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Original Research Article

Conserving unprotected important coastal habitats in the Yellow Sea: Shorebird occurrence, distribution and food resources at Lianyungang

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A B S T R A C T

The Yellow Sea coastline in East Asia, an important staging area for migratory shorebirds in the East Asian-Australasian Flyway (EAAF), is rapidly deteriorating. Conserving the declining shorebird populations that rely on the Yellow Sea requires habitat protection and management based on sound ecological knowledge, especially on the seasonal occurrence of shorebirds, their daily movements and their food resources. However, in this region such ecological data are scarce, and expertise to collect them are less-established. Here we gather and assimilate such information for the coastal wetlands at Lianyungang on the Chinese Yellow Sea coast, an understudied and unprotected area where we found 27% of intertidal soft sediment habitats have been destroyed in 2003–2018 by reclamation. In 2008–2018, 43 shorebird species were recorded along this coastline, including 12 globally threatened or 'Near Threatened' species. In terms of number of shorebird species exceeding 1% of the EAAF population, with 22 species meeting this criterion, Lianyungang ranks highest among the >300 shorebird sites in East Asia. The benthic mollusc community of the intertidal flats were dominated by small soft-shelled bivalve species at very high densities, including 9399 individuals/m^2 of *Potamocorbula laevis*, which are high-quality food for shorebirds to refuel during migration. Satellite tracked bar-tailed godwits (*Limosa lapponica*) and great knots (*Calidris tenuirostris*) stopped at Lianyungang for 5–30 days during northward and southward migration. The tidal movements of satellite-tagged birds indicated high-tide roosts and low-tide foraging areas, some of which are inaccessible on-ground. These movements can also be used to evaluate whether roosts and foraging areas are close enough to each other, and direct where to create new roost sites. Potential measures to increase the capacity of Lianyungang to support shorebirds include reducing human disturbances, creating roosts at undeveloped parts of the reclaimed land, and removing recently-built sea dikes to restore intertidal flats.

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1. Introduction

The conservation of migratory shorebirds in the East Asian-Australasian Flyway (EAAF) has progressed in the past decades through field research that collected baseline information primarily on bird numbers (Bai et al., 2015; Barter, 2002). This has resulted in the discovery and recognition of major staging sites, many of which are in the Yellow Sea (Conklin et al., 2014). However, many coastal sites along the EAAF are undergoing extensive habitat loss and degradation (Melville et al., 2016; Murray et al., 2014, 2015; Piersma et al., 2016). Habitat loss in the Yellow Sea is suggested to be the main driver of declines in adult survival for shorebird populations migrate annually along the EAAF (Piersma et al., 2016), resulting in decreasing bird numbers, especially for those populations that rely most on the coastal staging areas along the Yellow Sea (Studds et al., 2017).

In the recent years, the governments in the Yellow Sea region have recognised the ecological value of their coastlines and are committing to protect them (Melville, 2018). In 2017, the Chinese government included 14 coastal sites in the Yellow Sea in a tentative nomination as UNESCO World Heritage (UNESCO, 2017) and released new policies regarding wetland protection and restoration, including the suspension and reconsideration of commercial reclamation at intertidal areas (Melville, 2018; Zhao, 2018). The design of effective protection and restoration measures needs to be based on solid ecological knowledge at the local scale, such as shorebird's habitat use and prey availability. Such knowledge is inadequate in many countries in East and Southeast Asia (Hua et al., 2015), the likely reason being the shorter history of science-based site management (Lee and Khim, 2017) and limited citizen science capacities (e.g. only one in about 65000 people in China are birdwatchers in 2010, Ma et al., 2013).

To exemplify how the gathering and assimilation of local ecological knowledge may facilitate ecosystem- and bird-friendly management, and to directly fill a key knowledge gap for conservation of the Yellow Sea region, we present the information needed for managing one of the proposed World Heritage sites in the Yellow Sea that is particularly understudied and unprotected, the Lianyungang Coast (34.5–35.2°N, 119.1–119.7°E) in northern Jiangsu Province, China. We first establish the site's importance for shorebirds based on counts conducted in 2008–2018. We also assess the site's importance by the staging duration of satellite-tagged shorebirds. To identify the shorebird habitats along the Lianyungang Coast that require protection and management, we describe how shorebirds use current coastal habitats from our on-the-ground observations and from local movements of the satellite-tagged individuals. Since land reclamation has reduced the area of intertidal flats in the Yellow Sea substantially (Murray et al., 2015), we describe coastal habitat changes along the Lianyungang Coast by measuring rate of coastal reclamation and mapping current status of the reclaimed coastal land from satellite images. We also assess the quality of the intertidal feeding habitat by estimating densities of benthic shellfish, the staple food of many shorebird species (Choi et al., 2017; Tulp and de Goeij, 1994; Yang et al., 2013; Zhang et al., 2019).

2. Material and methods

2.1. Study area and background

Our study area comprises the entire 162 km coastline of Lianyungang City, Jiangsu Province, China (34.5–35.2°N, 119.1–119.7°E), in the southern Yellow Sea. The salt ponds along this coastline were listed as an IBA in 2009 (BirdLife International, 2018a) and were proposed as a tentative World Heritage site in 2017 (UNESCO, 2017). The proposal was based on the over 18 000 shorebirds detected in the salt ponds on a single survey in 2004 (Barter and Xu, 2004). Salt production in Lianyungang has a history of over 1100 years, but declined after the discovery of nearby salt mines in the 1980s. The over 500 km^2 of salt ponds were steadily converted to aquaculture and industrial uses and are almost non-existent today (Xie and Gao, 2011; pers obs). Currently, most of the coastline is enclosed by man-made seawalls with aquaculture ponds on the landward side and intertidal flats and rocky coast on the seaward side. During the 2004 survey of the northern portion of these intertidal flats, over 15 000 shorebirds were counted (Barter and Xu, 2004).

2.2. Bird surveys

To describe the number of birds using this coastline, we summarised citizen science count data of the Chinese Coastal Waterbird Census (Bai et al., 2015). These counts were conducted between February 2008 and May 2018 at eight areas along the coast (Fig. 1), covering all the main shorebird habitats (for details see Table A.1). For all shorebirds, we present the maximum numbers and whether the numbers have exceeded 1% of the EAAF population estimates (Conklin et al., 2014), and conservation status (i.e., Near Threatened, Vulnerable, Endangered, Critically Endangered; IUCN, 2017). We also present the maximum counts of waterbird species of other families with numbers that had exceeded 1% of the EAAF population (Wetlands International, 2018) and/or listed as 'Near Threatened' or above in the IUCN Red List (IUCN, 2017). Physical habitat characteristics were noted during some count sessions in spring 2015–2018 (Table A.1).

2.3. Satellite tracking

We characterize bird movements from the tracking data of six great knots and six bar-tailed godwits (maximum counts of these two species at Lianyungang exceed 1% of their EAAF population, Table 1) which staged at the Lianyungang Coast during 2015–2018. Solar Platform Terminal Transmitters (PTTs, Microwave Telemetry, USA) of 4.5 and 9.5 g were deployed onto great

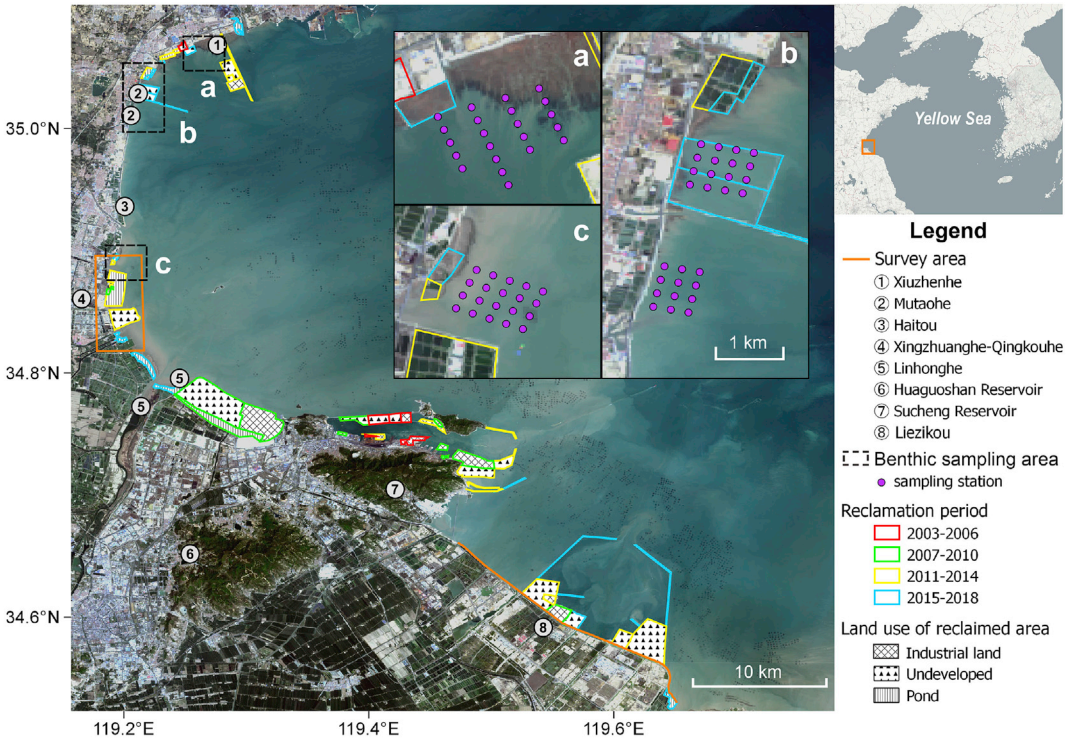

Fig. 1. Map of the Lianyungang Coast showing the eight bird survey areas and 70 benthic sampling stations at (a) Xiuzhenhe (b) Mutaohe and (c) Xingzhuanghe. Reclaimed areas are depicted on the map with respective year range (coloured outlines) and the type of land use (shaded). The background Sentinel-2 (ESA) image is from June 2018. In the map of the Yellow Sea (upper-right), the Lianyungang Coast is shown as an orange square. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

knots and bar-tailed godwits, in September and October 2014, 2015 and 2016, and February 2017, at the northern beaches of Roebuck Bay, Broome, Northwest Australia (17.98°S, 122.31°E). PTTs were programmed to operate on a duty cycle of 8 h on and 25 h off. Positions were received from Argos (Collecte Localization Satellites, CLS, 2016). The work was carried out under Regulation 17 permits SF 010074, SF010547 and 01-000057-2 issued by the West Australian Department of Biodiversity, Conservation and Attractions.

For migration timing analysis, we kept all standard Argos locations (i.e. the location classes 3, 2, and 1) and removed implausible auxiliary locations (i.e. classes 0, A, B and Z) by applying the Hybrid Douglas filter (Douglas et al., 2012). The filtering parameters were set at 120 km/h for the maximum sustainable rate of movement and 10 km for the minimum redundant distance. To calculate arrival and departure times to Lianyungang of each bird, the first point with speed <20 km/h within the site boundary was defined as the first point recorded when the individual stopped at Lianyungang, the same for the last point. Arrival times were estimated by extrapolating the average speed of a non-stop flight over the intervening distance between the first stopping point and the previous in-flight point i.e. bird was moving at >20 km/h or was >50 km away from the shoreline. If the previous point was a stop, we assumed that the flight from the previous site occurred at the mid-point of the time interval between the two. We estimated departure times in the same way. Staging duration is the difference between estimated arrival and departure times. Given that the Yellow Sea is the main staging area for both species during northward and southward migrations (Battley et al., 2012; Chan et al., 2019), to assess whether Lianyungang is a major refuelling site for an individual's migration, we expressed staging duration at Lianyungang as a percentage of an individual's total staging duration within the Yellow Sea (calculated in the same way as described above; the Yellow Sea is defined as locations between the latitudes 30.9° and 41.5°).

For the analysis of local distributions and movement, we only used standard locations, as the auxiliary locations have an error radius that is too large for the size of our study area (Douglas et al., 2012). These standard locations were classified as being collected at low or high tide using water level predictions from the China Seas Regional model of the Oregon State University Tidal Prediction Software (http://volkov.oce.orst.edu/tides/otps.html; Egbert and Erofeeva, 2002). Since some tracking data points were on land where there were no water level predictions, for each tracking point, we extracted the predicted water level at its nearest point along a transect at sea, 500 m away from and parallel to the coastline. A point is assigned as 'high tide' if the predicted water level is higher than 0.5 m, which is the 60% quantile of a sample of predicted water levels (every 10 min for a month) along this transect, or is assigned as 'low tide' if the water level is lower than −0.5 m (the 40% quantile).

Table 1
Maximum counts of shorebird species along the Lianyungang Coast in 2008–2018, sorted by English common name. Species with counts exceeding 1% of the EAAF population are in bold. IUCN Red List status in parentheses (NT=Near Threatened, VU=Vulnerable, EN = Endangered, CR=Critically Endangered). [m] indicates species observed to occur on intertidal mudflats.

Species	1% of EAAF Population	Maximum count, date and location					
		Northward Migration (March–June)		Southward Migration (July–November)		Wintering Period (December–February)	
Asian Dowitcher (NT) [m] *Limnodromus semipalmatus*	230	**7000**	12 May 2018 Xingzhuanghe-Qingkouhe	**1000**	17 Jul 2017 Xingzhuanghe-Qingkouhe		
Bar-tailed Godwit (NT) [m] *Limosa lapponica*	2790	**4702**	14 Apr 2013 Xingzhuanghe-Qingkouhe	2700	25 Jul 2015 Linhonghe	8	19 Feb 2017 Xingzhuanghe-Qingkouhe
Black-tailed Godwit (NT) [m] *Limosa limosa*	1390	**19810**	5 May 2018 Xingzhuanghe-Qingkouhe	**4423**	7 Aug 2012 Linhonghe & Liezikou		
Black-winged Stilt *Himantopus himantopus*	250-1000	88	Jun 2010 Linhonghe	350	25 Jul 2015 Linhonghe	6	11 Jan 2015 Xingzhuanghe-Qingkouhe
Broad-billed Sandpiper [m] *Calidris falcinellus*	250	**720**	5 May 2018 Xingzhuanghe-Qingkouhe	105	12 Sep 2015 Xingzhuanghe-Qingkouhe		
Common Greenshank [m] *Tringa nebularia*	1000	600	May 2008 Linhonghe	694	7 Aug 2012 Linhonghe	8	15 Jan 2011 Liezikou
Common Redshank [m] *Tringa totanus*	1000	500	May 2008 Linhonghe	241	7 Aug 2012 Linhonghe	130	Dec 2008 Linhonghe
Common Sandpiper *Actitis hypoleucos*	500	3	9 May 2011 Linhonghe	10	Jul 2008 Linhonghe		
Common Snipe *Gallinago gallinago*	1000-10000	5	1 Apr 2014 Xingzhuanghe-Qingkouhe	3	Oct 2010 Liezikou	1	Dec 2008 Linhonghe
Curlew Sandpiper (NT) [m] *Calidris ferruginea*	1350	**2500**	16 May 2014 Xingzhuanghe-Qingkouhe	12	25 Jul 2015 Linhonghe	8	27 Jan 2018 Xingzhuanghe-Qingkouhe
Dunlin [m] *Calidris alpina*	6500	**14000**	May 2008 Linhonghe	**8000**	22 Oct 2017 Linhonghe	**7500**	13 Dec 2015 Xingzhuanghe-Qingkouhe
Far Eastern Curlew (EN) [m] *Numenius madagascariensis*	320	300	16 Apr 2017 Xingzhuanghe-Qingkouhe	**543**	23 Oct 2016 Xingzhuanghe-Qingkouhe	30	27-Jan 2018 Xingzhuanghe-Qingkouhe
Eurasian Curlew (NT) [m] *Numenius arquata*	1000	**1110**	18 Mar 2017 Xingzhuanghe-Qingkouhe	825	25 Nov 2017 Xingzhuanghe-Qingkouhe	**2400**	11 Jan 2015 Xingzhuanghe-Qingkouhe
Eurasian Oystercatcher (NT) *Haematopus ostralegus*	110	**406**	16 Mar 2013 Xingzhuanghe-Qingkouhe	70	10 Nov 2013 Xingzhuanghe-Qingkouhe	**3130**	11 Jan 2015 Xingzhuanghe-Qingkouhe
Great Knot (EN) [m] *Calidris tenuirostris*	2900	**4520**	8 May 2018 Xiuzhenhe	**2968**	8 Aug 2012 Xingzhuanghe-Qingkouhe	350	27 Jan 2018 Xingzhuanghe-Qingkouhe
Greater Sand Plover *Charadrius leschenaultii*	790	270	1 May 2016 Mutaohe	130	Oct 2010 Liezikou	6	27 Jan 2018 Xingzhuanghe-Qingkouhe
Green Sandpiper *Tringa ochropus*	250-1000	6	8 May 2018 Mutaohe	4	Oct 2010 Linhonghe	4	12 Feb 2012 Huaguoshan Reservoir
Grey Plover [m] *Pluvialis squatarola*	1040	**8870**	16 Mar 2013 Xingzhuanghe-Qingkouhe	**3500**	19 Aug 2015 Xingzhuanghe-Qingkouhe	**3000**	20 Feb 2018 Xingzhuanghe-Qingkouhe
Grey-headed Lapwing *Vanellus cinereus*	250-1000	6	12-Mar 2011 Liezikou	8	Oct 2010 Linhonghe		
Grey-tailed Tattler (NT) [m] *Tringa brevipes*	440	25	9 May 2011 Liezikou	25	Aug 2010 Liezikou		
Kentish Plover *Charadrius alexandrinus*	1000	**2000**	Mar 2010 Linhonghe	**2500**	14 Oct 2012 Linhonghe	100	Feb 2008 Linhonghe
Lesser Sand Plover [m] *Charadrius mongolus*	385[a]	**750**	12 May 2013 Xingzhuanghe-Qingkouhe	**1425**	19 Aug 2016 Linhonghe	60	27 Feb 2018 Xingzhuanghe-Qingkouhe
Little Ringed Plover *Charadrius dubius*	250	10	16 Apr 2017 Xingzhuanghe-Qingkouhe	60	26 Jul 2011 Linhonghe		
Little Stint *Calidris minuta*	NA	1	10 Apr 2014 Linhonghe	1	8 Sep 2012 Liezikou		
Long-billed Dowitcher *Limnodromus scolopaceus*	NA	3	15 Apr 2011 Linhonghe				
Long-toed Stint *Calidris subminuta*	250	4	9 May 2011 Linhonghe	**600**	21 Jul 2012 Liezikou		
Marsh Sandpiper [m] *Tringa stagnatilis*	1000-10000	4150	18 Apr 2015 Xingzhuanghe-Qingkouhe	600	Sep 2010 Linhonghe	145	27 Jan 2018 Xingzhuanghe-Qingkouhe
Nordmann's Greenshank (EN) *Tringa guttifer*	12	**77**	12 May 2018 Xingzhuanghe-Qingkouhe	**40**	11 Oct 2015 Xingzhuanghe-Qingkouhe		
Oriental Pratincole *Glareola maldivarum*	28800	6	9 May 2011 Linhonghe	1	Oct 2010 Liezikou		
Pacific Golden Plover [m] *Pluvialis fulva*	1000	240	22 Apr 2014 Xingzhuanghe-Qingkouhe	4	15 Oct 2011 Linhonghe	1	14 Dec 2011 Linhonghe
Pied Avocet [m] *Recurvirostra avosetta*	1000	**7000**	3 Apr 2016 Xingzhuanghe-Qingkouhe	**11000**	18 Oct 2014 Xingzhuanghe-Qingkouhe	**7000**	13 Jan 2012 Linhonghe

Table 1 (*continued*)

Species	1% of EAAF Population	Maximum count, date and location					
		Northward Migration (March–June)		Southward Migration (July–November)		Wintering Period (December–February)	
Red Knot [m] *Calidris canutus*	990	**4010**	1 and 2 May 2017 Xingzhuanghe-Qingkouhe & Xiuzhenhe	300	12 Aug 2009 Liezikou	35	27 Jan 2018 Xingzhuanghe-Qingkouhe
Red-necked Phalarope *Phalaropus lobatus*	1000-10000			4	10 Sep 2017 Xingzhuanghe-Qingkouhe		
Red-necked Stint (NT) [m] *Calidris ruficollis*	3150	**4900**	18 Apr 2015 Xingzhuanghe-Qingkouhe	**6837**	8 Aug 2012 Liezikou	250	27 Jan 2018 Xingzhuanghe-Qingkouhe
Ruddy Turnstone [m] *Arenaria interpres*	285	85	5 May 2018 Xingzhuanghe-Qingkouhe	90	12 Aug 2009 Liezikou		
Ruff *Calidris pugnax*	NA	8	16 Apr 2011 Linhonghe	6	10 Sep 2017 Xingzhuanghe-Qingkouhe		
Sanderling *Calidris alba*	220	**232**	May 2010 Liezikou	200	Nov 2010 Liezikou	25	14 Feb 2011 Haitou
Sharp-tailed Sandpiper [m] *Calidris acuminata*	1600	**8000**	May 2008 Linhonghe	**3000**	19 Aug 2015 Xingzhuanghe-Qingkouhe	80	27 Jan 2018 Xingzhuanghe-Qingkouhe
Spoon-billed Sandpiper (CR) *Calidris pygmaea*	6[b]	1	22 Apr 2014 Xingzhuanghe-Qingkouhe	2	16 Sep 2016 Linhonghe		
Spotted Redshank [m] *Tringa erythropus*	250	**406**	16 Apr 2011 Linhonghe & Liezikou	**250**	26 Jul 2011 Linhonghe	48	17 Dec 2011 Liezikou
Terek Sandpiper [m] *Xenus cinereus*	500	**650**	16 Jun 2012 Linhonghe	180	10 Sep 2017 Xingzhuanghe-Qingkouhe		
Whimbrel [m] *Numenius phaeopus*	550	40	13 Jun 2009 Linhonghe	87	12 Aug 2009 Liezikou	1	27 Jan 2018 Xingzhuanghe-Qingkouhe
Wood Sandpiper *Tringa glareola*	1000	100	May 2008 Linhonghe	12	8 Sep 2012 Liezikou		

[a] For Lesser Sand Plover, the 1% threshold is derived from the population estimates of the two populations using the Yellow Sea coast (*C. m. mongolus* and *C. m. stegmanni*).
[b] For Spoon-billed Sandpiper, the 1% threshold is derived from Clark et al., 2018.

We visualized high- and low-tide locations in heatmaps based on Kernel Density Estimation, using the 'Heatmap' plugin in QGIS 2.18.11 (QGIS Development Team, 2019). The radius of each point was two times the published 68% percentile error radius (Douglas et al., 2012) and weighed by the inverse of this radius, and therefore each point is designated as the same 'heat', but is more concentrated (for class 3 locations) or spread out (for the less precise class 2 and 1 locations). We used locations at least 1 h apart from one another. If there were more than 1 locations within the hour, we chose the point with highest accuracy, or the earliest point in the case of ties. To describe daily movements, we calculated distances between pairs of points of the same individual within a high-tide, within a low-tide, and between consecutive high- and low-tide, using points that were more than 1 h apart.

2.4. Mapping changes in intertidal area

Coastal reclamations were mapped from satellite images from January 2003 to June 2018. Landsat and Sentinel-2 images of 30 m resolution were visualized in Google Earth Engine (GEE; Gorelick et al., 2017). Of the 154 satellite images acquired, we analysed 80 (52%) that had $\geq$90% of the coastline visible and not covered by clouds. Coastal reclamations usually started with enclosing an intertidal or subtidal area with seawalls, and then gradually pumped water out and filled sand in. We defined an area as 'reclaimed' when it was completely enclosed by new seawalls visualized at the scale of 1:5000. Satellite images were displayed in false colours, and reclaimed areas were manually mapped on GEE. Mudflat area was estimated from the Murray Global Intertidal Change Dataset (Murray et al., 2019). Beside natural tidal flats, this dataset include other systems with intertidal dynamics, such as rocky shores, aquaculture ponds with frequent wet-dry periods, and tidal flats undergoing reclamation. We manually excluded all these other intertidal systems to obtain the area of natural tidal flats. The rate of reclamation was calculated from 3 separate periods, the break points determined by fitting a piecewise regression onto the area-date relationship with R package 'segmented' (Muggeo, 2008). Land use of the reclaimed areas (as of June 2018) were classified into aquaculture ponds, industrial land or undeveloped land (for details see Table A.2).

2.5. Benthic survey

Sampling grids covered the main intertidal mudflats used by foraging shorebirds at Xiuzhenhe, Mutaohe and Xingzhuanghe (Fig. 1). Sampling stations were evenly distributed 250 or 500 m apart depending on the local situation (Fig. 1; for methodological rationale, see Bijleveld et al., 2012). During the spring migration period of the birds, a total of 41 stations were visited from 5 to 7 May 2015, 70 stations from 28 April to 1 May 2016, and 60 stations from 28 April to 2 May 2017. At each station, a sediment core with a surface area of 0.019 m^2 was taken to a depth of 20 cm and washed over a 0.5 mm sieve. The sieved sample was then stored frozen prior to analysis. In the laboratory, molluscs were counted, identified and measured to the species level using a dissecting microscope, and high density species were subsampled by a Motodo Splitter.

3. Results

Overall, 43 shorebird species were recorded in the surveys, including 12 globally threatened or ‘Near Threatened’ species (Table 1). For 22 species, their numbers have exceeded the 1% of the EAAF population; for 4 out of the 22 species, which are the Asian Dowitcher (*Limnodromus semipalmatus*), Black-tailed Godwit (*Limosa limosa*), Eurasian Oystercatcher (*Haematopus ostralegus*) and Pied Avocet (*Recurvirostra avosetta*), their numbers have exceeded 10% of the EAAF population. The highest total number recorded was the over 100 000 shorebirds at the Qingkouhe mudflats (area 4 in Fig. 1) on 5 May 2015. Moreover, 80 species of other waterbird families were recorded in the surveys, in which 13 were globally threatened or ‘Near Threatened’, and 7 had numbers exceeded the 1% of the EAAF population (Table A.3). Notably, the single count of 63 Dalmatian Pelican (*Pelecanus crispus*) in winter 2012 had exceeded the East Asian population estimate of 50 individuals (Wetlands International, 2018).

During both northward and southward migration, the Lianyungang Coast was used by satellite-tracked great knots and bar-tailed godwits, either as a short stop of 5–8 days, or for the long-staging individuals, their time in Lianyungang (18–30 days) was 59–100% of their staging period in the Yellow Sea. In April and May, one great knot stopped for 8 days (representing 22% of its time spent in the Yellow Sea) and two for 27 (100%) and 28 days (84%), respectively. Also, two bar-tailed godwits stopped for 5 days (SD = 0.3; 18–20%), and three for a long period of 29 days (SD = 1.5; 76–100%). During southward migration, three tracked great knots stopped for 18 days (SD = 1.4; 59–100%) in August to September, and one bar-tailed godwit stopped for 8 days (14%).

We have observed 24 species of shorebirds foraging on the intertidal mudflats from Qingkouhe to Xiuzhenhe (Table 1). During high-tide, shorebirds roosted in mixed-species flocks in aquaculture ponds or undeveloped land with little vegetation and patches of very shallow water, and sometimes on open bunds of ponds (Fig. A.1). Satellite tracking can collect distributional data even at locations that were not accessible during our surveys. During high tide, the tracked great knots mostly roosted at a piece of undeveloped reclaimed land at Xiuzhenhe, while roosts of bar-tailed godwits were scattered along the coastline (Fig. 2). At low-tide, tagged individuals of both species occurred on the Mutaohe and Xingzhuanghe mudflats, but only the great knots occurred on the Xiuzhenhe mudflats, and only the bar-tailed godwits occurred on the Linhonghe mudflats (Fig. 2). One godwit stayed at the southern tip of Liezikou but only for 5 days (Fig. 2b). Bar-tailed godwits moved shorter distances than great knots, both within and between high and low tides (Fig. 2g and 2h; Table 2).

The intertidal flats were muddy at most areas, especially at estuaries of Linhonghe, Qingkouhe and Xingzhuanghe, while sandy at Mutaohe (Fig. 1). The exotic Smooth Cordgrass (*Spartina alterniflora*) have invaded mudflats next to seawalls, and at Linhonghe extended outwards for around 500 m, and at Xiuzhenhe for around 1 km. From 2003 to 2018 a total of 71.4 km^2 of land was claimed along the Lianyungang coastline, in which 39 km^2 was converted from intertidal flats. Although 10 km^2 of new intertidal flats was formed during this period, overall there is still a net loss of 27% of intertidal flats. More than half of this new land (40.4 km^2) remained undeveloped as of June 2018. Of the land that was developed, 60.3% (18.7 km^2) were used for industrial purposes and the rest (12.3 km^2) for aquaculture ponds (Fig. 1). From January 2003, the rate of land claim was low (0.7 km^2/year), but since October 2007 it increased more than fourfold (8.3 km^2/year), before slowing down from February 2015 to June 2018 (2.5 km^2/year; for details see Fig. A.2).

A total of 25 species of molluscs were recorded in the benthic surveys (Table 3). The Xingzhuanghe and Mutaohe mudflats were dominated by *Potamocorbula laevis,* while Xiuzhenhe was dominated by *Musculus senhousia*. Although the community composition was rather different between the three areas, the most abundant species (*P. laevis, M. senhousia, Ruditapes philippiarum, Sinonovacula constricta* and *Retusa cecillii*) were all small (averaged 3.5–9.9 mm), rather soft-shelled, bivalves. These species comprised >98% of the molluscs in each area (Table 3).

4. Discussion

The high numbers of shorebirds recorded over the past decade indicate that the coastal wetlands at Lianyungang are important for shorebirds, especially during migration. Particularly, we found that Lianyungang supported over 1% of the flyway populations of 22 shorebird species. This 1% criterion is commonly used by global inventories such as the Important

Table 2
Average distances travelled within and between tidal cycles by individual bar-tailed godwits (n = 6) and great knots (n = 6) at Lianyungang based on satellite-tracked locations.

Tide type	Distance travelled (km±SD)	
	Bar-tailed godwits	Great knots
High	1.52 ± 1.20, n = 17	3.84 ± 4.55, n = 25
Low	1.94 ± 0.63, n = 3	2.76 ± 2.79 n = 14
Between consecutive high and low	3.07 ± 2.22, n = 29	6.45 ± 4.36 n = 33

n = number of pairs of points.

Table 3
Mean density (MD), percentage (Perc) and shell length of mollusc species at Xingzhuanghe, Mutaohe and Xiuzhenhe of the Lianyungang Coast.

Species (sorted by abundance)	Xingzhuanghe		Mutaohe		Xiuzhenhe		Overall MD (ind/m^2)	Shell Length		
	MD (ind/m^2)	Perc (%)	MD (ind/m^2)	Perc (%)	MD (ind/m^2)	Perc (%)		Mean (mm ± SD)	Range (mm)	Number of individuals measured
Potamocorbula laevis	21724.1	99.56	6471.2	87.52	0	0.00	9398.5	4.80 ± 2.69	1.03–27.77	4831
Musculus senhousia (Arcuatula senhousia)	14.4	0.07	390.8	5.28	1897.5	81.69	767.6	3.52 ± 2.53	1.10–19.71	569
Ruditapes philippiarum	12.8	0.06	462.8	6.26	65.9	2.84	180.5	4.31 ± 4.71	1.40–39.33	409
Sinonovacula constricta	6.3	0.03	14.1	0.19	259.8	11.19	93.4	9.87 ± 2.61	3.50–17.60	230
Retusa cecillii	0.9	0.00	0.7	0.01	60.8	2.62	20.8	4.73 ± 1.83	2.52–15.70	48
Umbonium thomasi	30.5	0.14	7.8	0.11	0.0	0.00	12.8	7.26 ± 3.16	1.67–14.81	54
Mactra veneriformis	2.8	0.01	16.3	0.22	3.9	0.17	7.6	24.24 ± 10.19	1.71–41.86	40
Moerella iridescens	9.9	0.05	4.2	0.06	5.2	0.22	6.4	7.54 ± 3.67	2.30–18.81	21
Nassarius festiva	1.8	0.01	4.9	0.07	5.2	0.22	4.0	9.72 ± 3.57	3.41–13.00	13
Salinator fragilis	0.0	0.00	0.0	0.00	10.3	0.45	3.4	2.08 ± 0.61	1.27–3.04	8
Cyclina sinensis	0.0	0.00	0.6	0.01	9.0	0.39	3.2	4.34 ± 4.00	2.11–14.55	9
Meretrix pethechialis	0.0	0.00	9.2	0.12	0.0	0.00	3.1	9.01 ± 4.85	3.20–19.60	22
Theora lata	7.2	0.03	0.7	0.01	0.0	0.00	2.6	6.40 ± 3.40	3.36–13.91	9
Bullacta exarata (B. caurina)	1.0	0.00	1.4	0.02	3.9	0.17	2.1	6.78 ± 2.30	3.95–10.88	6
Solen gouldi (S. strictus)	0.9	0.00	1.4	0.02	1.3	0.06	1.2	17.56 ± 8.20	10.23–28.69	4
Stenothyra glabra	2.7	0.01	–	–	–	–	0.9	2.96 ± 0.26	2.70–3.22	3
Meretrix meretrix	1.8	0.01	0.7	0.01	–	–	0.8	12.90 ± 17.98	1.70–33.64	3
Scapharca subcrenata (Anadara kagoshimensis)	0.9	0.00	1.4	0.02	–	–	0.8	4.24 ± 2.85	2.01–7.45	3
Endopleura lubrica	1.8	0.01	–	–	–	–	0.6	8.91 ± 1.63	7.75–10.16	2
Nassarius semiplicatus	–	–	1.4	0.02	–	–	0.5	2.64 ± 0.11	2.56–2.72	2
Nassarius variciferus	–	–	1.4	0.02	–	–	0.5	15.41 ± 2.57	13.59–17.23	2
Cerithidea sinensis	–	–	0.7	0.01	–	–	0.2	14.47	–	1
Mitrella bella (M. albuginosa)	–	–	0.7	0.01	–	–	0.2	11.48	–	1
Neverita didyma	–	–	0.7	0.01	–	–	0.2	5.49	–	1
Punctacteon yamamurae	–	–	0.7	0.01	–	–	0.2	5.84	–	1
Total	21819.8	100	7394.0	100	2322.8	100	10512.2	–	–	6292

Bird and Biodiversity Areas (IBAs) to assess site importance (BirdLife International, 2018b), and Lianyungang ranked highest among the >300 shorebird sites in East Asia with this metric being reported (Bai et al., 2015; Conklin et al., 2014; Jaensch, 2013). The occurrence of threatened waterbirds of other families, as well as the long staging duration recorded in most of the satellite-tracked individuals, boosted the importance of the site. Clearly these coastal wetlands fulfilled criteria for inclusion as an IBA and as a Ramsar site (BirdLife International, 2018b; Ramsar Convention Secretariat, 2018).

Although reclamation has taken away more than one-fourth of the intertidal habitats along the Lianyungang Coast (see Results and Fig. 1), the remaining intertidal flats are still productive; particularly, the exceptionally high densities of small soft-shelled bivalves are high-quality food for benthivorous shorebirds to refuel during their migration (Choi et al., 2017; Yang et al., 2013; Zhang et al., 2019). Compared with two other major shorebird staging sites in the Yellow Sea where benthic surveys have been conducted in spring, the mollusc densities at Lianyungang were much higher than in Yalu Jiang estuary (Zhang et al., 2018), and of similar densities as Luannan County, northern Bohai Bay (Yang et al., 2016).

While supporting a large number of shorebirds with high densities of food, the intertidal flats along the Lianyungang Coast are entirely unprotected. Immediate conservation actions are necessary to protect them from future reclamation projects, especially the core foraging areas which can be delineated from the satellite tracking data (Fig. 2). Another cause of loss of intertidal flats is the expansion of the invasive cordgrass (*S. alterniflora*). These cordgrass trap sediments and cause intertidal areas to become supratidal and lose their ecological value (Wan et al., 2009). Even worse, these supratidal habitats could be lost eventually through reclamation, as they are not considered as 'marine' and reclamation can still proceed under the new coastal reclamation policy of China (Zhao, 2018). Limiting the growth and spread of invasive cordgrass is essential to prevent further loss of intertidal flats. Moreover, it is worth to consider restoring intertidal flats by removing cordgrass at intertidal areas where it has a high coverage (Frid et al., 1999) and removing sea dikes at areas recently being enclosed but remained undeveloped (Fig. 1), e.g. where the new seawalls were built around some of our benthic sampling stations at Mutaohe (in blue outline in Fig. 1b). Additionally, human disturbances to shorebird flocks on the mudflats should be reduced, especially those caused by fishermen and their vehicles while harvesting seafood such as shellfish, crabs, fishes and worms on the mudflats (causing flocks flying up every few mins, pers obs).

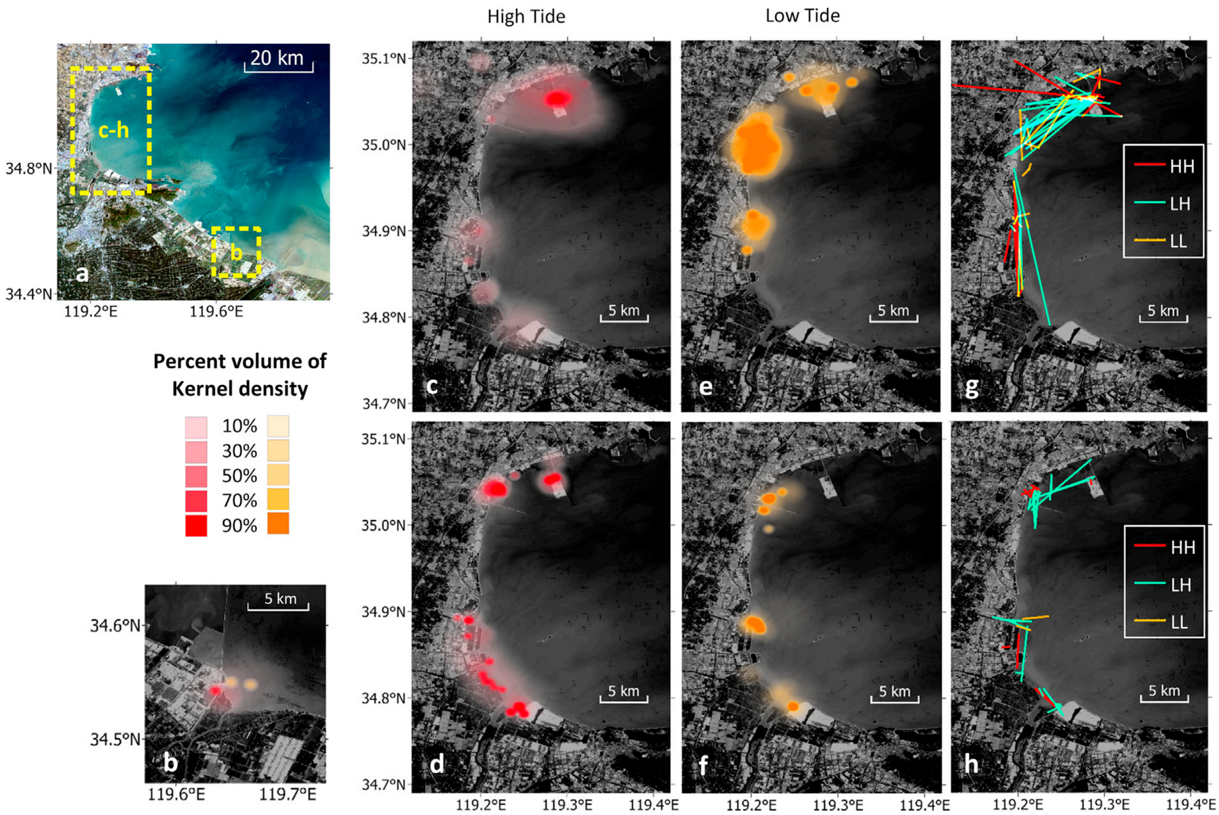

Fig. 2. (a) Areas of occurrence (yellow rectangles) of satellite-tracked great knots and bar-tailed godwits at Ganyu (c–h) and Liezikou (b) along the Lianyungang Coast. (b) High tide (red) and low tide (orange) Kernel densities of locations of an individual bar-tailed godwit at Liezikou. Kernel densities of locations during high tide and low tide for great knots (c, e) and bar-tailed godwits (d, f) at Ganyu. Movements within or between tides as depicted by lines connecting pairs of points (within a high tide-HH, between consecutive high and low tides-LH and within a low tide-LL) of the same individual for great knots (g) and bar-tailed godwits (h). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The spatial coupling of suitable supratidal high-tide roosts with the existing intertidal foraging areas is an important aspect for managing the area for shorebirds. If there are no suitable roosts nearby and/or roosts are disburbed too frequently, foraging areas may become underused or abandoned because the energetic costs of commuting and/or alarm flights outweigh the energy gain from foraging (Rogers et al., 2006). In addition to the high-tide roosts known from ground observations, satellite tracking have highlighted an important roost at the newly reclaimed 'island' at the port development area of Xiuzhenhe that is not publicly accessible (Fig. 1). This roost is intensely used by tracked great knots, and to a lesser degree by bar-tailed godwits (Fig. 2). Whether the current set of roosts are within the distance tolerated by great knots and bar-tailed godwits to commute daily can be evaluated by the travel distances between and within tides (Table 2) measured in this study. For example, a simple exercise will be to assess if suitable roosts exist within a 3 km radius (Table 2) of potential foraging area of bar-tailed godwits. If necessary, roosts can be created within this radius, either by restricting human disturbances at locations that already have the suitable biophysical features (having little or no vegetation, an open view and wet substrate; Burton et al., 1996; Zharikov and Milton, 2009; Fig. A1), or creating such habitats at the many undeveloped land along the coast (Fig. 1).

Gaps remained in our knowledge on Lianyungang Coast as our study is limited by manpower and resources; e.g. our surveys along this 162 km coastline were mostly conducted by one person (YXH) on a voluntary basis, and the number of birds using this site is likely to be considerably higher. Since the benthic sampling stations were reached by foot, sampling could not be done at the mudflats with extremely soft sediment. Nevertheless, by putting together the results from the counts, benthic surveys, satellite tracking and satellite imagery analysis, we have established the site's importance and proposed a set of site management actions. Given the fast pace of destruction and degradation of coastal habitats in Lianyungang, regular and continuous monitoring of bird numbers, movements, their food densities and habitat status are necessary. This combined issue of fast degradation and lack of related ecological knowledge is widespread in many sites in the EAAF and developing countries around the world (Lee and Khim, 2017). We hope that our study stimulates the gathering of ecological knowledge and science-based management, and the funding and facilitating of such practices from both the government and non-governmental organisations, at the many ecological important sites that are understudied (BirdLife International, 2017).

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Appendix A. Supplementary data

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