Gulf from 1960s to 2010s. ND: No data

TABLE 1 Questionnaire results from different sectors (s) across the northern Beibu Gulf. No effective questionnaires were collected from sectors D and F. n_s: Number of effective questionnaires collected at sector s. $\overline{A_s}$: Average age of interviewees at sector s. $\overline{T_s}$: Average length of fishing of interviewees at sector s. $\%_{A \geq 40}$: % interviewees who are older than 40 years old

Sector	A	B	C	D	E	F	G	H	I	J	K	L
n_s	61	30	40	0	23	0	34	23	25	28	6	30
$\overline{A_s}$	62.6	60.8	41.1	ND	56.2	ND	54.8	43.7	58.7	58.5	47.5	53.2
$\overline{T_s}$	46.4	41.3	29.1	ND	36.8	ND	37.1	22.4	36.2	40.8	22.8	35.7
$\%_{A \geq 40}$	95.1%	80.0%	45.0%	ND	91.3%	ND	85.3%	69.6%	96.0%	89.3%	83.3%	83.3%

ND: no data.

2.27%). In sectors A, E, J and L, SPUF were generally higher than 10%. SPUF in sectors C, H and K, on the other hand, was numerically low, with less than 5% probability of sighting per fisherman per year in all decades (Figure 2c).

3.2 | Extent of habitat loss

Landsat images of the study site from 1973 (Figure 3a), 1991 (Figure 3b), 2001 (Figure 3c) and 2014 (Figure 3d) revealed substantial alteration of coastal waters for land reclamation or harbour developments in sectors C, E and L. In the study area, 129.6 km^2 of natural coastal waters were permanently lost between 1973 and 2014, with most of the change happening after 2001 (Figure 3e).

Figure 4a shows Hc and Hm (likely core habitats and likely habitat maximum) in the northern Beibu Gulf. The major losses of Hc occurred inside sectors C (12.58 km^2) and E (27.78 km^2) (Figure 4b), while habitat loss in sectors B, D and L was also substantial, 6.14, 6.92 and 4.43 km^2, respectively (Figure 4b). In terms of Es, habitat loss in sectors B, C and E could have been the most influential, accounting for 13.84%, 18.30% and 21.86% of undisturbed Hc (Figure 4c). A moderate correlation was observed between SPUF and Hc_s (Pearson r = 0.565) although this correlation appears to be not statistically significant (t = 1.937, P = 0.088, Figure 4d). Correlations between SPUF and Hl_s (Pearson r = −0.133, t = −0.151, P = 0.715) or E_s (Pearson r = −0.0294, t = 0.869, P = 0.411) were not significant.

4 | DISCUSSION

The accuracy and effectiveness of questionnaire results, or local ecological knowledge (LEK), in identifying animal distribution, habitat-use and population trends can be sometimes uncertain (Ruddle & Davis, 2013). Factors such as insufficient sample size, differentiated social-economical status and educational backgrounds of responders, and misidentification of the target species can increase the uncertainty, or even bias, in the application of LEK (Ruddle & Davis, 2013; Shepperson, Murray, Cook, Whiteley, & Kaiser, 2014; Turvey et al., 2014). Also, memory of experience of sightings may fade with time, thus increasing the uncertainties when examining population trends by questionnaire results. For this study, the greatest uncertainty may arise from directly connecting temporal changes in SPUF with the true demographic trend of the dolphins, although this technique has been shown to be useful for some rapidly disappearing species (Turvey, Risley, Barrett, Hao, & Wang, 2012; Turvey et al., 2010; Wu et al., 2014). In the northern Beibu Gulf, the humpback dolphin is still frequently sighted in most sectors. Meanwhile, distribution gradients of the dolphins, indicated by SPUF, did not change significantly over past decades. These results might lead to a conclusion that the demographic status of the humpback dolphin in northern Beibu Gulf is stable, but this might be too optimistic, considering the increasing habitat loss (in this study) and anthropogenic activities in the northern Beibu Gulf in the past decades (Chen et al., 2016; Wu et al., 2017). Instead, these results perhaps indicate the shortcomings of using questionnaire results to assess demographic status of humpback dolphin in northern Beibu Gulf. As most reclamation activities have happened since 2001, the adverse impacts of habitat loss on population status may be too recent and therefore difficult to detect with current techniques (Huang, Hao, Mei, Turvey, & Wang, 2012).

The correlations between humpback dolphin distribution (SPUFs) and habitat loss (Hls and Es) were not significant. This result, however, should not be literally interpreted to mean that the distribution of the humpback dolphin in the northern Beibu Gulf does not correlate with the habitat change events, or that habitat loss from land reclamation, embankment and harbour construction does not affect the distribution of humpback dolphins. On the contrary, this result may simply indicate that the LEK database collected does not provide sufficient resolution to disclose temporal changes in the population baseline, especially if this change comes from recent anthropogenic events.

The moderate correlation between SPUFs and Hcs, on the other hand, suggests the effectiveness of LEK in identifying distribution patterns and likely habitats over a mesoscopic range. Along the coast of the northern Beibu Gulf, occurrence of the humpback dolphin has been formerly reported from the waters east of sector L (Hepu Dugong Reserve) and the centre of sector G (the Sanniang Bay–Dafenjiang River Estuary waters) (Chen et al., 2016, 2009; Wu et al., 2017). A recent review of humpback dolphin status in this region claims that there are two somewhat distinct social communities inhabiting these two areas, separated by a possible gap in distribution (Chen et al., 2016). Both the SPUF gradients and likely core habitat identification, however, indicate that distribution of the humpback dolphin may be continuous along the entire northern Beibu Gulf. There is no apparent oceanographic or geographic barrier partitioning the habitat structure along the coast of the northern Beibu Gulf. As such, regarding the humpback dolphins of the northern Beibu Gulf as one population with two or more social sub-units (Chen et al., 2016) therefore may be most appropriate. From this perspective, habitat protection actions and population conservation management need to be revised to address the entire northern Beibu Gulf coast, rather than just specific 'hot-spots'.

Throughout the northern Beibu Gulf, higher sighting probabilities (SPUF) of humpback dolphins were indicated at sectors A, G and L. Across the sectors F–I, recent field surveys reveal significantly higher sighting probabilities of humpback dolphins at the centre of sector G (the Dafengjiang River Estuary), which implies a core habitat with important biological and ecological functions for the animals (Wu et al., 2017). Based on the correlation between SPUF results and field survey observations, it was suspected that waters at sectors A and L may be additional important habitats for humpback dolphins.

If sectors A, G and L are important habitats with biological and social functions for the dolphins, waters between these three sectors may represent travelling corridors between neighbouring habitats. Research on humpback dolphins in other habitats has revealed seasonal changes in distribution and habitat use (Chen et al., 2008; Chen, Hung, Qiu, Jia, & Jefferson, 2010; Wang, Wu, Turvey, et al., 2016), and movements between different habitats (Jutapruet et al., 2015; Wang, Wu, Chang et al., 2016). For instance, in Hong Kong, some waters near the airport are used mainly for travelling between core areas, which in turn are primary feeding and socializing areas (Würsig et al., 2016). Similar patterns may also occur in the northern Bebiu Gulf. In such cases humpback dolphins may use the core habitats routinely through

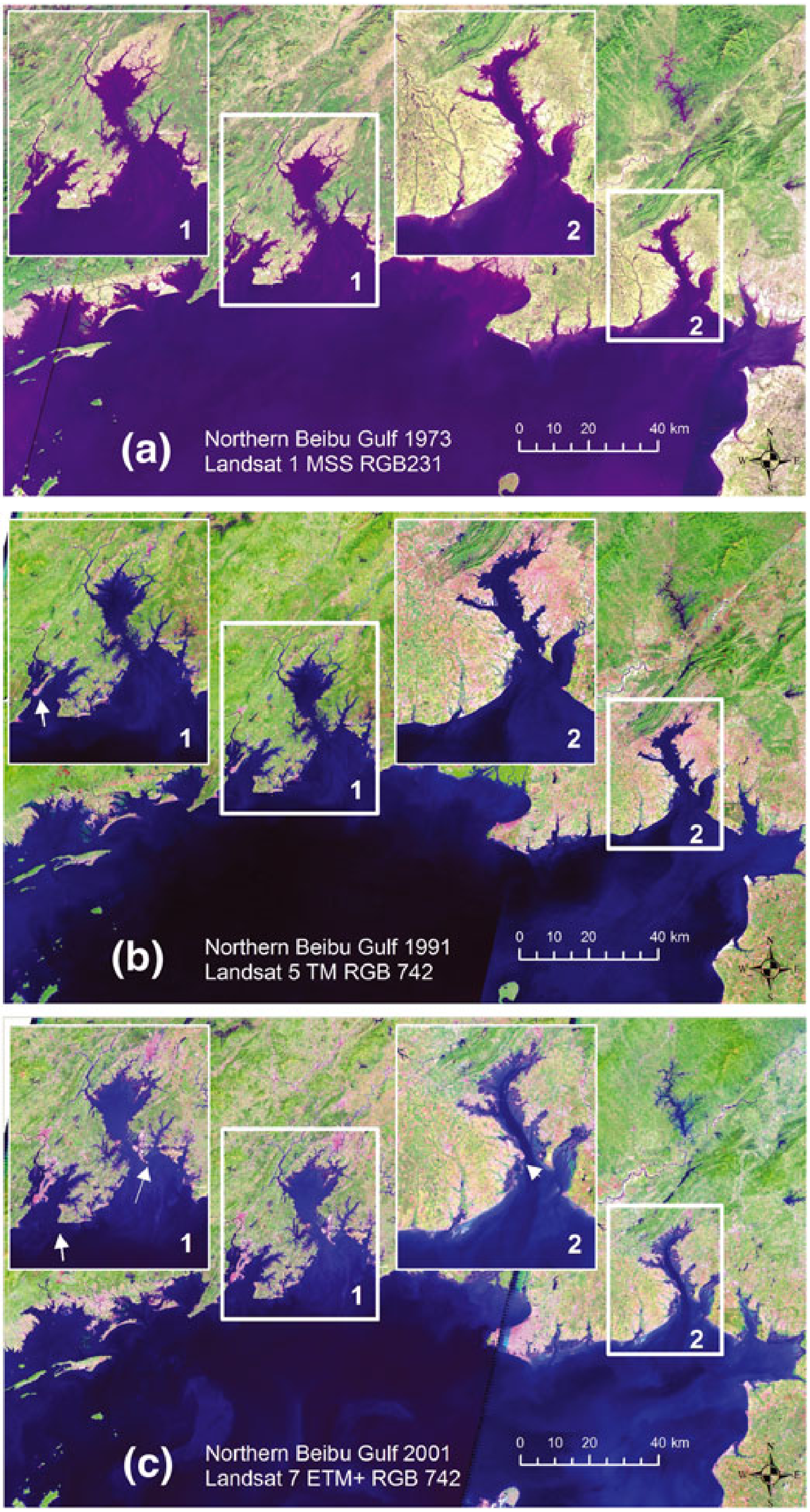

FIGURE 3 Chronological series of Landsat images from the study site in (a) 1973, (b) 1991, (c) 2001 and (d) 2014. Areas where substantial coastal waters were altered into artificial landscapes are highlighted in box 1 and 2 and indicated by arrows and summarized in (e)

the linking coastal waters. If so, the greatly extended seaward land-reclamations or embankments in sectors C, E and L may block the movements of humpback dolphins between core habitats and hence have negative impacts on humpback dolphin population structure. Recent sighting histories of humpback dolphins in sector E imply a dramatic decline of humpback dolphin occurrence since the construction of land reclamation and a seaward-extended bank after 2012 (Xianyan Wang and Haiping Wu, unpublished data). Movement of humpback dolphins across sectors C–G may have been re-routed through sector F, which is supported by current field survey data (Wu et al., 2017). It is of

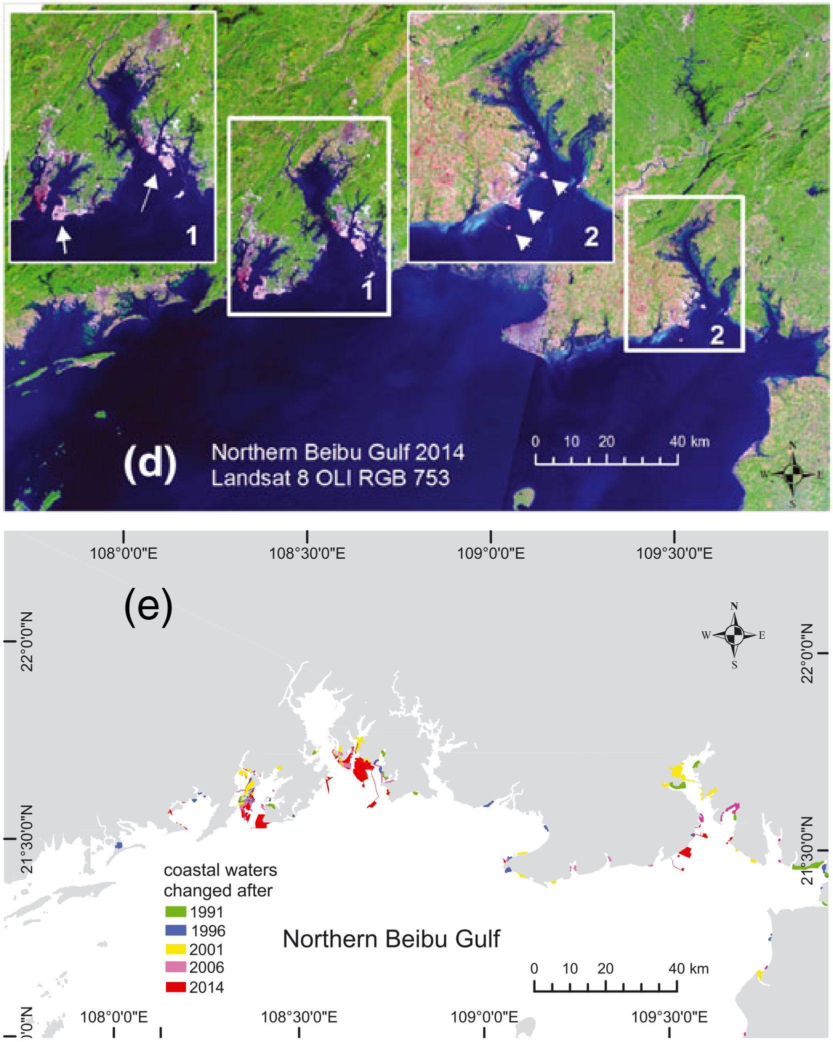

FIGURE 3 (continued)

concern that similar changes may have also happened to the dolphin activities–habitat function in sector L, where three major artificial structures have been constructed. If as a result the movement route of humpback dolphins was displaced to offshore waters, humpback dolphin sightings may be substantially reduced and hence the importance of the affected waters could be overlooked. In the worst-case scenario, social interactions of the humpback dolphin between sectors G and L will decrease (Chen et al., 2016), as has already happened in other locations like Hong Kong waters (Dungan et al., 2012), Xiamen Bay (Wang et al., 2015, 2017) and the western Taiwanese coast (Chang, 2011; Karczmarski et al., 2017). If this condition persists, humpback dolphins in the northern Beibu Gulf may become more prone to population fragmentation that would increase local population vulnerability (Huang et al., 2014).

The challenges to implement effective conservation actions for the humpback dolphins and their habitat in the northern Beibu Gulf can be summarized as follows: (i) the lack of baselines on distribution, density, and habitat characteristics; (ii) the improper interpretation of survey results; (iii) the inappropriate zoning plan of coastal use and protection; and (iv) the insufficient scope and extent of conservation actions. Until now, systematic surveys on the humpback dolphin in the northern Beibu Gulf have been implemented in sectors F–I and the waters east of sector L (the Hepu Dugong Reserve). Surveys on the other waters are at best sporadic (sectors I–L) or non-existent (sectors A–D). Although questionnaire surveys as done in this study can be used to reveal the distribution pattern of humpback dolphin qualitatively (Wang, Yang et al., 2016; Wu et al., 2014), this technique does not have sufficient precision and resolution to disclose the habitat use patterns of the humpback dolphin on a fine scale. Systematic surveys along the coastal waters of the northern Beibu Gulf are needed to fill this information gap.

Conceptually, establishing a protected area in the important habitat of the humpback dolphin can be the most efficient way to effect protection for both the humpback dolphin and the ecosystem (Hoyt, 2011; Hyrenbach, Forney, & Dayton, 2000; Ross et al., 2010). In practice, effectiveness of habitat protection and management depends in part on the extent of the protected areas (Silva et al., 2012; Zhao, Wang, Turvey, Taylor, & Akamatsu, 2013). Along the northern Beibu Gulf there is no active protected area or reserve that protects humpback dolphin habitats, though one reserve, the Hepu Dugong Reserve,

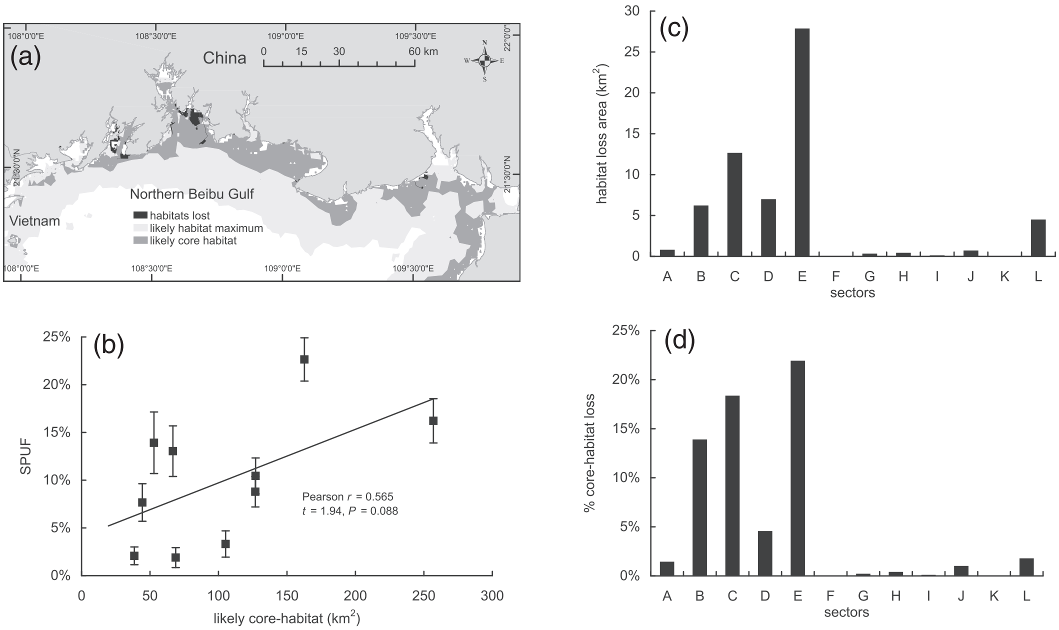

FIGURE 4 Areas of likely habitat maximum, likely core habitat and habitat loss to land reclamation or harbor construction (a), correlation between core habitat area and SPUF (% probabilities of sighting per fisherman per year) (b), and sector-wise measurement of habitat loss in area (c) and percentage to core habitat area (d)

has been established in the waters east of sector L. Thus, the most urgent recommendation should be to design and establish suitable protected areas over the core habitats of humpback dolphins. A protected area in the DRE is currently in planning and will be launched in 2017, based on the recently identified distribution pattern (Wu et al., 2017), in order to mitigate immediate risks from unsustainable electric pulse beam trawl fisheries and sand mining. As the western part of sector L is currently unprotected, extending the current Hepu Dugong Reserve westward to enclose H_{c_L} may be needed. Precautionary measures to mitigate apparent anthropogenic impacts, such as banning electric pulse and benthic trawlers and minimizing projects turning native coastline into artificial structures, are also needed in sectors A, E, I, and J, owing to their relatively high SPUF.

In this study, the impact of habitat loss was measured by the percentage of area lost to reclamations, embankments and harbours. Their real impact, however, could be much higher than the estimates presented. The construction associated with reclamations, embankments and harbours concurrently alters oceanographic features in neighbouring waters, including water current patterns, sediment-erosion dynamics and benthic structure, as has been observed around the reclamation sites in western Taiwan (Karczmarski et al., 2017). These changes, along with the significant reduction in local productivity and biodiversity (Fraschetti et al., 2011; Lin, Xue, & Lu, 2007; Wu, Fu, Lu, & Chen, 2005) and shifting faunal composition (Fraschetti et al., 2011; Gedan, Silliman, & Bertness, 2009; Ryu et al., 2014), can lead to intense habitat deterioration and degradation (Karczmarski et al., 2017; Liu & Mou, 2016; Wang et al., 2017). In the northern Beibu Gulf, the Landsat data implied a change in water flow characteristics around the greatly extended seaward land-reclamations or embankments in sectors C, E and L, and also intense environmental degradation at the land–sea interface from sectors H to L. Numerically decreasing SPUF in sectors E, I, J and L, as well as the apparently fragmented social structure between sectors G and L (Chen et al., 2016) imply that changes in habitat quality and function that alter the regional preferences of the dolphins to these sectors may already have been occurring and could become worse in the future.

Thus, the scope of the habitat protection actions in northern Beibu Gulf should not be restricted to passively maintaining the current population status by mitigating apparent anthropogenic impacts. More proactively, the habitat protection actions need to further consider restoration measures in both coastal waters and surrounding landscape quality (Barbier et al., 2008; Fahrig, 2001; Stoms et al., 2005; Tallis, Ferdaña, & Gray, 2008; Wang et al., 2017). Measures to repair and restore local ecosystem function and hence habitat quality are urgently needed in sectors C, E and L, including settlement of created/restored wetlands (Meng, Hu, & Wang, 2014; Zhao, Bai et al., 2016), native mangroves (Tamin, Zakaria, Hashim, & Yin, 2011), salt marshes (Chang, Veeneklaas, Bakker, Daniels, & Esselink, 2016; Kelly & Condeso, 2017) and (where possible) artificial reefs along cemented coasts by coastal/estuarine zone management (Weinstein & Litvin, 2016; Zhao, Wang, Cai, & Liu, 2016). As many of the reclamation sites in sectors C, E and L accommodate large industrial factories, associated industrial sewage discharges require effective treatment and monitoring systems. For the planning of coastal development projects, environmental impact assessments need to include measuring likely habitat loss, and assessing possible changes in neighbouring oceanographic features due to construction, influences on biodiversity and ecosystem productivity in peripheral environments, and corresponding ecological and habitat restoration and repair measures.

The pattern of distribution and habitat use observed may not be unique to the northern Beibu Gulf habitat, but may also occur in many other places (as in Jutapruet et al., 2015; Wang et al., 2015). Recent studies on habitat characteristics of the humpback dolphin indicate a significant preference for specific environmental features (Dungan et al., 2012; Jefferson & Karczmarski, 2001; Jutapruet et al., 2015; Wang, Wu, Turvey et al., 2016; Wu et al., 2017; Würsig et al., 2016). Extrapolating those results to a wider spatial extent implies a series of major habitats connected by waters used as movement corridors. Integrity of all these waters, including their various functions and connectivity, needs to be one of the essential elements to ensure long-term viability of humpback dolphin populations. Thus, the scale of habitat protection for humpback dolphins must incorporate the protection of both major and linking habitats, rather than just 'valuable' distribution hot-spots.

With escalating anthropogenic activities occurring in the coastal waters in Chinese and south-east Asian waters (Chen et al., 2014; Huang & Karczmarski, 2015; MacKinnon et al., 2012), it is a concern that integrity of those coastal waters and their capability to accommodate a population long-term is being substantially jeopardized. Preliminary analyses based on chronological Landsat images estimate at least 1200 km^2 of humpback dolphin habitat may have been permanently lost to land reclamation, coastal modification or port construction in the waters of the northern Beibu Gulf (this study), western Taiwan (Karczmarski et al., 2017), Xiamen (Wang et al., 2017), and the Pearl River Delta (Huang & Karczmarski, 2015). The extent and range of habitat loss may be even more drastic than has been presented in this study when other uninvestigated areas are factored in. Though some of the habitats appear to still accommodate a large number of humpback dolphins currently (Chen et al., 2010, 2016; Xu et al., 2015), the habitats that remain may have already suffered reduced carrying capacity, and movements of dolphins across habitats may already have been reduced (Wang et al., 2017). Regional population viability of humpback dolphins may be lower than currently believed (Huang et al., 2014; Jefferson & Smith, 2016). We therefore emphasize the urgent need to incorporate more active measures to protect and (where possible) restore habitat quality and connectivity in those highly impaired habitats. We also highlight the need for the identification and prioritization of the areas where habitat integrity has not yet been substantially impacted, which should be protected immediately. Techniques, such as those presented in this study, can help in the process of reaching these goals with minimal expense.

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