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Key research issues concerning the conservation of migratory shorebirds in the Yellow Sea region

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Summary

The widespread decline of migratory shorebirds in the East Asian-Australasian Flyway (EAAF) is one of the greatest crises for migrating birds. Among the migratory species with known population trends, 88% (22 of 25 species) show population declines, and seven have been listed as threatened or Near Threatened in the IUCN Red List. The decline of migratory shorebirds is related to the deterioration of stopping sites (including staging and stopping sites) in the Yellow Sea, including loss of intertidal wetlands, spread of invasive smooth cordgrass *Spartina alterniflora* on intertidal flats, an increase in pollution, and an increase in human disturbance. We review research concerning shorebird migration through the Yellow Sea and highlight key research activities required for the conservation of shorebirds in the region. These activities include: confirming the population consequences of loss of stopping sites, estimating migration timing and numbers of shorebirds at stopping sites, determining the differing abilities of species to use alternative habitats, understanding intra- and interspecific differences in the use of stopping sites, maintaining and expanding surveys on shorebirds and habitat condition, and identifying threats to shorebirds beyond habitat loss by reclamation. The information generated by these research activities is required for the design and selection of effective conservation actions to reverse the decline in shorebird populations.

Introduction

The migration of birds is an amazing natural phenomenon that is threatened by global change (Wilcove and Wikelski 2008). Currently, one of the greatest crises of migratory birds is the widespread population decline of migratory shorebirds in the East Asian-Australasian Flyway (EAAF) (Kirby 2011, MacKinnon *et al.* 2012). The EAAF covers a vast region stretching from the Arctic in Siberia and Alaska southwards through East and South-East Asia to Australia and New Zealand (Figure 1). Among the global flyways, the EAAF supports the highest numbers of shorebird species and individuals (58 species and five million individuals; Table 1) (Wilson 2003, Stroud *et al.* 2006) but also includes the highest number of threatened species and declining populations (Kirby 2011, Wetlands International 2012). Among the migratory species with known population trends, 88% (22 of 25 species) show population declines, and seven have been listed as threatened or Near Threatened in the IUCN Red List (Table 1; data from Wetlands International 2012). It is clearly important to determine the reasons for these population declines and that we take effective conservation measures.

Because the environment in shorebird breeding and non-breeding grounds has been relatively stable, the population decline of migratory shorebirds in the EAAF has been linked to the loss and degradation of stopping sites (including staging and stopping sites) *en route* (reviewed in MacKinnon *et al.* 2012). Most shorebirds depend on intertidal wetlands at stopping sites and non-breeding grounds. Many researchers have concluded that the major cause of population

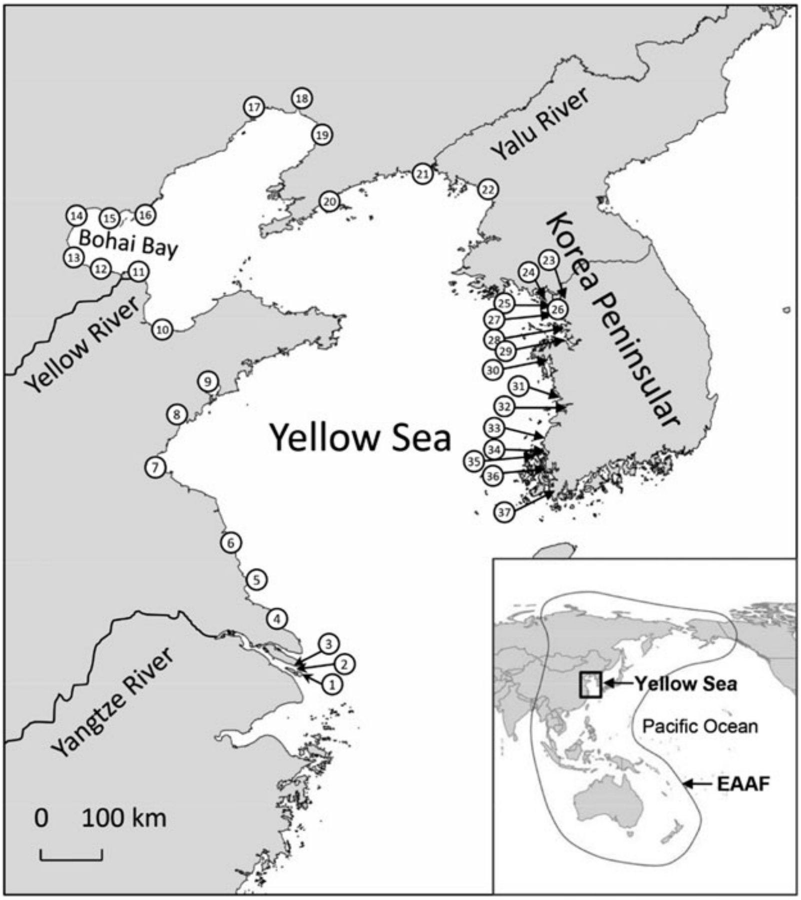

Figure 1. Location of sites that support at least one shorebird species that meets the 1% criterion of Ramsar sites (the site is visited by > 1% of the total population in the flyway). Site names in the figures: 1: Jiuduansha Nature Reserve; 2: Hengsha East Shore; 3: Chongming Dongtan Nature Reserve; 4: Rudong Coast; 5: Dongsha Islands; 6: Yancheng Nature Reserve; 7: Haizhou Bay; 8: Qizi Bay; 9: Jiaozhou Bay; 10: Laizhou Bay; 11: Yellow River Delta Nature Reserve; 12: South Bohai Bay; 13: Southwest Bohai Bay; 14: Northwest Bohai Bay; 15: Luannan Coast; 16: Shi Jiu Tuo/Daqing He; 17: Linghe Estuary; 18: Shuangtaizihekou Nature Reserve; 19: Northeast Liaodong Bay; 20: South Dalian Peninsula; 21: Yalu Estuary Nature Reserve; 22: Mundok Migratory Bird Wetland Reserve; 23: Han-Imjin Estuary; 24: Ganghwa Island; 25: Yeongjong Island (south); 26: Song Do; 27: Daebu Island; 28: Namyang Bay; 29: Asan Bay; 30: Cheonsu Bay; 31: Geum Estuary; 32: Saemangeum Area; 33: Paeksu Tidal flat; 34: Hampyeong Bay; 35: Muan-Gun Tidal flats; 36: Aphae Island; 37: Haenam Tidal flats. Data are absent for North Korea except for limited information from Mundok Migratory Bird Wetland Reserve. Barter (2002) included Suncheon Bay and Nakdong Estuary along the southern coast of the Korean Peninsula among 27 sites that meet the 1% criterion of Ramsar sites. We did not include these two sites because they are outside of the traditional Yellow Sea region. Data sources: Barter (2002), Moores (2006), Yang (2006), and China Coastal Waterbird Census Group (2009, 2011).

Table 1. Checklists of migratory shorebirds in the Yellow Sea. Species that are only occasionally recorded in the Yellow Sea but are abundant in other flyways are not included. Species that meet the 1% criterion of Ramsar sites (the site is visited by > 1% of the total number in the flyway) at one or more sites in the Yellow Sea are marked with an asterisk (*). LC, NT, VU, EN, and CR indicate the IUCN Red List categories of Least Concern, Near Threatened, Vulnerable, Endangered, and Critically Endangered, respectively. Under "Population trend," DEC, INC, and FLU indicate that the population has been decreasing, increasing, or fluctuating, respectively. Data are from Barter (2002), Chen (2006), Moore (2006), Bamford *et al.* (2008), and China Coastal Waterbird Census Group (2009, 2011). Population trends are from Wetlands International (2012).

Species	Scientific name	Red List category	Population trend
Common Snipe	*Gallinago gallinago*	LC	Unknown
Japanese Snipe	*Gallinago hardwickii*	LC	DEC
Swinhoe's Snipe*	*Gallinago megala*	LC	Unknown
Solitary Snipe	*Gallinago solitaria*	LC	Unknown
Pintail Snipe	*Gallinago stenura*	LC	Unknown
Wood Snipe	*Gallinago nemoricola*	LC	DEC
Jack Snipe	*Lymnocryptes minimus*	LC	Unknown
Eurasian Woodcock	*Scolopax rusticola*	LC	Unknown
Black-tailed Godwit*	*Limosa limosa*	NT	DEC
Bar-tailed Godwit*	*Limosa lapponica*	LC	DEC
Little Curlew*	*Numenius minutus*	LC	Unknown
Whimbrel*	*Numenius phaeopus*	LC	DEC
Eurasian Curlew*	*Numenius arquata*	NT	Unknown
Far Eastern Curlew*	*Numenius madagascariensis*	VU	DEC
Spotted Redshank*	*Tringa erythropus*	LC	Unknown
Common Redshank*	*Tringa totanus*	LC	Unknown
Marsh Sandpiper*	*Tringa stagnatilis*	LC	Unknown
Common Greenshank*	*Tringa nebularia*	LC	Unknown
Spotted Greenshank*	*Tringa guttifer*	EN	DEC
Green Sandpiper	*Tringa ochropus*	LC	Unknown
Wood Sandpiper*	*Tringa glareola*	LC	Unknown
Terek Sandpiper*	*Xenus cinereus*	LC	Unknown
Common Sandpiper*	*Actitis hypoleucos*	LC	Unknown
Grey-tailed Tattler*	*Heteroscelus brevipes*	LC	DEC
Ruddy Turnstone*	*Arenaria interpres*	LC	DEC
Asian Dowitcher*	*Limnodromus semipalmatus*	NT	DEC
Great Knot*	*Calidris tenuirostris*	VU	DEC
Red Knot*	*Calidris canutus*	LC	DEC
Sanderling*	*Calidris alba*	LC	Unknown
Red-necked Stint*	*Calidris ruficollis*	LC	Unknown
Long-toed Stint*	*Calidris subminuta*	LC	Unknown
Temminck's Stint*	*Calidris temminckii*	LC	Unknown
Sharp-tailed Sandpiper*	*Calidris acuminata*	LC	Unknown
Dunlin*	*Calidris alpina*	LC	DEC
Curlew Sandpiper*	*Calidris ferruginea*	LC	DEC
Spoon-billed Sandpiper*	*Eurynorhynchus pygmeus*	CR	DEC
Broad-billed Sandpiper*	*Limicola falcinellus*	LC	Unknown
Rock Sandpiper	*Calidris ptilocnemis*	LC	Unknown
Red-necked Phalarope*	*Phalaropus lobatus*	LC	DEC
Asian Painted-snipe	*Rostratula benghalensis*	LC	Unknown
Pheasant-tailed Jacana	*Hydrophasianus chirurgus*	LC	DEC
Pheasant-tailed Jacana	*Hydrophasianus chirurgus*	LC	DEC
Eurasian Oystercatcher*	*Haematopus ostralegus*	LC	Unknown
Black-winged Stilt*	*Himantopus himantopus*	LC	Unknown
Pied Avocet*	*Recurvirostra avosetta*	LC	Unknown
Pacific Golden Plover	*Pluvialis fulva*	LC	Unknown

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Table 1. Continued.

Species	Scientific name	Red List category	Population trend
Grey Plover*	*Pluvialis squatarola*	LC	DEC
Little Ringed Plover*	*Charadrius dubius*	LC	Unknown
Kentish Plover*	*Charadrius alexandrinus*	LC	Unknown
Double-banded Plover	*Charadrius bicinctus*	LC	DEC/INC?
Lesser Sand Plover*	*Charadrius mongolus*	LC	DEC/Unknown
Greater Sand Plover*	*Charadrius leschenaultii*	LC	DEC
Long-billed Plover	*Charadrius placidus*	LC	DEC
Oriental Plover*	*Charadrius veredus*	LC	Unknown
Grey-headed Lapwing*	*Vanellus cinereus*	LC	DEC
Northern Lapwing*	*Vanellus vanellus*	LC	Unknown
Oriental Pratincole	*Glareola maldivarum*	LC	Unknown
Australian Pratincole	*Stiltia isabella*	LC	FLU

declines in the EAAF is the loss of intertidal wetlands in the Yellow Sea (Figure 1), which contains the most important stopping sites in the flyway (e.g. Rogers *et al.* 2009, Amano *et al.* 2010, Wilson *et al.* 2011, Szabo *et al.* 2012).

The Yellow Sea (including Bohai Bay) is a semi-enclosed, shallow sea between the Korean Peninsula in the east and the Chinese mainland in the north and west (Figure 1). It extends for 1,000 km from north to south and 700 km from east to west. The total area of intertidal wetlands in the Yellow Sea is about 20,000 km^2 (Chen 2006). Field surveys have revealed that the Yellow Sea region is critical for migratory shorebirds in the EAAF (Barter 2002, Chen 2006, Moores 2006, Bamford *et al.* 2008). Annually, over two million shorebirds, or about 40% of the total birds in the flyway, stop over in the Yellow Sea during their northward migration, and about one million during their southward migration (Barter 2002, Bamford *et al.* 2008). At least 41 shorebird species occur in "internationally important numbers" (> 1% of the total number in the flyway) at one or more sites in the Yellow Sea (Table 1), and 37 sites support (or until recently supported) at least one shorebird species with internationally important numbers (Figure 1). Moreover, more than 30% of the estimated flyway breeding populations of 18 shorebird species stop over in the Yellow Sea during their northward migration, and the region supports almost the entire flyway breeding population for at least six species (Barter 2002).

Many shorebird species use intertidal wetlands, and the intertidal specialists are restricted to these habitats except when breeding. However, intertidal wetlands in the Yellow Sea have suffered serious pressure from increases in the human population and rapid economic development. About 600 million people (> 8% of the global population) live in the Yellow Sea region in China, North Korea, and South Korea (Chen 2006) and this region is experiencing rapid economic development. This has caused dramatic environmental changes, including the loss of intertidal wetlands, spread of invasive smooth cordgrass *Spartina alterniflora* on intertidal flats, an increase in pollution and an increase in human disturbance. All of these have seriously harmed migratory shorebirds (reviewed in MacKinnon *et al.* 2012).

Developing effective measures for the conservation of shorebirds will depend on understanding their current status, population trends and the effects of environmental change. Research can provide solid evidence of the actual effect of threats on shorebirds and predict what will happen in the future, thus offering guidance for conservation actions. This paper reviews recent studies on shorebirds in the Yellow Sea and discusses key research on six topics required for prioritizing conservation objectives, setting targeted actions and evaluating conservation effectiveness (Table 2): 1) confirming the population consequences of loss of stopping sites; 2) estimating migration timing and numbers of shorebirds at stopping sites; 3) determining the differing abilities of species to use alternative habitats; 4) understanding intra- and interspecific differences in the use of stopover sites; 5) maintaining and expanding surveys of shorebirds and their habitats; 6) Identifying threats to shorebirds beyond habitat loss by reclamation.

Table 2. Key research issues and their main targets for conservation actions

Research issues	Targets for conservation actions
Confirming population consequences of loss of stopping sites	Convincing conservation necessity
Estimating migration timing and numbers of shorebirds at stopping sites	Prioritizing conservation sites
Determining different abilities of species to use alternative habitats	Prioritizing conservation objectives
Understanding intra- and interspecific differences in the use of stopping sites	Setting targeted conservation actions
Maintaining and expanding surveys on shorebirds and habitat condition	Evaluating conservation effectiveness
Identifying threats to shorebirds beyond habitat loss by reclamation	Making conservation integrity

1) Understanding the population consequences of loss of stopping sites

Although many studies have linked shorebird population declines in the EAAF to the loss of stopping sites in the Yellow Sea, solid evidence is still lacking. A frequently mentioned piece of evidence is that the population decline of Great Knots *Calidris tenuirostris* in their non-breeding grounds followed reclamation at the Dongjin and Mangyeong Estuary (Saemangeum) on the east coast of the Yellow Sea. This reclamation, which caused a decline of nearly 90,000 Great Knots in the enclosed and surrounding area during northward migration (Moores *et al.* 2008), just matched the population decline of Great Knots on the main non-breeding grounds in north-west Australia (Rogers *et al.* 2009). At the same time, however, the Great Knot wintering population was increasing in South-East Asia, perhaps because of a northward shift in their non-breeding distribution (Round 2006, D. Melville pers. comm.).

Loss of stopping sites, especially refuelling sites, can have two important consequences for shorebird populations: 1) Birds may not be able to store sufficient fuel for the ongoing migratory flight and thus fail to arrive at their destination; and 2) birds can arrive at their destination but perform poorly because of the carry over effects of inadequate refuelling *en route*, which could reduce reproductive success (Morrison *et al.* 2007, Vézina *et al.* 2012).

Comparing population survival rates at different life history stages is an effective method for elucidating the population consequences of loss of stopping sites. Over the past two decades in the EAAF, hundreds of thousands of shorebirds have been individually marked with traditional metal rings, engraved leg-flags, and combinations of colour rings (Minton 2005, Tang *et al.* 2011), providing an opportunity to estimate population survival rates at different stages in the annual cycle according to the recapture and resighting of marked individuals (Leyrer *et al.* 2013, Lok *et al.* 2013, Piersma *et al.* in prep.). Although monitoring population status is difficult at breeding grounds, where birds generally disperse over a large area, shorebirds concentrate in large flocks at stopping and wintering sites. The increasing numbers of birdwatchers and volunteers in the Yellow Sea region has led to a substantial increase in the reporting rate of marked individuals (e.g. Minton *et al.* 2011a, China Coastal Waterbird Census Group 2011).

Moreover, the combination of survival modelling with monitoring the age structure of populations (e.g. the ratio of first-year birds to total birds in non-breeding grounds) may provide the first indications of change in populations, which will be helpful in detecting the effects of loss of stopping sites on reproductive success and/or population dynamics of migratory shorebirds (Minton *et al.* 2005, Robinson *et al.* 2005, Rogers *et al.* 2005). Most shorebird species have differences in moult between age classes (e.g. adult vs. first-year birds); this makes it feasible to record the age ratio in flocks through visual scans (Lemke *et al.* 2012). Monitoring age structure also helps to understand the effects of environmental changes on different age classes (e.g. Gill *et al.* 2014).

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2) *Estimating migration timing and numbers of shorebirds at stopping sites*

Understanding the importance of a stopping site depends on accurate estimates of the numbers of birds that use the site. Since the 1980s in South Korea and since the mid-1990s in China, shorebird surveys conducted along the coasts of the Yellow Sea have provided valuable data concerning the importance of this region for migrating shorebirds in the EAAF (Table 1, Figure 1). Most of these surveys are "peak counts", i.e. they are conducted at the peak of migration. However, because arrival and departure times differ among individuals, the peak number of shorebirds that use a site will be consistent with the actual number only when departure occurs after all the individuals have arrived. Otherwise, peak counts will underestimate the number of birds by missing either the early departures or the late arrivals. Such underestimation is common at temporary stop-over sites where the migration period of the population is much longer than the length of stay of individual birds. At Chongming Dongtan in the southern Yellow Sea, for example, the migration period of Great Knots lasts for one month while the length of stay of individual birds is shorter than three days (Ma *et al.* 2013). As a consequence, many more birds pass through Chongming Dongtan than are detected by peak counts during migration.

Comparing the migration periods of species and length of stay of individuals is helpful in estimating the population turnover rate and thus the total number of birds that a site supports. Although the migration periods of species can be determined by bird counts, length of stay of individual birds is difficult to determine. Determining the arrival and departure times of individual birds has become increasingly possible because of the recent miniaturisation of remote-tracking equipment (satellite tags can weigh < 5 g) (e.g. Battley *et al.* 2012). Light-level geolocators also provide information of time schedules, especially for small and medium-sized species, and have been used for shorebirds in the EAAF (Minton *et al.* 2011b, Conklin *et al.* 2013). However, the migration routes of only a few species along the EAAF have been established with satellite tags (e.g. Bar-tailed Godwit *Limosa lapponica*, Battley *et al.* 2012; Far Eastern Curlew *Numenius madagascariensis*, Driscoll and Ueta 2002) or light-level geolocators (e.g. Ruddy Turnstone *Arenaria interpres* and Greater Sand Plover *Charadrius leschenaultia*, Minton *et al.* 2011b).

Length of stay of individual birds can also be estimated by the resighting of marked individuals in the field and the use of a capture-recapture model (Schaub *et al.* 2001, Verkuil *et al.* 2010, Masero *et al.* 2011) and, when modelled together with regular count data, researchers can estimate the total number of birds passing through (e.g. Gillings *et al.* 2009). In addition, modelling of continuous bird count data can also be used to estimate the actual number of birds at the stopping sites (Thompson 1993, Rogers *et al.* 2010, Choi *et al.* 2014a). This approach can be used on all species, in contrast to satellite telemetry (only possible on larger species) or geolocators (only practical for species with high recapture rates to retrieve geolocators).

Changes in migration timing at stopping sites (including changes in the rates of mass gain or a change in body condition at departure, see below) might reflect habitat changes and could be an early warning of population decline. For example, when food is insufficient at a site, birds might depart later and/or leave the site with lower fuel store than usual (Baker *et al.* 2004). Against the background of global climate change, migration timing of shorebirds may not keep pace and phenological mismatch between breeding and times of peak food availability might occur (e.g. Pearce-Higgins *et al.* 2005). At the moment there is still a lack of studies on the population consequences of changes in shorebird migration timing at stopping sites in the EAAF.

3) *Determining different abilities of species to use alternative habitats*

Although natural intertidal wetlands have been rapidly lost over the past three decades in the Yellow Sea (Ma *et al.* 2014, Murray *et al.* 2014), the area of artificial wetlands has increased, at least

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in China, because large areas of intertidal wetlands have been enclosed and changed into aquaculture ponds, saltworks, and paddyfields (Niu *et al.* 2012). Many studies have indicated that artificial wetlands provide both foraging and roosting habitats for various shorebirds (Masero *et al.* 2000, Barter *et al.* 2003, Ma *et al.* 2004, Moores 2006) and may mitigate the adverse effects of loss of intertidal wetlands. Effective management plays a critical role in enhancing the habitat quality of artificial wetlands for shorebirds (Elphick 1996, Erwin 2002, Ma *et al.* 2010). Unfortunately, artificial wetlands cannot completely substitute for natural intertidal wetlands as shorebird habitats (Ma *et al.* 2004). Specialists that rely exclusively on intertidal wetlands as foraging habitats are more likely to suffer from the loss of intertidal wetlands than habitat generalists.

A recent study indicated that, in the Africa-Eurasian flyway, Ruff *Philomachus pugnax* changed their migration route in response to the loss of refueling sites along their original migration route (Verkuil *et al.* 2012). Similarly, the use of new refueling sites by Black-tailed Godwit *Limosa limosa islandica* in the Netherlands and eastern England appears to be a response to environmental changes on their migration route (Alves *et al.* 2012). For those intertidal specialists in the EAAF, however, change in migration route is unlikely because the Yellow Sea is irreplaceable along their migration. Two case studies indicated that the response to the loss of intertidal wetlands in the Yellow Sea might be different for intertidal specialists (like Red Knot *Calidris canutus* and Great Knot) than for other shorebirds: first, after the surrounding intertidal wetlands had been lost on the Luannan Coast, Red Knots concentrated in the small area of intertidal wetlands that remained (Yang *et al.* 2011); second, the local population of Great Knots dramatically decreased after reclamation of the Saemangeum area (Moores *et al.* 2008). This suggests that population declines caused by reclamation of stopping sites may vary according to the condition of surrounding habitats: the very abundant food along the Luannan Coast (Yang *et al.* 2013) can still support large numbers of Red Knots, while high quality foraging habitats might be limited in the regions surrounding Saemangeum. Monitoring the population dynamics and spatial distribution of intertidal specialists will help us understand the response of shorebirds to habitat loss and help answer questions such as "Will some species refuel in the middle or southern Yellow Sea if their refuelling sites in the north have been lost?" Satellite tracking is an effective method to detect flexibility in habitat use (or the shift of stopping sites) after the loss of intertidal habitats. Moreover, population monitoring will also help researchers identify those forces that drive the evolution of migration routes and strategies.

4) Understanding intra- and interspecific differences in the use of stopping sites

Stopping sites can be classified as staging sites, where birds deposit large amounts of fuel, or as stop-over sites, where birds deposit smaller amounts of fuel or do not refuel at all (Warnock 2010). As critical refuelling sites for migratory birds, staging sites are a conservation priority. Although field surveys on the species and numbers of individuals at different stopping sites have provided valuable data for illustrating the importance of the Yellow Sea for shorebirds (Barter 2002, Chen 2006, Moores 2006), the functions of different stopping sites for shorebirds are still largely unexplored. For the northward migration of Great Knots, recent studies have indicated that the northern Yellow Sea provides critical refuelling sites, while the southern Yellow Sea supports temporary stop-over sites for weak individuals or for individuals under bad weather conditions (Ma *et al.* 2011, 2013). Studies have also indicated that Red Knots in the northern Yellow Sea take on large amounts of fuel that support both their northward migratory flight and their breeding ground activities (Hua *et al.* 2013). These results highlight the importance of conserving refuelling sites in the northern Yellow Sea. The temporary stop-over sites in the southern Yellow Sea are also important for maintaining a stable population as they provide "stepping stones" for weak individuals and for birds experiencing bad weather (Ma *et al.* 2013).

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There are also interspecific differences in the spatial distribution of refuelling sites for shorebirds in the Yellow Sea. Although species that migrate via "long-distance jumps" (such as Great Knots and Red Knots; Piersma 1987) are likely to use only the northern Yellow Sea for their refuelling sites during northward migration, those species that migrate via "short-distance hops and skips" may require more refuelling sites in the southern and middle Yellow Sea. Moreover, habitat and food conditions affect the use of refuelling sites. For example, although both Red and Great Knots mainly consume bivalves in the northern Yellow Sea, the Red Knots concentrate in a small area on the Luannan Coast (Yang *et al.* 2011) and are uncommon at other sites along the eastern and northern coasts of the Yellow Sea. Great Knots, however, are dominant in the Yalu Estuary and Shuangtaizi Estuary in the northern Yellow Sea and also form large flocks on the Luannan Coast (Barter 2002, Chen 2006). This might be related to the different sizes of bivalves on the tidal flats among sites: being small, the Red Knots prefer small bivalves that are dominant along the Luannan Coast, while the larger Great Knots prefer the larger bivalves that are dominant in the Yalu Estuary but they can also forage on small bivalves (Yang *et al.* 2013, H. B. Peng and Z. J. Ma pers. obs.). Curlew Sandpipers *Calidris ferruginea* concentrate on the Luannan Coast, perhaps because the large area of saltworks there provides them with suitable foraging habitat (Yang 2006). Those habitat and food specialists might suffer more seriously from habitat loss and degradation than those generalists (Rogers and Gosbell 2006, MacKinnon *et al.* 2012, Yang *et al.* 2013).

As indicated in the previous paragraph, understanding the habitat and food conditions at different sites is helpful for understanding the spatial distribution of shorebirds. Except for a few sites (Zhu *et al.* 2007, Yang *et al.* 2013, Choi *et al.* 2014b), however, such information is unavailable for the Yellow Sea. Although there have been extensive surveys on the macrobenthos along the coasts of the Yellow Sea, most of these surveys have focused on economic species, which might be unavailable to shorebirds. Moreover, reclamation, pollution, eutrophication, and overexploitation over the past two decades have seriously damaged the benthic community along the Yellow Sea coast, and this damage has been both direct and indirect; indirect damage results from changes in hydrology, sedimentation, and trophic levels (Choi *et al.* 2010). This damage to the benthic community has affected, and will continue to affect, use of the Yellow Sea by shorebirds. Understanding habitat and food conditions at different sites also helps in predicting the effects of ongoing and future environmental changes on shorebirds.

5) Maintaining and expanding surveys on shorebirds and their habitats

In order for conservation to be effective, research on demography and the annual cycle is essential to demonstrate where and when the population occurs in the flyway during the year. Although shorebird counts have indicated that a total of 37 sites in the Yellow Sea region support at least one shorebird species that meets the 1% criterion of Ramsar sites (Figure 1), those data were gathered from shorebird surveys since 1990s; some sites have not been visited again in recent decades. Because reclamation and development have dramatically changed the coastline of the Yellow Sea (MacKinnon *et al.* 2012, Ma *et al.* 2014, Murray *et al.* 2014), intensive development at some sites might have weakened their function as shorebird habitats. Regular surveys of shorebirds are important to evaluate conservation effectiveness at important sites (e.g. Ramsar sites and Important Bird Areas) and to take conservation action to reverse the disadvantageous changes.

With the rapid development of birdwatching in mainland China since the year 2000, an increasing number of birdwatchers have travelled to the coast and counted shorebirds during the migration season (Ma *et al.* 2013). Although information is lacking about shorebirds during the southward migration in China up to the early 2000s (Barter 2002, Chen 2006), local birdwatchers and volunteers have since provided a large amount of information concerning the use of stopping sites by shorebirds in the Yellow Sea during both the northward and southward migration (e.g., China Coastal Waterbird Census Group 2009, 2011). For example, more than 100 individuals of the Critically Endangered Spoon-billed Sandpiper *Eurynorhynchus pygmeus* were recorded at Rudong in October 2011, 2012, and 2013, suggesting that this region has been a stable stop-over site during the southward migration (Tong *et al.* 2012, J. Li pers. comm.). Shorebird surveys during the southward migration at the Yalu Estuary detected at least 13 species whose numbers were > 1% of their total flyway population estimates, including a peak number of 7,486 Far Eastern Curlews, equivalent to 23% of the total flyway population (Bai *et al.* 2012). This highlights the importance of the Yalu Estuary for shorebirds during their southward migration.

In contrast, the information about migratory shorebirds on intertidal wetlands in North Korea is quite limited. In light of the rapid loss of these wetlands in China and South Korea, the intertidal wetlands in North Korea, which have remained stable in area over the past three decades (Murray *et al.* 2014), might be increasingly important for the conservation of shorebirds along the EAAF.

In order to explain the population changes of shorebirds at stopping sites, one of the key issues is to track habitat changes. The rapid development of remote sensing techniques provides an effective tool for understanding land use and land cover changes over extensive areas and in the long-term (e.g. Murray *et al.* 2014). Monitoring habitat condition involves both abiotic and biotic factors, e.g. changes in the tidal area caused by reclamation, sedimentation, and erosion, vegetation area and composition (including the spread of invasive plants), macrobenthos that provide food for shorebirds, and pollutants at stopping sites (see below). All these might affect shorebirds directly or indirectly.

It is also important to gather the data on shorebirds and their habitats into a single database which is accessible to researchers, birdwatchers, conservationists and policy makers along the flyway. Comprehensive analysis of the data from long-term surveys at different stopping sites will be helpful in understanding the spatial and temporal changes in shorebirds associated with regional environmental changes, which are unlikely to cease in the near future.

6) Identifying threats to shorebirds beyond habitat loss by reclamation

Although the loss of intertidal wetlands in the Yellow Sea by reclamation is recognised as the most critical threat to migratory shorebirds along the EAAF (Moores *et al.* 2008, Amano *et al.* 2010, Wilson *et al.* 2011), there are other threats. Pollution is a potentially serious, but overlooked, threat to shorebirds in the Yellow Sea. Many studies have indicated the adverse effects of organic and non-organic pollutants and bioaccumulation of pollutants amplifies the adverse effects on long-lived birds (Rowe 2008). Although the eastern coast of the Yellow Sea is relatively free of pollution (Hong *et al.* 2006), the northern and north-eastern coasts of China have experienced rapid industrial and agricultural development, resulting in substantial pollution of intertidal wetlands (Academic Divisions of CAS 2010, Zhang *et al.* 2012). Recent data indicate that China's coastal wetlands have suffered from serious pollution and that Bohai Bay in the north-western Yellow Sea has been particularly affected (SOA 2013). For example, the level of persistent organic pollutants in shellfish exceeded the quality control standards of the U.S. Environmental Protection Agency at most sampling sites in Bohai Bay (Fan *et al.* 2008). Shorebirds consume large amounts of macrobenthos for fuel deposition, and some species double their body mass during their stay in the Yellow Sea (Hua *et al.* 2013, Ma *et al.* 2013). Pollutants will be taken up along with nutrients when shorebirds feed. Because shorebirds are long-lived (many recaptured individuals are > 10 years old), the effects of pollutants and their bioaccumulation cannot be ignored.

Along China's coasts, the exotic smooth cordgrass, which originated on the east coast of America and which was intentionally introduced into China in 1979, has spread rapidly through the intertidal wetlands over the past three decades and has occupied 25,000 ha in the Yellow Sea region (2007 data; Zuo *et al.* 2009). Because cordgrass stands are dense, they hinder shorebird movements and the spread of cordgrass has therefore caused a net loss of shorebird habitat (Gan *et al.* 2009). Cordgrass continues to spread on the intertidal wetlands, and such spread further adds to the losses caused by reclamation. Although there have been some trials of cordgrass removal from tidal flats (Ding *et al.* 2011, GFN 2014), the effectiveness of these trials remain to be seen.

Another threat is the increase in human activity on the coast, which disturbs the foraging and roosting of shorebirds and thus decreases their fuel deposition efficiency at refuelling sites. The effects of human disturbance at refuelling sites might be especially serious when food is insufficient. In addition, poaching still occurs in the Yellow Sea region and especially in China, although hunting has been legally prohibited since the 1980s and has probably declined in recent years. Moreover, accidental by-catch of shorebirds in fishing nets on the intertidal flats frequently occurs in some regions (Z. J. Ma pers. obs.).

Yet another threat to shorebirds that use the Yellow Sea region for refuelling during migration is the loss of tidal flats driven by reduced sedimentation from major rivers because of dams and barrages (CCICED 2011, Murray *et al.* 2014). Moreover, a rise in the level of the Yellow Sea (Iwamura *et al.* 2013, 2014) would further exacerbate the loss of available intertidal wetlands caused by reclamation and erosion.

Conclusions

Bird surveys conducted since the 1980s have revealed the importance of the Yellow Sea for migratory shorebirds in the EAAF (Barter 2002, Chen 2006, Moores 2006). Recent international and regional cooperation among shorebird researchers has increased our understanding of the migration ecology of shorebirds (Rogers *et al.* 2010, Battley *et al.* 2012, Ma *et al.* 2013, Yang *et al.* 2013). Results from these studies provide a foundation for designing conservation measures, some of which have been put into practice; these protective measures include the establishment of protected areas and the designation of sites as "wetlands of international importance" (Chen *et al.* 2006). However, threats to shorebirds are numerous and may increase in future (MacKinnon *et al.* 2012, Ma *et al.* 2014, Murray *et al.* 2014). To counter these threats and to reverse the decline of shorebird populations, ornithologists and conservationists must work together to clarify the problem for the public and for policy-makers and to provide solid evidence in support of effective conservation actions. Besides the six key issues mentioned in this paper, some examples in other flyway can be helpful (e.g. Davidson *et al.* 1998, Bart *et al.* 2005, Sutherland *et al.* 2012).

In addition to providing stopping sites for millions of shorebirds in the EAAF, the intertidal wetlands in the Yellow Sea support a rich, internationally shared biodiversity and provide enormous ecosystem services (MacKinnon *et al.* 2012, Murray *et al.* 2014). Conservation of intertidal habitats will not only benefit shorebirds but will also benefit society as a whole by ensuring that intertidal wetlands provide the valuable ecosystem services required for sustainable development.

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