



Assessing Changes of Habitat Quality for Shorebirds in Stopover Sites: a Case Study in Yellow River Delta, China

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Abstract

The population of shorebirds in the East Asian–Australasian Flyway (EAAF) has severely declined over the past several decades. One reason for this condition is low survival in stopover sites in the Yellow Sea Ecoregion (YSE) due to habitat degradation. Here, we focused on shorebird habitat quality in the Yellow River Delta (YRD), which is a representative shorebird stopover site in the YSE on the EAAF. We used the InVEST model to assess the past and future shorebird habitat quality changes by considering the effects of anthropogenic threats. The entire duration of the study was 1999–2016, and the modeling was done on 2000 and 2015 data. Our results indicate that the abundance of 11 shorebird species had significant downward trends (70–97% reduction) during 1999–2015. Tidal flats in the nature reserve had higher habitat quality than that in the northwestern (NW) and eastern (E) parts of the YRD because major mariculture occurred in NW and E. The mean habitat qualities in NW and E decreased by 27 and 31% during 2000–2015, respectively. The optimal habitat in the YRD declined from 1433 km² in 2000 to 1154 km² in 2015. The habitat quality decreased significantly in E and Dongying Port parts during 2015–2020.

Keywords Shorebird · Habitat quality · Tidal flat · InVEST

Introduction

The East Asian–Australasian Flyway (EAAF) has the highest shorebird populations among the world's flyways (International Wader Study Group 2003; Milton 2003). The population of migratory shorebirds in EAAF has severely declined over the past several decades (Amano et al. 2010). Migratory shorebird populations in this flyway have declined up to 48% (International Wader Study Group 2003), along with perpetual annual declines of as much as 8% for some shorebirds (Studds et al. 2017). The tidal mudflats of the

Yellow Sea Ecoregion (YSE) have been a crucial migratory bottleneck for the millions of shorebirds that migrate through this flyway (Barter 2002; Studds et al. 2017). The YSE has lost 28% tidal flat area at a mean rate of $-1.2\% \text{ yr}^{-1}$ over the past three decades for land reclamation, leading to growing concerns that habitat degradation at stopover sites may be driving the declines in shorebird populations (Murray et al. 2014). Previous studies implied that population declines are driven by low survival during or after staging in the YSE tidal mudflats because birds are unable to replenish their energies to meet the demands of migration (Amano et al. 2010; Studds

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et al. 2017). Considering that shorebirds rely on stopover sites along their migratory path, they are vulnerable to various threats in these habitats (Piersma and Lindström 2004). Such threats include habitat losses and degradation due to agriculture, mariculture, and industrial developments (Newton 2004; Burton et al. 2006; Yasué and Dearden 2006). To ensure the persistence of migratory shorebird populations, a balance needs to be achieved between conservation and human development requirements. However, achieving such a balance with inadequate information about the consequences of land use (LU) change is difficult. Thus, understanding and predicting the effects of these threats on shorebird habitat quality are valuable for making an initial assessment of conservation needs on shorebird flyways and for projecting changes across time.

On this basis, models have been designed to help planners in determining LU configuration to ensure that the biodiversity value of each area can be maximized. Several models, such as the Global Biodiversity (GLOBIO) (Alkemade et al. 2009) and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) models, have predicted habitat status and biodiversity as a function of anthropogenic threats (Sharp et al. 2016). GLOBIO is a modeling framework that is used to calculate the past, present, and future impacts of environmental drivers on biodiversity on the global to national scale (Alkemade et al. 2009). The habitat quality module of InVEST (Kareiva et al. 2011; Sharp et al. 2016) has successfully been applied to assess the relative extent and degradation of different habitat types. Considering the hypothesis that areas with high habitat quality support high richness of native species, the InVEST model combines LU/land cover (LU/LC) changes and threats to biodiversity to produce habitat quality maps. In this study, we used the InVEST model rather than the GLOBIO model on the regional scale.

In this study, we focused on the Yellow River Delta (YRD), which is a representative and ecologically important shorebird stopover site in the YSE on the EAAF. We used the InVEST model to assess the shorebird habitat quality change in the YRD by considering the effects of anthropogenic threats. The entire duration of the study was 1999–2016, and the modeling was done on year 2000 and year 2015 data. We also applied the model under future scenario based on government policy planning. The results would help decision makers avoid inefficiencies in LU management.

Study Area

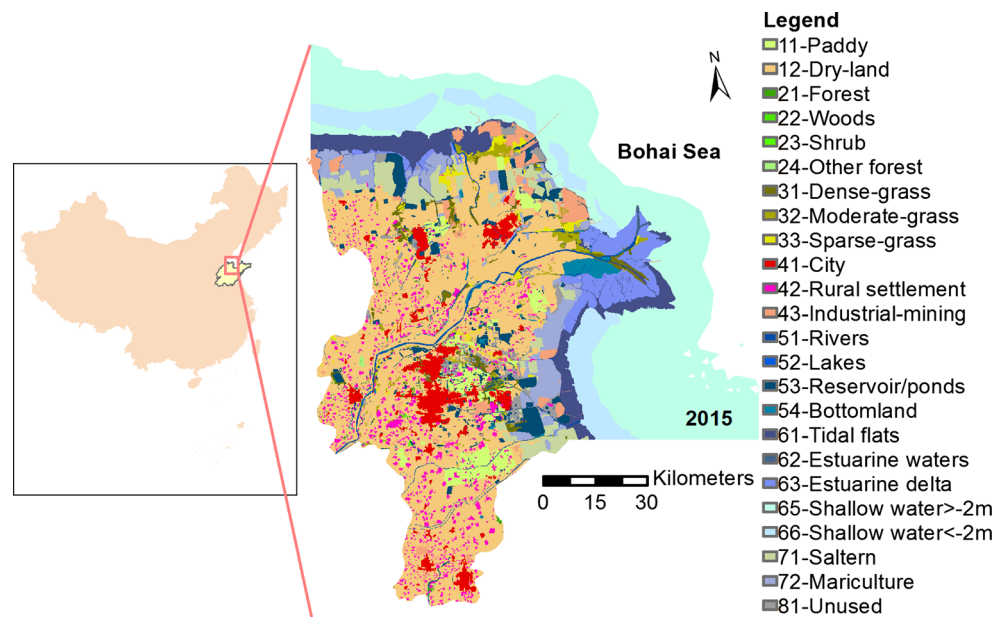
YRD (118°33'E–119°20'E and 37°35'N–38°12'N) is located in the estuary of the Yellow River in Dongying City, Shandong Province, China (Fig. 1). The Yellow River, which is the sixth longest river in the world, originates from the Tibetan Plateau, flows through the Loess Plateau to the

North China Plain, and drains into the Bohai Sea. Approximately 1.26×10^8 t of silt were carried by the river and deposited at the river mouth to form new marshes each year during 2000–2015. YRD has a warm temperate continental monsoon climate with distinctive seasons and rainy summers (Cui et al. 2009; He et al. 2009; Cui et al. 2011). YRD is known for its rich biodiversity (phytoplankton, vascular plants, invertebrates, fishes, birds, etc.) supported by various habitats and has become an important overwintering stopover and breeding site for migrating birds in EAAF. This site used to support >100,000 shorebirds during northward migration and an estimated >70,000 during southward migration (Barter 2002). In the YRD, 10 types of shorebird habitats are found: paddy (farmlands with guaranteed water resources and irrigation facilities for rice growing), sparse grass (grassland with canopy cover between 5%–20%), bottomland (lands between normal water level and flood level), tidal flats (lands between high tide and low tide levels), estuarine waters (permanent water of estuaries and rivers that are affected by tidal waters), estuarine delta (alluvial low plain in estuary area usually composed of sandy island, sandbank, and spit), shallow water (areas at a low tide depth of 2 m below sea level, including gulfs and straits), saltern (salt exploitation sites on the shoals, usually including evaporation ponds, crystallizing ponds, and ancillary facilities), mariculture (ponds usually constructed and managed for commercial aquaculture production), and unused lands (lands that are not used for practical application or difficult to use and have sparse vegetation, such as saline land, bare soil, and bare rock). With its number of internationally important shorebird species, YRD ranked first among all the stopover sites in the YSE (Kelin et al. 2016). The YRD National Nature Reserve was established by the Chinese government in 1992 to protect the wetland ecosystem for diversity conservation (Li et al. 2015). In recent decades, YRD has undergone rapid economic development, such as oil field utilization, industrialization, urbanization, agricultural development, and mariculture and saltern expansion.

Data Description

LU maps in 2000 and 2015 were interpreted based on Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) and Landsat Operational Land Imager (OLI) images at a scale of 1:100000. Landsat TM/ETM+ and OLI images were downloaded from the United States Geological Survey (USGS) global visualization viewer (<http://glovis.usgs.gov>) and were all captured in the growing season with a good quality (total cloud cover <5%). We used an improved classification system of LU in China's coastal zone, which includes farmland, forest, grassland, city, rural settlement, isolated industrial mining, inland freshwaters, coastal saltwater, saltern, mariculture, and unused lands (DI et al.

Fig. 1 YRD map, China



2014). For the coastal wetland subdivisions, the coastal salt-water has five subtypes, namely, tidal flats, estuarine waters, estuarine delta, coastal lagoons, and shallow water (along the coast). Furthermore, reference materials, including ground-truthing data, Google images, DEM data, vegetation maps, topographic maps, and historical LU maps, were utilized to provide auxiliary information for classification accuracy controls.

Shorebird Surveys

Data on shorebird richness were collected from the 2016 field survey. This shorebird survey data and online journal databases were used to define the parameters and build the habitat quality model. Surveys at diurnal high tides involved counting the number of feeding or roosting shorebirds during one complete scan of the entire field by using a telescope and binoculars during daytime. The number and species of shorebirds seen within each plot during a 15-min observation period were recorded, except for shorebirds that flew over and did not use the sampling plots. We surveyed the variates (such as distance to the road and vegetative cover) of the survey habitat in a 1 km radius of each initial sampling site. The total surveyed area at each site varied based on road accessibility. Prior to the initial survey at each site, center points were marked along the access roads by using GPS to demarcate sites. These points were used for the classification and quantification of the landscape that surrounded the survey site with LU data. In addition, bird surveys in 1999 and 2015 were conducted once a month by well-trained local observers to analyze changes in shorebird populations in the YRD.

Habitat Quality Assessment

We applied the habitat quality model of InVEST (v.3.4.2) (Sharp et al. 2016) to model the shorebird habitat availability changes across the YRD from 2000 to 2015. We also applied the model on the policy planning scenario based on the Dongying marine functional area planning document (2020). The InVEST habitat quality model combines the LU and threats information to biodiversity to produce habitat quality maps. The input layers of the model were elaborated in ArcGIS 10.2 using a cell size of 30×30 m. The LU layers from Landsat-TM were interpreted for 2000, 2015, and 2020, and LUs were aggregated in 25 different categories (Fig. 1). Considering the conservation objective of functional group diversity that focused on feeding tidal flat shorebirds, and based on data elicited from field shorebird survey in the YRD, each LU type was given a habitat suitability score of 0 to 1 for a particular measure of shorebird biodiversity, with non-habitat scored as 0 and perfectly suitable habitat scored as 1. We referred to a species–area relationship to determine the capacity of each LU/LC map to support shorebirds. The score on a given LU/LC map depended on the amount of actual and potential habitat area provided for shorebirds and on data taken from the literature.

In InVEST, habitats were influenced by their distance from potential threats and their sensitivity to those threats. On the basis of a reclassification process of LU layers using ArcGIS and the interpretation of road network from Landsat-TM, we developed six threat layers to shorebird habitat, namely, (1) road, (2) city, (3) rural settlement, (4) industrial mining, (5) mariculture, which discharged considerable wastewater to the tidal flats through the tidal channel, and (6) unused land, that is, reclaimed coastal wetlands with sparse vegetation. The

accessibility to sources of degradation was developed on the boundaries of the nature reserve (Fig. 2). The InVEST habitat sensitivity and threat parameters, such as habitat suitability scores, sensitivity of habitat types to each threat, maximum distance, threat weights, and decay functions, were determined based on data elicited from the field shorebird survey in the YRD and on data taken from the literature. These parameters are reported in Tables 1 and 2.

We created maps by using the output layers of the model to indicate the changes in shorebird habitat quality. Summary tables were produced based on these maps to quantify the optimal habitat area by ecoregions. On a scale of 0 to 1 of habitat quality score, with 1 being ideal habitat, the optimal habitat area was defined to be 0.7 or above. The habitat quality score for each ecoregion was generated by averaging all the ecoregion's grid cell-level habitat quality scores.

Results

Changes in the Shorebird Populations

A total of 48 shorebird species were observed in the YRD in the bird surveys during 1999–2015. The individual species abundance ranged from two individuals for Common Ringed Plover (*Charadrius hiaticula*) to 40,672 individuals for Kentish Plover (*Charadrius alexandrinus*) in 1999. However, the individual species abundances ranged from one individual for Eurasian Woodcock (*Scolopax rusticola*) to 12,000 individuals for Pied Avocet (*Recurvirostra avosetta*) in 2015 (Fig. 3). Among the 48 species, three species were of conservation concern, namely, Eastern Curlew (*Numenius madagascariensis*), Great Knot (*Calidris tenuirostris*), which were listed as Vulnerable (VU) in the International Union for Conservation of Nature (IUCN) Red List, and Nordmann's Greenshank (*Tringa guttifer*) listed as Endangered (EN) in the IUCN Red List. The total abundance of shorebirds in the YRD decreased from 187,296 to 74,412 during 1999–2015.

Table 1 Characteristics of threats to shorebird habitat quality considered in the YRD. W and Max.D refer to the mean values of weights and maximum distance over which the threats affect habitat quality and were obtained based on data elicited from the field

Threats	Max.D (km)	W[0–1]	Decay	Literature
City	7.1	0.9	Exponential	(Czech et al. 2000; Zhao 2001; Zhong et al. 2006;
Rural settlement	4	0.68	Exponential	Wang et al. 2008; Chen et al. 2015; Terrado et al. 2016;
Industrial mining	5.6	0.8	Exponential	Robbins et al. 2017)
Mariculture	14	0.92	Linear	
Unused	0.1	0.5	Linear	
Roads	0.5	0.71	Exponential	

Decay refers to the type of decay over space for the threat, which can have the value of either “linear” or “exponential”

The abundance of 11 shorebird species had a significant downward trend, namely, Bar-tailed Godwit (*Limosa lapponica*, 97% reduction), Eastern Curlew (*Numenius madagascariensis*, 97% reduction), Terek Sandpiper (*Xenus cinereus*, 96% reduction), Kentish Plover (*Charadrius alexandrinus*, 94% reduction), Marsh Sandpiper (*Tringa stagnatilis*, 92% reduction), Sharp-tailed Sandpiper (*Calidris acuminata*, 85% reduction), Grey Plover (*Pluvialis squatarola*, 81% reduction), Eurasian Curlew (*Numenius arquata*, 73% reduction), Great Knot (*Calidris tenuirostris*, 73% reduction), Red-necked Stint (*Calidris ruficollis*, 73% reduction), Dunlin (*Calidris alpina*, 70% reduction). The abundance of some shorebird species had an upward trend, namely, Pied Avocet (*Recurvirostra avosetta*), Black-winged Stilt (*Himantopus himantopus*), Common Redshank (*Tringa totanus*), Common Greenshank (*Tringa nebularia*), Red Knot (*Calidris canutus*), Spotted Redshank (*Tringa erythropus*), Whimbrel (*Numenius phaeopus*).

Changes in LU and Shorebird Habitat

The study area was primarily clustered into five major parts based on the dissimilarities of habitat composition (Fig. 5). In 2000, the northwestern part (NW), the nature reserve (NR), and the eastern part (E) were strongly dominated by estuarine delta and tidal flats, as indicated by the vector area. The Dongying Port part (DP) was strongly dominated by industrial mining, and the other was strongly dominated by farmland. In 2015, NW and E had extensive mariculture, and salt pans occurred in large contiguous patches and were predominant LU. Relatively large patches of secondary tidal flats occurred. The inland part (IL) was influenced by farmland reclamation and urban development. The saltern, mariculture, city, isolated industrial mining, and road developments had a high association with the coastal area during 2000–2015.

The most prominent LU changes in the YRD during 2000–2015 were the shrinkage of estuarine delta and dense grass along with the expansion of city, saltern, and mariculture

shorebird survey in the YRD and on data taken from the literature and were subsequently adjusted during the calibration of the habitat quality model

Table 2 Mean values for habitat suitability (H) and the relative sensitivity of habitat types to threats (S) considered in the YRD, which were obtained based on data elicited from the field shorebird survey in the YRD and on data taken from the literature and were subsequently adjusted during the calibration of the habitat quality model. LU refers to the

land use codes, namely, 11-Paddy, 33-Sparse grass, 54-Bottomland, 61-Tidal flats, 62-Estuarine waters, 63-Estuarine delta, 64-Coastal lagoons, 66-Shallow water, 71-Saltern, 72-Mariculture, and 81-Unused land

LU	H [0–1]	Relative sensitivity of habitat types to threats (S)							Literature
		City	Rural settlement	Industrial mining	Mariculture	Unused	Roads		
11	0.55	1	0.8	0.6	0.10	0.01	0.80	(Tang and Lu 2002; Dias et al. 2006; Zhong et al. 2006; Evans Ogden et al. 2008; Amano et al. 2010; Sripanomyom et al. 2011; Hou et al. 2012; Lunardi et al. 2012; Katayama et al. 2015; Robbins et al. 2017)	
33	0.29	0.8	0.6	0.9	0.01	0.01	0.70		
54	0.18	1	0.5	0.4	0.10	0.10	0.30		
61	1.00	0.8	0.29	0.35	0.95	0.20	1.00		
62	0.89	0.7	0.21	0.34	0.7	0.10	0.8		
63	1.00	0.75	0.39	0.32	0.8	0.10	0.8		
64	1.00	0.2	0.4	0.5	0.98	0.10	0.9		
66	0.31	0.4	0.1	0.3	0.60	0.10	0.01		
71	0.98	0.31	0.3	0.01	0.01	0.01	0.6		
72	0.21	0.41	0.4	0.01	0.01	0.10	0.5		
81	0.19	0.9	0.75	0.95	0.30	0.01	0.5		

(Fig. 4). Estuarine delta and dense grass decreased by 42 and 75% and city, saltern, and mariculture increased by 200%, 301%, and 395%, respectively. The main cause of estuarine delta loss was mariculture and saltern expansions. During 2000–2015, 13,175 ha of estuarine delta were converted to mariculture, which contributed to 43.61% of the total loss of

estuarine delta. In addition, the dry land and industrial mining areas increased by 8.5 and 15.2%, and rural settlement and tidal flats decreased by 13.7 and 10.4%, respectively.

We analyzed the changes in habitat areas in the YRD on the basis of LU data during 2000–2015. Ten types of shorebird habitats were found in this study area. In saltern and paddy, the

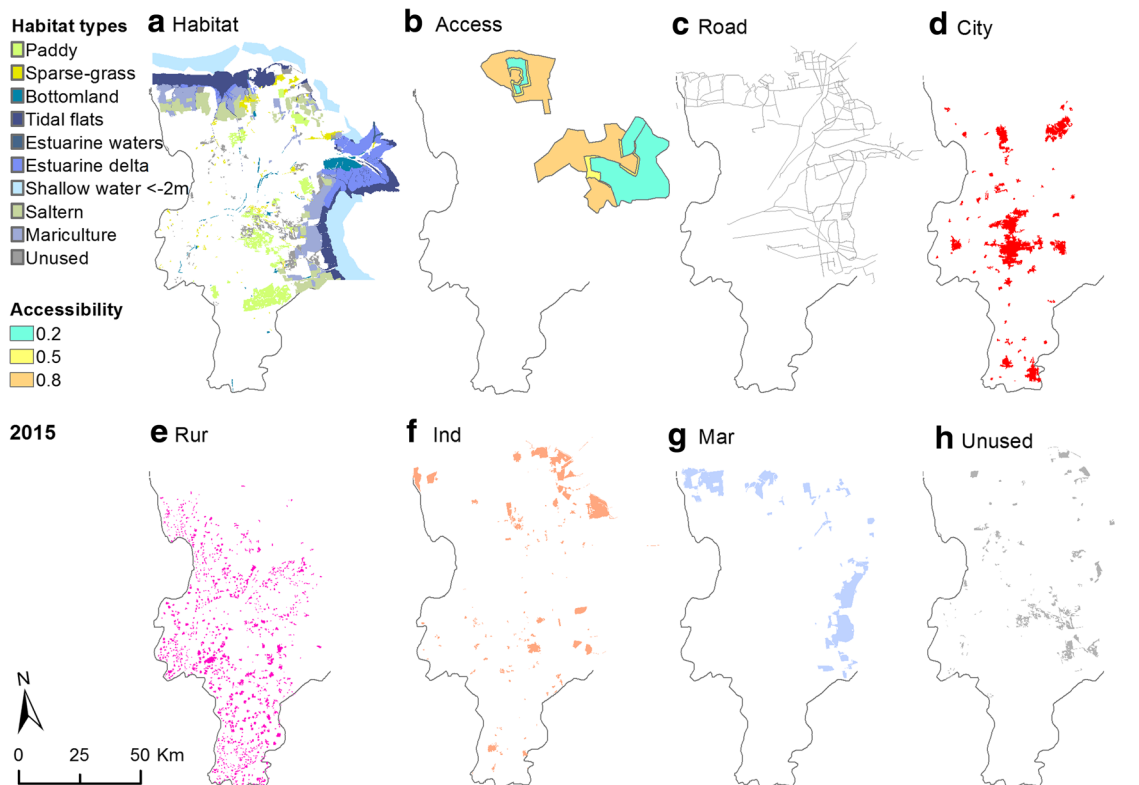


Fig. 2 Maps of habitat types (a), accessibility to sources of degradation (b), and threats in the YRD. Considered threats: (c) roads; (d) city; (e) rural settlement; (f) industrial mining; (g) mariculture; and (h) unused

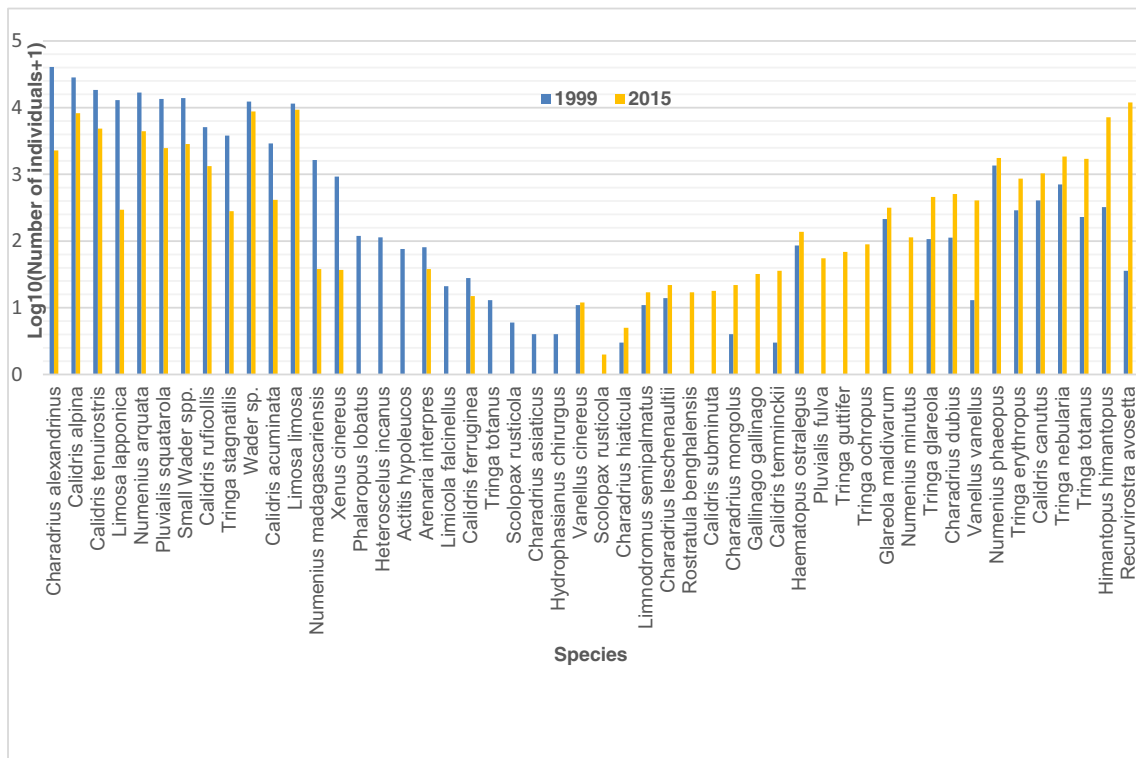
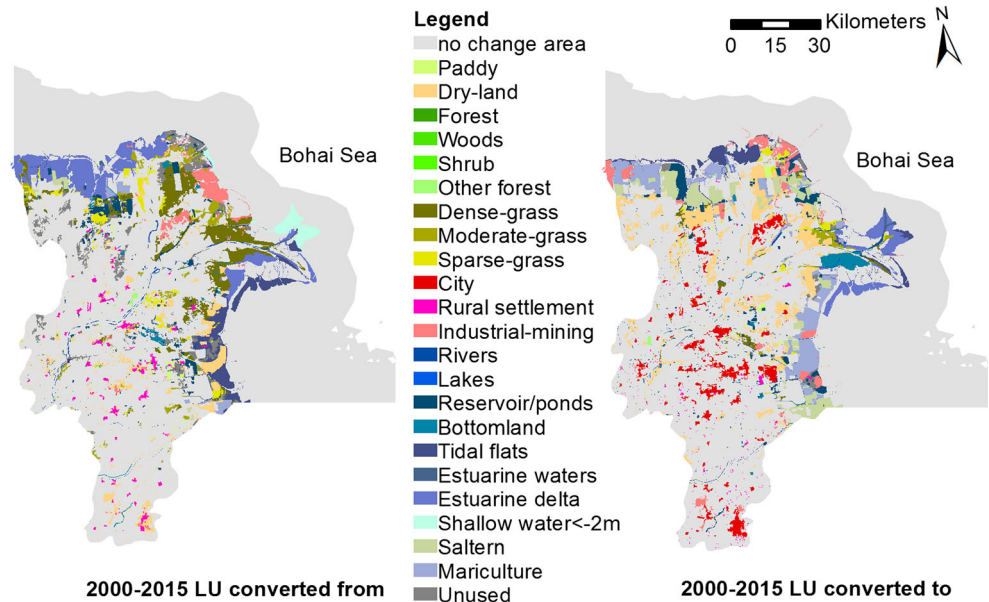


Fig. 3 Annual sums of shorebirds (migratory and resident) counted across the local survey bands (1999–2015)

majority of shorebirds were observed in these habitat types during high tide. In tidal flats, estuarine waters, and estuarine delta, the majority of shorebirds were observed in these habitat types during low tide. Shorebirds used mariculture ponds when water was drained for harvesting, and they used mariculture pond dykes for roosting in small numbers. Small

canals running through mariculture and saltern were used by shorebirds in several sites. The tidal flat and estuarine delta areas were 62,841 and 71,540 ha, respectively, in 2000. The areas of four habitat types had a significant downward trend during 2000–2015. The most prominent habitat area change in the YRD during 2000–2015 was the shrinkage of estuarine

Fig. 4 LU change in the YRD during 2000–2015



delta with a 30,214 ha reduction. The areas of unused land, tidal flats, and sparse grass reduced by 21,792, 6510, and 6166 ha, respectively, over 15 years.

Modeled Shorebird Habitat Quality and its Changes in the YRD

High spatial heterogeneity was observed in the modeled habitat quality in the YRD (Fig. 5). Considering the influence of adjacent patches on quality scores, the LU spatial pattern and the amount of habitat were considered in determining the landscape habitat quality score. Tidal flat areas in NR, NW, and E had higher quality than the areas in IL and DP in 2000. However, tidal flat areas in NR had a higher habitat quality than the areas in NW and E of the study area because major mariculture occurred in NW and E in 2015. The mean habitat quality in NW and E was 26 and 44% lower than that in NR, respectively (Table 3). The mean habitat quality in NW and E decreased by 27 and 31% during 2000–2015, respectively, and the mean habitat quality in NR, DP, and IL increased by 7%, 66%, and 4%, respectively.

Optimal Habitat Changes in the YRD

The results show that over the 2000–2015 period, the optimal habitat in the YRD declined from a high of 1433 km² in 2000 to a low of 1154 km² in 2015. The percentage of optimal habitat in the NW and E ecoregion declined by approximately 23 and 10% between 2000 and 2015, respectively. The NW, NR, and E ecoregions accounted for over 90% of the optimal habitat available among the five investigated ecoregions (Table 3). The IL ecoregion provided a smaller optimal habitat compared with the four other ecoregions and showed the lowest change (0.3%) in the past 15 years. The percentage of optimal habitat in the DP and NR ecoregions increased by 7 and 1% in the 2000–2015 period, respectively.

Fig. 5 Shorebird habitat quality in the YRD during 2000–2015

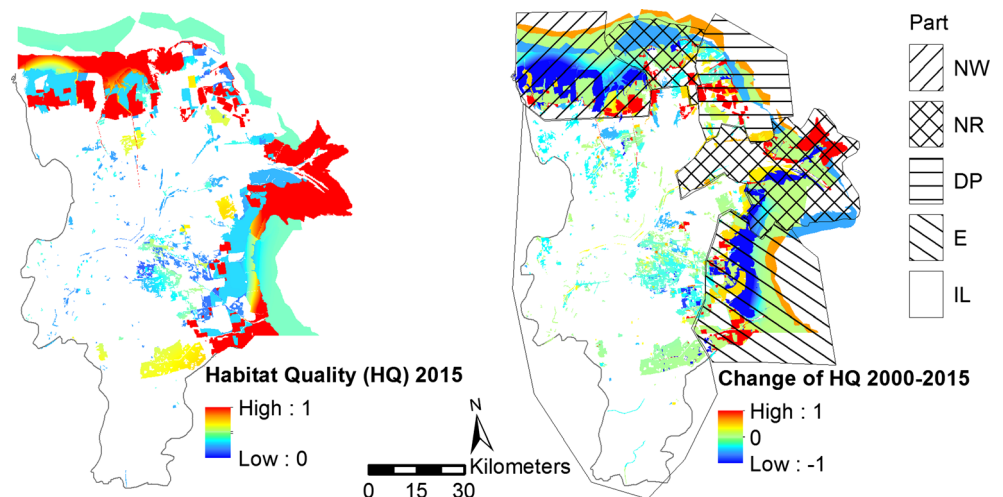


Table 3 Habitat quality score for ecoregions in 2000 and 2015. QM refers to the mean habitat quality score on grid cell-level in each ecoregion, and HQA refers to the percentage of optimal habitat in each ecoregion

	2000		2015		Change	
	QM	HQA	QM	HQA	QM(%)	HQA
Total	0.12	14.5%	0.10	11.7%	-13.94	-2.8%
NW	0.76	48.3%	0.55	25.2%	-27.42	-23%
NR	0.70	33.9%	0.75	35.2%	7.16	1%
DP	0.27	0.5%	0.45	7.6%	66.05	7%
E	0.60	22.0%	0.41	12.1%	-31.07	-10%
IL	0.33	0.2%	0.35	0.5%	4.71	0.3%

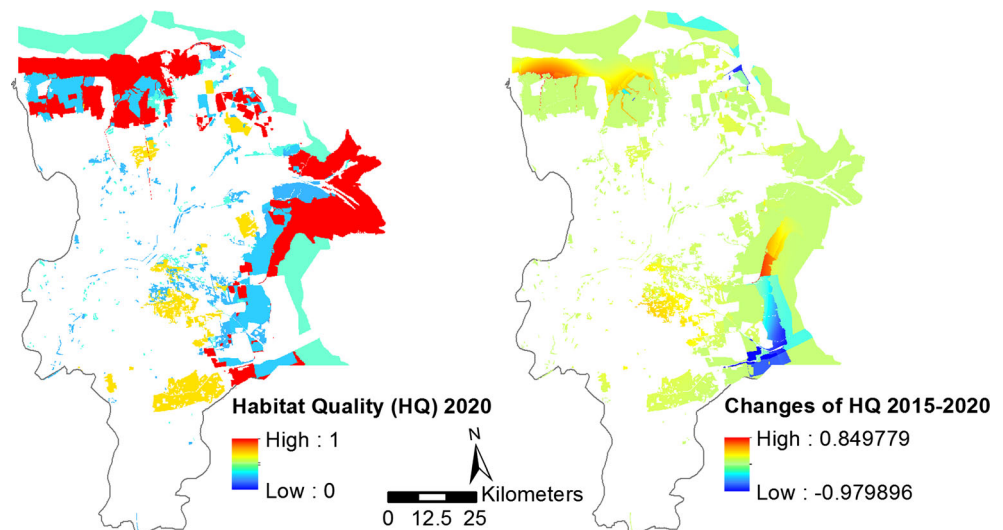
Scenario Simulation Analysis Results

The 2020 habitat quality of the policy planning scenario is calculated through the scenario simulation based on government policy planning, and the results are compared with the 2015 habitat quality (Fig. 6). In the 2020 planning scenario, a large area of tidal flats in E is developed as industrial and mining lands, and its habitat quality shows a significant downward trend during 2015–2020. The DP area occupies the tidal flats and shallow water of the surrounding area due to port construction, which reduces the habitat quality of this area. Because the tidal flats in the NW and E beach areas are encroached by human activities, the remaining tidal flat areas become more significant for shorebirds than before due to their scarcity and their habitat quality exhibits a rising trend.

Discussion

In previous studies on global (Baillie et al. 2004; Vié et al. 2009) and national scales (Wilcove et al. 1998; Venter et al. 2006), researchers determined that habitat loss was the

Fig. 6 Shorebird habitat quality in the YRD during 2015–2020



primary driver of imperilment for threatened species and urbanization had major and widespread impacts on native biodiversity, which will worsen with future increases in human population and consumption (Kingsford et al. 2009). In this study, habitat degradation in the YRD was pronounced near mariculture and industrial mining areas (Fig. 7). Meanwhile, habitat degradation in the YRD in many other multiple use areas was pronounced near urban settlements. This finding demonstrates the threat of urban LU/LC to natural ecosystems and biodiversity (James et al. 1999; Yencken and Wilkinson 2000; Beeton et al. 2006; Martinuzzi et al. 2014) and supports the previous findings that identified the industrial mining area as the major threat to biodiversity. On the basis of species distribution as a surrogate for threats, Evans et al. (2011) determined that urban settlements combined with agriculture, infrastructure, and extractive activities were the threats to biodiversity in Australia (Evans et al. 2011).

In the YRD, many deep, permanent, and steep-sided mariculture ponds existed for holothurian and shrimp cultivation, and the original natural characteristics of these areas have been completely destroyed by soil excavation. These mariculture ponds discharged considerable sewage in the tidal flat

area and threatened the shorebird populations in EAAF. In addition, these mariculture ponds were largely unusable because they provided limited access for shorebirds and other waterbirds. Industrial-scale mariculture was considered a significant threat to shorebird populations in the Atlantic and Pacific flyways due to water pollution and hydrological alteration (Redstone Strategy Group 2008). In the Inner Gulf of Thailand, sites in which the surrounding landscape held higher proportions of salt pans and lower proportions of aquaculture had significantly higher levels of shorebird richness and abundance than sites which held higher proportions of aquaculture (Sripanomyom et al. 2011). Along EAAF, mariculture was also considered the cause of decreasing shorebird populations at stopover and wintering sites in South Korea, Thailand, Malaysia, and Australia (Gosbell and Clemens 2006; Sripanomyom et al. 2011). This trend also occurred along the coast of clam farms in France and the mariculture in the Mediterranean region because such mariculture was sometimes set up on tidal flats which were highly productive feeding sites for shorebirds or on abandoned salt ponds (Amet et al. 2005; Godet et al. 2009). On the basis of the planning scenario analysis, we also determined that mariculture

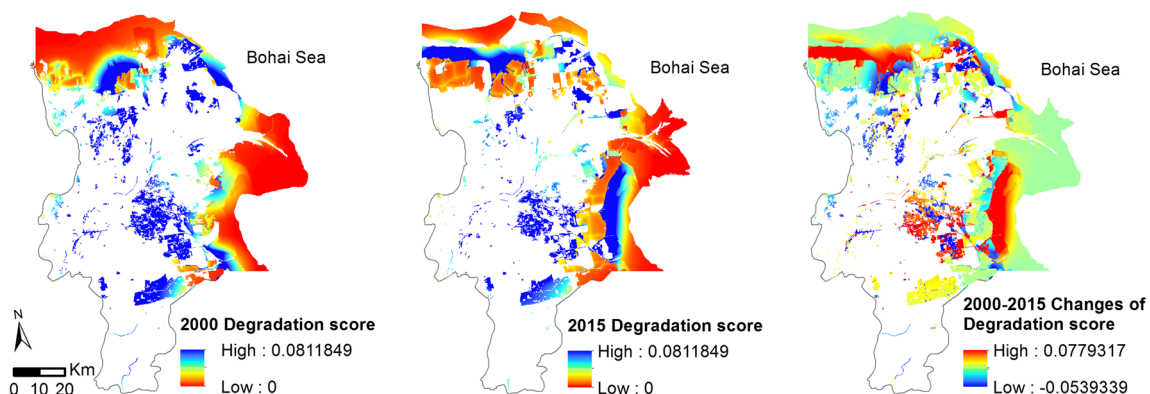


Fig. 7 YRD degradation score and changes during 2000–2015

expansion would further damage the shorebird habitats. Thus, we suggest that the discharge of coastal holothurian mariculture wastewater should be controlled, standards for holothurian mariculture ponds should be formulated and implemented, the water quality monitoring system should be improved, an accountability mechanism should be developed, and ecological compensation measures should be implemented.

As indicated by the degradation score, we determined that tidal flat habitats were more affected by threats than other habitats. The high habitat degradation in tidal flat habitats was due to the reduction in habitat suitability values and that the tidal flat habitat quality was affected by more threats than terrestrial habitat quality caused by mariculture, industrial mining area, road, and urbanization. From 2000 to 2015, the construction of coastal roads resulted in the degradation of a large area of tidal flats. The direct economic value of tidal flats was not obvious for the local people and the government. The direct economic value of the tidal flats was lower than that of mariculture and saltern. However, the tidal flat value is irreplaceable in terms of shorebird habitat requirement. Therefore, shorebird habitat value should be considered in future LU planning, and sustainable LU and management should be conducted.

The parameter values used in the model (Tables 1 and 2) can be transferred to other YSEs with similar characteristics when site-specific data are unavailable. The parameters, namely, habitat sensitivity to threats, maximum distance of threat effect, and threat weight, will be different in different coastal areas. The habitat suitability values could be transferred in the YSE when shorebird biodiversity is considered. Otherwise, the specific values for other considered species need to be defined. In future research, we will combine the LU data of the YSE and evaluate the quality of shorebird habitat and its spatial and temporal variation in the entire region.

Although the implementation of conservation policies could help protect shorebird biodiversity from future LU change in national reserve regions, we also found that areas with no conservation policies experienced extensive alteration. Specifically, through planning scenario analysis, we determined that human activities would further damage the shorebird habitats. These limitations emphasize the necessity of combining national, regional, and local initiatives with on-the-ground management to effectively conserve tidal flat areas across the YRD. In future land planning, the irreplaceability of shorebird habitats should be considered in the environmental impact assessment on the reclamation of tidal flats as holothurian mariculture ponds. Investigation data indicate that several existing holothurian mariculture ponds offer poor economic benefits. Therefore, reasonable adjustment and recovery should be considered in several areas in future planning.

Although substantial uncertainties remained in the effects of changing LU and climate on the world's coastal

ecosystems, conservation actions should be conducted as we approach the upper limit for human use and water degradation with the loss of essential ecosystem services (the benefits people obtain from ecosystems) (Carpenter et al. 2009) and irreplaceable species assemblages (Dudgeon et al. 2006). Detailed spatial analyses on LU and coastal biodiversity are available at regional to global scales (Seto et al. 2012), offering many opportunities for policy-relevant analysis. Our results illustrate powerful insights on the potential future of natural resources that can be gained by coupling these new LU simulations within a scenario-based approach.

The shorebird habitat in the YRD is undergoing continuous fragmentation and degradation due to the increasing intensity of coastal land development. Two aspects of control should be developed for coastal land development activities. First, an ecological assessment of the existing reclamation project should be conducted, the ecological function loss caused by the surrounding reclamation should be analyzed to provide guidance for subsequent sustainable management, and ecological restoration should be considered, especially in abandoned areas. Second, the irreplaceability of shorebird habitat should be considered in the environmental impact assessment of the proposed reclamation project to avoid one-sided evaluation results.

Land development, industrial and mining development, and pollution result in shorebird habitat degradation. Sustainable natural resources are lost in pursuit of significant economic interests. Our generation and future generations should reflect on the trade-off between these values. Quality assessment on shorebird habitat indicates that the sense of responsibility of stakeholders should be improved and the practical implementation of protection actions should be promoted.

Conclusions

This paper focused on the shorebird habitat quality in the YRD, which is a representative and ecologically important shorebird stopover site in the YSE on the EAAF. The InVEST model was used to assess the past and future shorebird habitat quality changes in the YRD by considering the effects of anthropogenic threats. The optimal habitat in the YRD declined from a high of 1433 km² in 2000 to a low of 1154 km² in 2015. Considering the influence of adjacent patches on quality scores, the LU spatial pattern and the amount of habitat affected the landscape habitat quality score. Tidal flat areas in NR had a higher habitat quality than areas in the NW and E of the study area because major mariculture occurred in NW and E. The mean habitat quality in NW and E decreased by 27 and 31% during 2000–2015, respectively. The mean habitat quality in the NW and E was 26 and 44% lower than that in NR in 2015, respectively. In the 2020

planning scenario, a large area of tidal flats in the E of the YRD was developed as industrial and mining lands, and its habitat quality showed a significant downward trend during 2015–2020. As indicated by the degradation score, we determined that tidal flat habitats were more affected by threats than other habitats. The high habitat degradation in tidal flat habitats was due to the reduction in habitat suitability values, and that tidal flat habitat quality was affected by more threats than terrestrial habitat quality caused by mariculture, industrial mining area, road, and urbanization. We determined that areas with no conservation policies were completely impacted by human activities. Specifically, through planning scenario analysis, we determined that human activities would further damage the shorebird habitats. These limitations emphasize the necessity of combining national, regional, and local initiatives with on-the-ground management to effectively conserve tidal flat areas across the YRD. The results would help decision makers improve ecological sustainability and avoid inefficiencies in LU management.

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