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Focusing on rapid urbanization areas can control the rapid loss of migratory water bird habitats in China

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Over 240 migratory water bird species depend on China's 18,000 km coastline as a vital stopover area. However, the rapid loss of natural wetlands has threatened this seasonal water bird migration over the last few decades. In the present study, to improve our understanding of the pattern and amount of habitat loss in key stopover areas (KSAs) and the spatial covariance between habitat loss and economic development, we conducted a spatially explicit evaluation of coastal habitat loss in KSAs and explored its relationship with social and economic dynamics along the China coast by integrating high-spatial resolution satellite imagery with an updated coastal water bird investigation data set. The remote sensing survey detected a habitat loss percentage of 19.4% in the KSAs during 2000 and 2010. Aquaculture, urbanization, and land reclamation were responsible for the most severe disturbances to coastal habitats. These results demonstrate that the losses of wetland habitats in the KSAs in Chinese coastal areas are more severe than those in other coastal areas even though more protective measures have been implemented in these areas. Risk-based analysis showed that the risk of habitat loss was greatest in undeveloped regions with rich natural wetland and large populations, thereby demonstrating the critical importance of shifting the focus of water bird conservation to these regions to ensure the conservation of migratory water birds in the East Asian–Australasian Flyway. These findings disagree with the hypothesis that more habitats are lost when the economy is more developed. Therefore, we suggest that focusing conservation decisions on areas undergoing urbanization might improve the effectiveness of conservation measures given the pressures due to various forms of wetland exploitation.

1. Introduction

Coastal areas contain productive tidal flats, which provide vital habitats for millions of migratory water birds, but the impacts of fishing, industry, tourism, housing, and transportation continue to grow. This increasing pressure has caused losses of water bird habitats worldwide and led to population declines for many species of migratory birds (Studds et al., 2017). This trend is considered difficult to arrest given that 40% of the world's human population lives in coastal regions that cover only 4% of the Earth's surface (Barragán and Andrés, 2015). The consensus among conservationists is that maintaining rare water bird populations requires protecting the key habitat patches in particularly important stopover areas in order to prevent rare

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habitats from undergoing coastal artificialization (Valiela and Fox, 2008). China has 18,000 km of coastline that crosses three climate zones, with the second highest area of tidal mudflats in any country on Earth, as well as abundant estuarine wetlands and mangroves. As crucial parts of the East Asian–Australasian flyway (EAAF), these wetlands are essential stopover areas for over 240 migratory water bird species (Barter, 2002; Bai et al., 2015).

However, from the 1950s to the 2000s, 70.2% of China's natural coastal wetlands were lost due to various processes, including the impacts of meeting economic goals (Wu et al., 2014; Murray et al., 2014). This rapid decline resulted in the widespread loss of water bird habitats, with greater negative effects on the sustainability of their populations compared with hunting, egg collecting, and road mortality (Heinrichs et al., 2016). Habitat losses can occur due to the following three main changes: (1) the available habitat may be reduced because of sea level rises or increasing human water demands (Clausen and Clausen, 2014); (2) water pollution or species invasions may reduce the suitability of wetland habitats for migratory water birds (Robichaud and Rooney, 2017); or (3) the wetlands may become occupied by humans for food production or affected by engineering, which comprise the most direct and major modes responsible for habitat loss (Tilman et al., 2017).

The year 2000 was a milestone for conservation work in China, which began investing heavily in protecting and restoring natural resources. According to a report on China's national ecosystem assessment, six out of seven ecosystem services improved between 2000 and 2010, where habitats for wild species comprised the only ecosystem service that underwent decline (Ouyang et al., 2016). Given these findings, losses of water bird habitats are important and should not be ignored (Yang et al., 2017). Indeed, previous studies have indicated that coastal wetlands were still being lost after 2010 (Murray et al., 2014). Our poor understanding of the relationships between habitat losses and social and economic indicators in key stopover areas (KSAs) hinders the conservation of China's coastal environment. This information would improve our understanding of the main mechanisms responsible for coastal habitat loss in the most important areas for water bird conservation to facilitate the development and implementation of conservation activities at the national scale by the government.

Moderate resolution (500 m > resolution > 30 m) satellite images have been the preferred data source for measuring habitat dynamics and threat factors in many previous studies (Zhang et al., 2011), mainly because they allow the objective tracking of changes across a long coastline (Hu et al., 2017). Identifying the transformation path from wetland to other land use types to meet economic goals in coastal zones can provide the most direct information for representing the effects of human disturbances on water bird habitats. Higher resolution images (resolution < 30 m) can also help to improve the accuracy of land use mapping because they contain more detailed texture information (Mccarthy et al., 2015). In addition to the direct exploitation of water bird habitat patches, factors such as demographic, economic, and organizational factors indirectly drive habitat changes. Therefore, wetland habitat clearance and socioeconomic factors should all be considered in order to understand the causes of water bird habitat losses and the spatial relationship between habitat loss and economic development.

The identification of important threats to water bird habitats involves two main problems: identifying the key habitats for stopovers by migratory water birds within large coastal zones, and clearly understanding the causes of habitat losses along China's coastline to ensure the effective conservation of coastal habitats and maintaining water bird populations along the EAAF. Therefore, based on the KSA data set reported by Zhang et al. (2017), we conducted comparative remote sensing analysis to track the pathways for wetland habitat losses inside and outside the KASs. This data set was generated by integrating IBA and field observation data from 132 coastal zone regions in China in a spatially explicit manner. We then examined the spatial relationships between habitat losses and the possible factors responsible for these losses. In particular, we tested the following hypotheses: (1) the lost area of water bird habitats in KSAs in China is lower than that in other coastal areas because more conservation activities are conducted in the KSAs (e.g., in terms of establishing conservation networks) than outside areas, which are beneficial for the maintenance of coastal wetlands; and (2) the amount of lost water bird habitats is primarily related to increased economic development, which requires land resources, and coastal wetlands have high economic value due to their flat terrain, abundant water resources, and convenience for transportation.

2. Methods

2.1. Satellite data and ecosystem mapping

In this study, the coastal zone considered was a 10 km zone around the 18000-km coastline of China. Ecosystem maps for 2010 were generated from satellite data using pansharp in CBERS 02b HR (panchromatic band resolution of 2.36 m) and TM (multispectral band resolution of 30 m) with an object-based classification method. The partition parameters calculated using the FNEA model (Baatz and Schape, 2000) and interpretation symbol library were established based on a field transect survey. The classification and regression trees method was used to classify the ecosystem. Based on the results for 2010, a map was produced for 2000 using Landsat ETM+ (panchromatic band resolution of 15 m and multispectral band resolution of 30 m) images based on the spectral angle mapper change detection method. Nineteen types of ecosystems were identified comprising seven non-wetland types, seven natural wetlands, and five artificial wetlands (Table 1) with a resolution of 15 m after resampling. The user accuracy of the maps was calculated as >92% based on 2430 ground control points.

2.2. Identification of KSAs

The KSA data employed were the same as those described by Zhang et al. (2017). We briefly summarize the workflow as follows. (1) In order to identify the potential KSAs for migratory water birds, we integrated two sources of site data that

Table 1
Classification of China's coastal ecosystems.

Code	Artificial land	Code	Natural wetland	Code	Artificial wetland
41	Paddy field	311	Mangrove	351	Reservoir
42	Dry land	321	Shrub swamp	352	Pond
51	Settlement	331	Reed swamp	353	Aquaculture
52	Factory land and road	340	Lake	354	Salina
54	Mining site	361	River and Flood plain	392	Sea reclamation
109	Orchard	381	Bare tidal flat		
111	Urban green land	382	Vegetated tidal flat		

covered most of the known water bird surveys published in ornithological and conservation studies (Cao et al., 2008a, 2008b; 2009, 2010; China Coastal Water bird Census Group, 2009, 2011; Conklin et al., 2014; China Coastal Water Bird Census Group, 2011; Jia et al., 2016) for feeding Ramsar site criteria (Ramsar Convention Secretariat, 2010). (2) We determined the boundaries of potential KSAs based on the discrete divisions between habitats used by migratory water birds, which included the largest extent of the water bird habitat area whenever possible according to the wetland distribution and field inspections. (3) We identified the bird conservation gaps based on each conservation regime, i.e., the areas of significant sites for water bird conservation outside the current IBAs and national nature reserves in each province.

2.3. Defining human disturbance and statistical analysis

Human disturbance factors can be identified with land use or ecosystem maps based on comparisons between the start and end time point, which can indicate whether natural wetland patches at time 1 were converted into artificial habitats or human exploitation types at time 2. By combining the different types in this study, we defined seven threat factors related to water bird habitat losses (Table 2).

In addition to the direct transformation of wetland habitats due to their economic utilization, many factors are correlated with wetland losses, such as the increasing demands caused by growth in urbanization, human populations, and the economy. Therefore, in this study, we examined the spatial covariance of habitat loss (km^2) according to economic, population, and climatic factors by selecting a set of variables as indicators for each factor. The gross domestic product in 2000 (GDP2000, 10,000 ¥/km^2) and gross domestic product change from 2000 to 2010 (GDP_CH, 10,000 ¥/km^2) were selected as economic indicators. The population density in 2000 (POP2000, persons/km^2), population change from 2000 to 2010 (POP_CH, persons/km^2), urban population density in 2000 (URPOP2000, persons/km^2), and change in urban population density from 2000 to 2010 (URPOP_CH, persons/km^2) were selected as population indicators. Climate change is expected to have little effect on habitat loss in the short term (10 years), and thus we used the mean annual precipitation (mm) and temperature (°C) from 1956 to 2010 to detect habitat losses along a climatic gradient. These economic and population data were obtained from the Institute of Policy and Management at the Chinese Academy of Sciences. Climate data were produced using Aunsplin 4.3 (Hutchinson, 2004).

Ordinary least squares multiple linear regression was conducted using each KSA as a sample to determine the effects of the independent variables on habitat loss. However, this model could have exhibited bias if there was a significant spatial autocorrelation with habitat loss, so we addressed this potential problem by applying a Lagrange multiplier to determine whether the spatial lag model was suitable for our estimation (Anselin et al., 2006). The performance of the model was tested using Nagelkerke's R^2. We then used a boosted regression tree (BRT) model to examine the contributions of significantly correlated social and economic variables to habitat loss because this model can help to achieve greater accuracy when handling nonlinear relationships. We constructed the BRT model with the R package gbm (Ridgeway, 2013) using the following settings recommended by Elith et al. (2008): family = "poisson," tree complexity = 5, learning rate = 0.005, and bag fraction = 0.6.

3. Results

3.1. Water bird habitat losses in coastal area and KSAs in China

According to the remote sensing survey, the total area of China's coastal zone at the beginning of the 2000s was 101,630 km^2 and 1775 km^2 (14.9%) of natural wetlands were lost from China's coastal regions between 2000 and 2010. High rates (density of habitat loss > 1 km^2/25 km^2) of habitat losses occurred mainly in the following three regions: (1) massive land reclamation and transformation to aquaculture production occurred in the southern part of Bohai Bay in Shandong province (Fig. 1a); (2) the northern region of the Yangtze estuary in Jiangsu province as well as the area between the Yancheng Nature reserve and the estuary flats clearly lacked conservation activities (Fig. 1b); and (3) the region along the coastline of Zhejiang province is important for protecting many gull species (e.g., *Sterna bernsteini*), and together with the eastern islands, it tends to have been ignored by previous conservation networks (Fig. 1c).

We found that the 132 KSAs for rare water birds were distributed in China's coastal region, where 12.2% of the whole coastal zone contained 45.4% of the natural wetlands, whereas natural wetlands only accounted for 10% of the regions outside

Table 2
Types and definition of threat factors related to losses of coastal habitats for water birds.

Threat factor	Abbreviation	Definition
Salina	SL	Natural wetland converted into salt field
Hydrographic engineering	HE	Natural wetland converted into reservoir and pond
Reclamation	RC	Natural wetland converted into land reclamation/land fill
Aquaculture	AQ	Natural wetlands converted into aquaculture feeding pond
Infrastructure construction	IC	Natural wetland converted into road
Urbanization	UB	Natural wetland converted into settlement, port, and factory land
Agricultural cultivation	AC	Natural wetland converted into paddy field and dry land

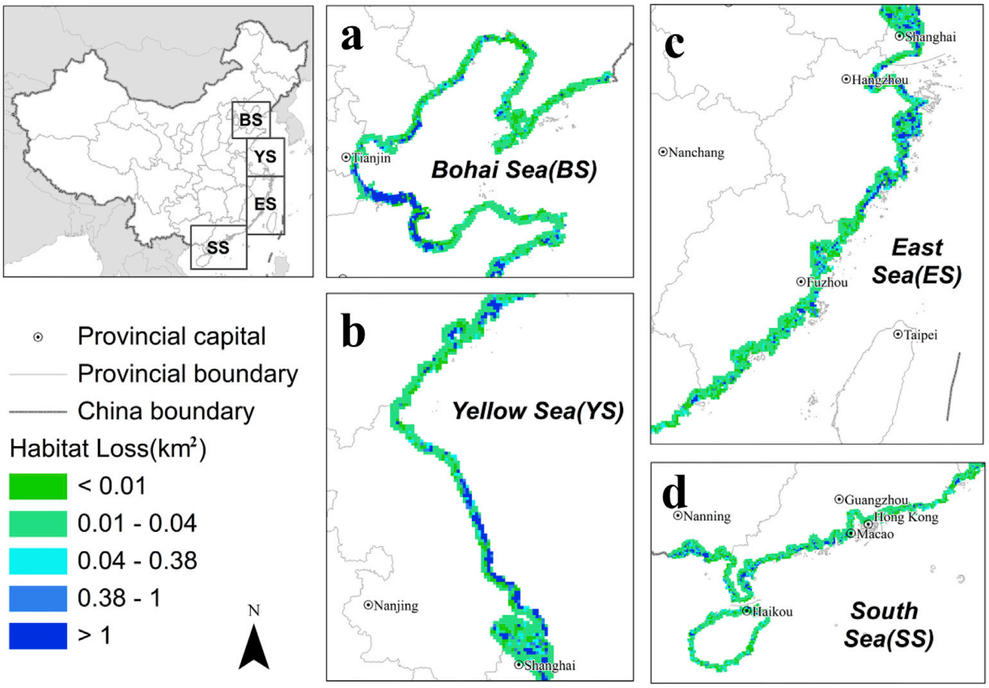

Fig. 1. Coastal habitat decreases in China per 5-km grid cell (km^2) from 2000 to 2010.

the KSAs. The natural wetlands to the north of the Yangtze estuary (around 30° N) included more mudflat habitats than those in the southern areas (71% versus 29%), and they were mainly concentrated in Bohai Bay and the Yangtze estuary (Fig. 2).

In total, 1775 km^2 (14.9%) of natural wetlands were lost from China's coastal regions between 2000 and 2010. The potential water bird habitats outside the KSAs declined by 11.2% and the natural wetlands inside the KSAs declined by >19%. The area of river and flood plains and tidal flats in KSAs decreased by 1171 km^2, whereas the area of habitats including mangroves, shrub swamps, reed swamps, and lakes increased by 124 km^2 (Fig. 3).

Fig. 4 shows the main causes of wetland losses due to human exploitation inside and outside the KSAs. The proportion of land with salt exploitation in KSAs was generally higher than that in other coastal zones. The loss of natural wetlands caused by the construction of hydrographic engineering in rivers and lakes occurred mainly outside KSAs. The proportion of unused land occupied by wetlands was less than 5%, and the development of aquaculture ponds was the major factor related to the loss of natural wetlands both inside and outside KSAs. In the coastal zone outside KSAs, the increased development of aquaculture ponds accounted for 56.4% of the total loss of wetlands, and the proportion was 70.5% within KSAs. The proportion of aquaculture development was highest in mangrove with 77.6% outside KSAs and 85.6% inside KSAs. The proportions of road, urban area construction, and farmland reclamation were lower than those in KSAs, but all of the lakes in KSAs were lost due to agricultural reclamation. Other causes of wetland losses were mainly represented by the shrinkage of natural wetland without direct exploitation by humans. This type of natural wetland loss had the largest impact on bare tidal flats in KSAs, where the proportion was 14.5%, and it was the main causes of losses in coastal shrub swamps outside KSAs.

3.2. Spatial relationships between habitat loss and climatic, social, and economic factors

We determined whether habitat losses differed according to different socio-economic conditions and fundamental climatic settings. Using a spatial lag model, we identified the initial habitat area ($P < 0.01$) and change in urban population

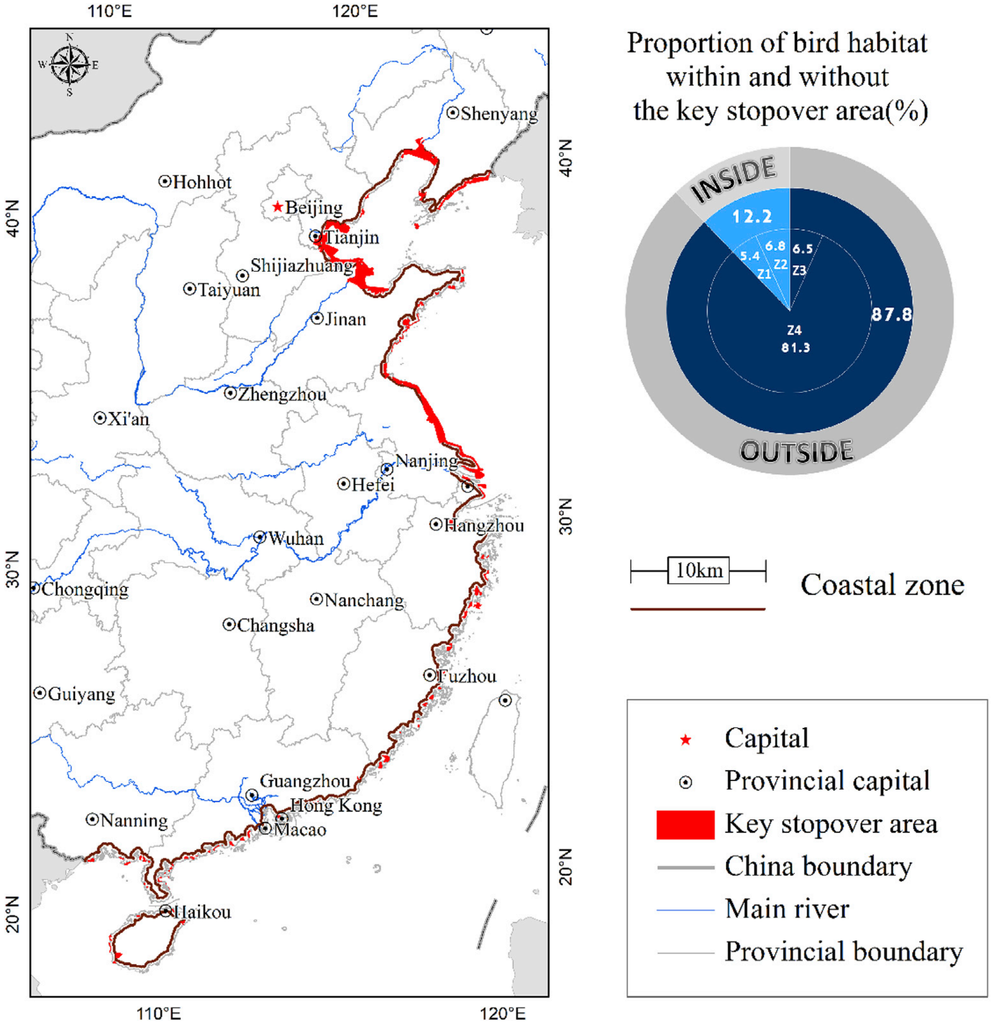

Fig. 2. Distributions and habitat loss in KSAs along China's coastline.

($P < 0.01$) as factors that had positive effects on the degree of habitat loss in KSAs. KSAs with a high rate of change in the urban population were more likely to occur in areas of low urbanization in 2000 ($P < 0.01$) (Table 3).

The contributions of three significant variables that correlated with habitat losses in KSAs were identified by regression tree analysis. As shown in Fig. 5, among the variables considered, the change in the urban population ratio was the key factor that indicated natural wetland losses in KSAs (explained 45.2% of the variance), following by the area of wetland habitats in 2000 (39.4%), and population in 2000 (15.4%) (Fig. 5).

In total, 1775 km^2 (14.9%) of natural wetlands were lost from China's coastal regions between 2000 and 2010. The potential water bird habitats outside the KSAs declined by 11.2% and the natural wetlands inside the KSAs declined by >19%. The area of river and flood plains and tidal flats in KSAs decreased by 1171 km^2, whereas the area of habitats including mangroves, shrub swamps, reed swamps, and lakes increased by 124 km^2 (Fig. 3).

4. Discussion

Increased human disturbance during the last few decades has led to extensive losses of coastal habitats for migratory water birds in China (Murray et al., 2014; Bai et al., 2015). Thus, it is important to examine the spatial trends in coastal KSAs in terms of habitat loss and their relationships with anthropogenic dynamics in order to inform future decisions regarding water bird conservation because efficient conservation networks should obtain the maximum effect with the least conservation resources to ensure the sustainability of coastal migratory bird populations (Margules and Pressey, 2000). However, our results indicated a high degree of overlap between lost habitats and KSAs, and they also suggested that natural wetlands suffered more disturbance than coastal regions as a whole (Fig. 2). Among the various natural wetland types, mangrove

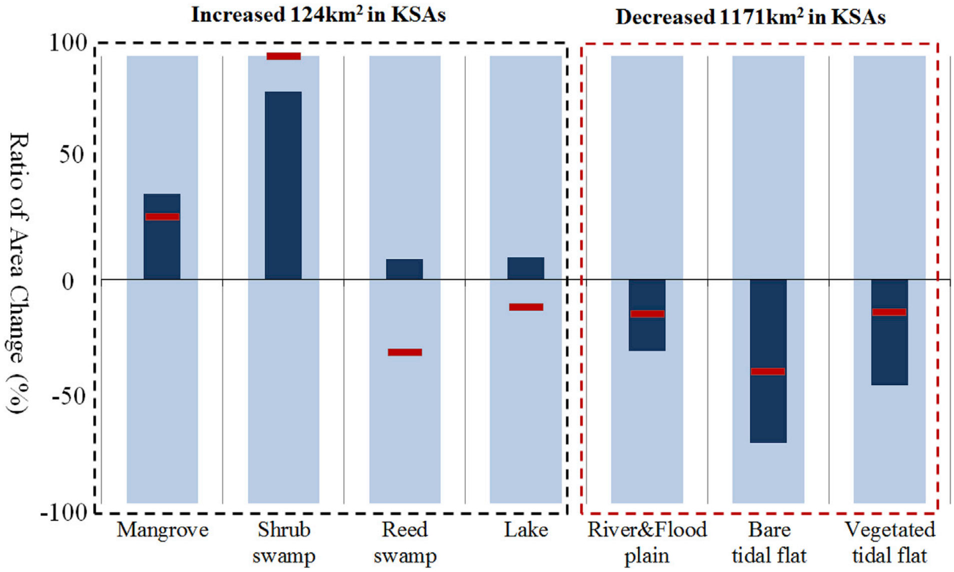

Fig. 3. Dynamic changes in natural wetlands inside and outside KSAs. The dark blue bars represent the net change (%) in each habitat type in KSAs and the red bars indicate changes outside the KSAs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

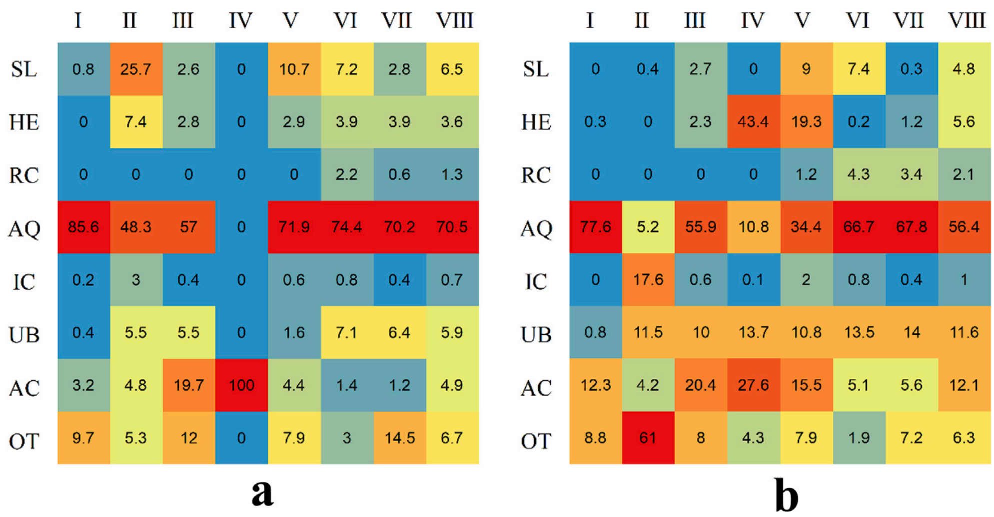

Fig. 4. Effects of human disturbances on various types of natural wetlands: (a) human disturbances inside KSAs and (b) human disturbances outside KSAs. I: mangrove; II: shrub swamp; III: reed swamp; IV: lake; V: river and flood plain; VI: bare tidal flat; VII: vegetated tidal flat; VIII: all wetland habitat. SL: salina; HE: hydrographic engineering; RC: reclamation; AQ: aquaculture; IC: infrastructure construction; UB: urbanization; AC: agricultural cultivation. Figures in heat maps are percentages denoting the effect of each type of human disturbance on different wetlands.

habitats have been restored as a consequence of protection policies, whereas tidal flats have declined severely within KSAs (Fig. 3). Spatially, our analysis identified Bohai Bay and the Yangtze estuary as hotspots for water bird conservation because of the high degree of habitat loss in these regions, and due to their high value for maintaining water bird populations under various sub-flyways of the EAAF (Tessler et al., 2015). These results indicate that the losses of wetlands from KSAs were not less severe than those in other coastal areas since the beginning of China's large-scale ecological protection policy, thereby disagreeing with our first hypothesis. Thus, an interesting question arose concerning the types of exploitative human activities in KSAs that caused the losses of natural wetlands over a broad geographical scale.

To address this question, we employed satellite mapping to identify seven exploitative forms of human disturbances that affected water bird habitats in KSAs, where they differed in terms of their intensities and spatial distributions. The results showed that some of the patterns were similar and different between the KSAs and other coastal areas. Throughout the whole coastal region of China, aquaculture and road construction accounted for the most and least losses of wetland habitats,

Table 3
Significance of spatial relationships between habitat loss and climatic, social, and economic factors. The *P*-values obtained using Moran's I test with two model residuals were less than 0.05, thereby suggesting that their spatially independence using spatial lag models.

Dependent variable	Independent variable	Coefficient	Standard Error	Probability
Habitat loss	CONSTANT	−0.08993	0.08966	0.31586
	GDP2000	−0.00008	0.00005	0.13186
	GDP_CH	0.00001	0.00002	0.44432
	POP2000	0.00011	0.00005	0.04446*
	URPOP2000	0.00044	0.00098	0.65385
	POP_CH	0.00005	0.00008	0.50728
	URPOP_CH	0.00537	0.00169	0.00153**
	HABITAT2000	0.15145	0.03591	0.00002**
	Temperature	0.00255	0.00398	0.52191
	Precipitation	−0.00001	0.00003	0.6822
$r^2 = 0.252$, AIC = −138.15				
Dependent variable	Independent variable	Coefficient	Standard Error	Probability
Urban population change	CONSTANT	19.76474	2.24444	0.00000
	GDP2000	0.0011	0.00312	0.72384
	GDP_CH	0.00173	0.00098	0.07828
	POP2000	−0.00244	0.00292	0.40233
	URPOP2000	−0.34956	0.05089	0.00000**
	POP_CH	−0.0113	0.00436	0.00957**
$r^2 = 0.412$, AIC = 781.14				

*$P < 0.05$, **$P < 0.01$.

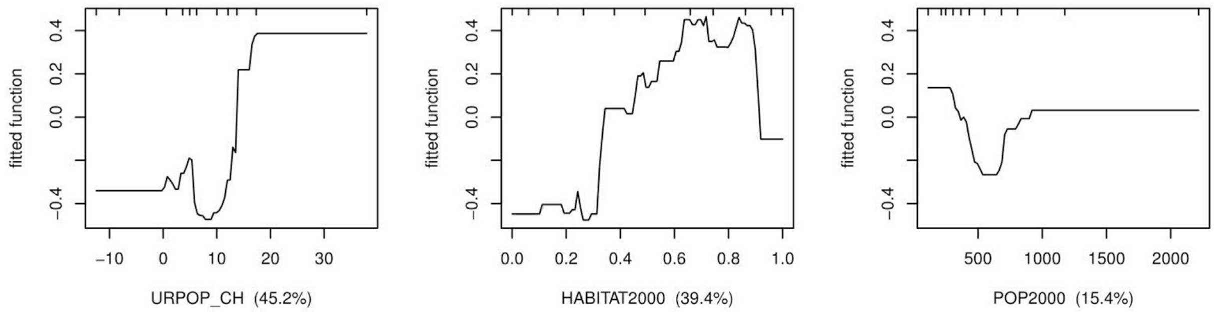

Fig. 5. Contributions of significant variables that affected wetland habitat losses in KSAs.

respectively, and the same results were obtained for coastal natural wetlands inside and outside KSAs. We also found that the proportions of hydrographic engineering, reclamation, road construction, urbanization, and agricultural cultivation were higher in KSAs than those in other coastal areas (Fig. 4a and b). The Chinese government has implemented several conservation policies to protect the natural habitats of coastal water birds, such as establishing nature reserves and zoning internationally and nationally important wetlands (CWA, 2018; Ministry of Ecology and Environment of the People's Republic of China, 2016). According to these conservation policies, activities such as the construction of roads and urban buildings are prohibited in order to prevent the loss of natural wetlands in these areas (SCPRC, 2018). However, due to the increasing demand for and price of aquatic products, aquaculture ponds that do not change the nature of wetlands have been developed in a large number of important natural wetlands. Aquaculture feeding ponds and irrigation ponds are used by many water bird species (Heng et al., 2011; Chen, 2013), but some key species rarely use these areas as habitats because of their low foraging efficiency due to the degradation of the aquatic environment and intensive human activities (Yu et al., 2017). Anti-bird mesh on aquaculture ponds is also a major cause of water bird mortality (Xie, 2019). Urban and infrastructure construction have major impacts by making wetlands unsuitable for migratory water birds due to increased human activity, habitat fragmentation, and road mortality (Benítez-López et al., 2010; Mckinney et al., 2011; Zhang et al., 2015). Building seawalls and other structures associated with land reclamation can completely eradicate intertidal zones, thereby severely damaging important habitats. Based on the severe negative impact of these types of structures on water birds, we suggest that this type of human exploitation should be strictly forbidden in KSAs.

Throughout China, the loss of natural wetlands has been higher in KSAs than other coastal areas. The development of aquaculture in important bird areas is the main cause of habitat loss, especially due to severe disturbances to coastal tidal flats. China has gradually introduced coastal natural wetland restoration projects and coastal breeding function zoning (GOQMG, 2014; DOFHPG, 2018; Yu and Zhang, 2018), but it still lacks a nationwide protection policy and legal support.

Previous studies suggest that the increased exploitation of natural resources is accompanied by rapid economic growth (Meng et al., 2017). Habitat loss in the short term is affected by economic development and human population change, and understanding the relationships involved is important for ensuring more effective conservation. Therefore, we investigated the spatial correlation between economic development and habitat loss in KSAs. However, our results showed that the habitat losses in KSAs were not significantly influenced by any of the economic covariates considered in this study, thereby suggesting that there are no sharp distinctions between the habitat losses in developed and undeveloped areas, or between rapidly developing areas and areas with slower development, which partly disagrees with our second hypothesis (Table 3). These results are different from those obtained in many previous studies (Tian et al., 2016), mainly because they considered the whole coastal zone in China, whereas we focused on KSAs in the research area. We employed this design because China's coastal zone covers a huge area and it is impossible to protect all of the coastal zones used by migratory water birds. Concentrating on KSAs will be more conducive for identifying key problems in important areas. One possible cause of the spatial differences in habitat loss and economic development in KSAs is that well-developed coastal regions have the most advanced industries in China, which are driven by intensive intellectual or financial capital rather than by the cost of land and natural resources (Loiseau et al., 2016).

We also analyzed the contributions of population density and population change to habitat loss. Habitat losses in many regions throughout the world reflect the increasing use of coastal wetlands and land reclamation as a consequence of population growth (Vitense et al., 2016). Our results support this view because we found that coastal habitat losses in China were significantly related to the population density. Population shifts from rural to urban areas in regions with low urbanization were also responsible for habitat losses (Fig. 5). By contrast, the proportion of habitat loss was higher in areas with low urbanization because of reduced transportation costs and the high demand for seafood production associated with the development of the tourist industry because the areas near large cities with high urbanization rates in the coastal zone are close to saturation or a diminishing marginal effect (Ancog and Ruzol, 2015). Thus, we suggest that future investment in conservation should focus on areas with low or medium urbanization because China is still undergoing rapid urbanization, and effective coastal development planning is needed to avoid the overuse of wetland resources at the very beginning of urban development projects.

5. Conclusions

In this study, we found that coastal wetlands with high value in terms of water bird conservation were concentrated in 12.2% of the whole coastal region of China. However, the natural wetlands in these KSAs have experienced more disturbance than other coastal regions. We also detected strong spatial correlations between habitat loss in KSAs and human population density changes, rather than associations with economic variables. These results indicate that rare water bird habitats are more likely to decline in undeveloped (rural regions with low economic gains) but rapidly urbanizing areas because the movement of rural populations to urban areas has increased the demand for building land and seafood production. These findings demonstrate the critical importance of shifting the focus of water bird conservation to these regions in order to facilitate the successful management of coastal wetlands and to protect the rare migratory water birds that depend on them.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00801.

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