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Moores, Nial; Rogers, Danny I.; Rogers, Ken; Hansbro, Philip M. "Reclamation of tidal flats and shorebird declines in Saemangeum and elsewhere in the Republic of Korea". Originally published in Emu Vol. 116, Issue 2, p. 136-146 (2016)

Available from: <http://dx.doi.org/10.1071/MU16006>

Accessed from: <http://hdl.handle.net/1959.13/1323952>

Tidal-flat Reclamation and Shorebird Declines in Saemangeum and the Republic of Korea

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Abstract. Saemangeum in the Republic of Korea (ROK, "South Korea") was one of the most important shorebird staging sites in the Yellow Sea. It supported at least 330,000 shorebirds annually in 1997-2001 including ~ 30% of the world population of Great Knot (*Calidris tenuirostris*) during both northward and southward migration. Construction of a 33km long seawall was completed in April 2006. We show that shorebird numbers at Saemangeum and two adjacent wetlands decreased by 130,000 during northward migration in the next two years. All species declined, with Great Knot among the most rapidly affected. National surveys (2008, 2011-2013) revealed further declines in shorebirds at Saemangeum, with fewer than 5,000 individuals recorded there during northward migration in 2014. We found no evidence to suggest that the majority of shorebirds of any species displaced from Saemangeum successfully relocated to other ROK sites. Instead, by 2011-2013 nearly all species had declined substantially in the ROK since previous national surveys in 2008 and 1998, especially at more heavily reclaimed sites. It is likely that these declines were driven by increased mortality rather than movement to alternate staging sites given that other studies have revealed concurrent declines in numbers and survival on the non-breeding grounds.

Key words

Shorebird, Reclamation, Saemangeum

Introduction

There is a growing body of literature describing rapid declines in the populations of many migratory shorebird species in the East Asian-Australasian Flyway (EAAF) (Amano et al. 2010; Wilson et al. 2011; Conklin et al. 2014; Piersma et al. 2016; Clemens et al. 2016). A number of publications present arguments that identify tidal-flat reclamation (defined as the conversion of natural wetland into dry land and artificial wetland by mechanical means: Birds Korea 2010) as the most probable cause of shorebird declines, first in Japan (Hanawa 1985), and more recently along the Yellow Sea coast shared by China,

the Republic of Korea (ROK, also known as South Korea) and the DPR Korea (e.g. Barter 2002; Moores 2006; Rogers et al. 2009; MacKinnon et al. 2012; Ma et al. 2014; Piersma et al. 2016).

In the ROK, where hundreds of thousands of shorebirds were previously reported (Barter 2002; Yi 2003, 2004; Moores 2006) an estimated 75% of historical tidal-flat area has now been reclaimed (Moores 2012; Moores et al. 2014), with almost two-thirds of estimated tidal-flat area lost between the 1950s and 2000s (Murray et al. 2014). During the past 25 years most river-mouths in the ROK have also been dammed with estuarine barrages further diminishing already low rates of accretion (Moores 2012). Independent assessments of satellite imagery by Birds Korea (2010) and Murray et al. (2014) concluded that only about 110,000-120,000ha of tidal-flat remained nationwide by the late 2000s, approximately half the area estimated to remain in formal reports submitted to the Convention on Biological Diversity (ROK 2009; ROK 2014).

The largest single reclamation project has been at Saemangeum (Figure 1), where approximately 29,000ha of tidal-flats and 11,100ha of sea-shallows of the Mangyeung and Dongjin estuaries were impounded behind a 33-km long seawall in 2006. Construction of the Saemangeum seawall started in 1991. The completion of some dyke sections resulted in a gradual reduction in tidal range in both estuaries during the early 2000s (Nial Moores personal observations), a change in sediments and the distribution of benthic species (Ryu et al. 2014), and a rapid decline in bivalves and gastropods in some affected areas from at least 2003 (Hong et al. 2007).

In 1997-2001, surveys by the national Ministry of Environment led to estimates of 138,000 shorebirds supported by the Mangyeung Estuary and 178,000 shorebirds supported by the Dongjin Estuary on northwards migration. On southward migration estimated numbers were 145,000 and 112,000 respectively (Yi 2003; Yi 2004). Barter (2002) estimated 330,000 shorebirds as staging at the two estuaries of Saemangeum annually, including over 240,000 during northward migration, identifying Saemangeum as the most important staging site during northward migration and the second most important staging site during southward migration in the Yellow Sea at that time.

In 2004, almost 130,000 shorebirds still staged at Saemangeum during northward (Table 1, in Results) and 201,000 during southward migration, though annual peak counts suggest shorebird numbers declined by about 15% between 2003 and 2005 (KARICO 2003; KARICO 2004; KARICO 2005). In April 2006, the Saemangeum seawall was closed. This restricted tidal movement through sluice-gates and highest tides behind the seawall on most dates fell from about 6m in early April 2006 to 10cm or less by 2008 (Moores 2012), resulting in the rapid degradation and loss of almost all tidal-flat at Saemangeum.

Migration studies have demonstrated that the Yellow Sea is a vital staging area for a large number of tidal-flat dependent shorebird species on the East Asian-Australasian Flyway (EAAF), with much of the flyway population of these species refuelling there for several weeks in preparation for long-distance flights of thousands of km (Barter 2002; Driscoll and Ueta 2002; Rogers et al. 2010; Battley et al. 2012; Minton et al. 2013; Choi et al. 2015; Piersma et al. 2016). Tracking studies and colour-band resightings have also revealed great individual site fidelity in some species, with many individuals using the same staging sites in the Yellow Sea year after year (e.g. Piersma et al. 2016). Thus, if shorebird habitat is lost to reclamation within preferred staging areas in the ROK, profound effects on shorebirds from these populations would be expected. Possible outcomes include affected shorebirds: (1) relocating to stage successfully at other sites; or (2) experiencing an increase in mortality and / or loss of fitness, with or without temporary relocation to other sites which proved to be less suitable (as reported in a study of Common Redshank *Tringa totanus* by Burton et al. 2006). In species where a substantial part of the population is affected, the latter scenario might lead to stepwise declines that are large enough to detect in the non-breeding range at well-monitored sites (as described by Minton et al. 2012).

Here we examine changes in shorebird numbers at Saemangeum during the later stages of its reclamation, and concurrent changes in shorebird numbers at all other major sites for shorebirds in the ROK, including the adjacent Geum Estuary and Gomso Bay (Figure 1). We focus on the northward migration period because few data are available from the peak of southward migration. Our intention was to find how shorebirds responded to the loss of a major staging area in a flyway where alternate habitat is rapidly being lost. We expected numbers of every tidal-flat dependent species to decline at Saemangeum after sea-wall closure in 2006. If the displaced birds successfully relocated to nearby tidal-flats, we hypothesised that numbers would increase at other tidal-flat sites in the ROK, with increases corresponding roughly to the numbers of birds lost from Saemangeum. If such relocations were successful, increased numbers at other ROK tidal-flat sites would be persistent rather than temporary. If, however, the remaining tidal-flat systems of the ROK were insufficient to support the birds displaced from Saemangeum local increases would fall short of the number of displaced birds or would be only temporary.

We examined changes in numbers of all shorebird species that occurred at Saemangeum, but emphasise two species, Great Knot (*Calidris tenuirostris*) and Spoon-billed Sandpiper (*Eurynorhynchus pygmeus*). Both species are more or less confined to the EAAF (Wetlands International 2006; BirdLife International 2016). Saemangeum previously supported 20-30% of the global population of Great Knot during both northward and southward migration (Barter 2002; Yi 2003; Yi 2004; KARICO 2004). The species is specialised to feed on bivalves (Tulp and de Goeij 1994), so may be more vulnerable to the loss of a core

staging site than species with a broader diet. There were estimates of 180 and 100 Spoon-billed Sandpiper at the Mangyeung and Dongjin estuaries respectively in the late 1990s during southward migration (Barter 2002). These were among the highest concentrations of this fast-declining species ever recorded, combined representing almost a third of the global population estimated to remain in 2000 (Zöckler et al. 2010). Away from the breeding grounds, Spoon-billed Sandpipers tend strongly to forage on tidal-flats with a sand/mud mix and to avoid areas with deeper muds (Bird et al. 2010) suggesting a high level of specialization and vulnerability to the degradation or loss of preferred areas.

Methods

Field Work

Counts for the Saemangeum Shorebird Monitoring Program (SSMP) were conducted by multiple teams of experienced volunteers from Birds Korea and the Australasian Wader Studies Group within Saemangeum (centred close to 35°50' N, 126°45' E) and at two adjacent intertidal wetlands, Geum Estuary (36°01' N, 126°35' E) and Gomso Bay (35°35' N, 126°36' E), containing approximately 6,000 and 7,000 ha of tidal-flats respectively (Figure 1). We refer to these three sites combined as 'The SSMP Study Region'.

Counts by 2-5 teams were made throughout the SSMP Study Region on multiple dates across three spring tide cycles in April and May 2006 and four spring tide cycles in April and May 2007 and 2008. Survey dates and tide heights are provided in supplementary material, Table A1. The greatest count effort was focused at high spring tides when shorebirds were concentrated in a relatively small number of high tide roosts, and land- and boat-based teams could count roost sites simultaneously. In the rising tide series preceding each of the high spring tide surveys, we carried out several days of reconnaissance in which we visited all known roosts in the area and explored for any new areas that birds may have begun to use. During neap tides, counters focused on searching tidal-flats for banded or flagged birds and on checking counts of species that are difficult to find at high tide roosts, including Spoon-billed Sandpiper. Whenever observers were in the field they looked for and noted migratory departures, which are associated with distinctive behaviours (Piersma et al. 1990). Further details on count methods and descriptions of the main count areas are presented by Moores (2012).

As part of the SSMP, a national survey (henceforth referred to as the 2008 ROK survey) was also conducted by several small teams from May 3rd-13th 2008. The intention was to replicate survey method and cover the same sites as surveyed at similar dates in 1998 (Moores 1999). With larger, more

experienced teams, however, our coverage was more thorough and the 2008 ROK survey also included the recently-accessible Song Do (Do = Island), now connected to the mainland in Incheon by reclamation. In total, the 2008 ROK survey covered 17 wetlands along the west and south coasts of the ROK, including all known internationally important shorebird sites nationwide, each over one or two high tides during a two-week period when the majority of tidal-flat dependent shorebirds are expected to reach their peak numbers during northward migration (Moores 2012).

Counts by the Shorebird Network Korea (Shorebird Network Korea 2013; 2014; 2016) were made on one or two dates each season (in e.g. mid-April, early May, mid-late May, mid-September and October) between 2010 and 2014 (though published data for all of the Geum Estuary were only available for 2010, 2013 and spring 2011). The timing of the April and May surveys coincided with expected peaks in abundance of almost all tidal-flat dependent shorebird species during northward migration.. Each team counted one or two sites, and most sites were counted twice every season, with other sites counted less frequently. Between 2011 and 2013, this survey effort covered a total of 35 sites, with 25-33 sites counted each year. Some of these sites were subdivisions of sites that were covered by the 2008 ROK Survey. Surveys by the Shorebird Network Korea between 2011 and 2013 therefore included all sites covered by the 2008 ROK Survey, in some cases extending count areas substantially, and an additional 12 mostly minor sites (Figure 1). At most sites teams counted the same areas and roost sites as counted by the 2008 ROK survey, allowing for direct comparison of counts though with caveats due to differences in count frequency and observer experience. Importantly, the Shorebird Network Korea surveyed almost all remaining tidal-flat areas and all known internationally important shorebird sites in the ROK, including all sites known to have supported Great Knot and Spoon-billed Sandpiper regularly. Saemangeum was counted twice during northward migration in all four years (2011-2014). The greatly reduced tidal exchange there meant that survey work was land-based, but nonetheless covered almost all areas suspected still able to support shorebirds.

Data presentation

We present data only from the northward migration period because of the higher quality of the data sets available to us. Moreover, although in all surveys fieldworkers attempted to count all birds present in the region at the peak of the northwards migration season, surveys by the SSMP, KARICO and Shorebird Network Korea differed in survey frequency per season, the size and experience of the counting teams, roost access and interpretation of local movements of birds. The data sets available to us are therefore not long enough nor were the surveys suitably designed for advanced statistical analysis.

During the SSMP, to calculate the peak number of shorebirds in the SSMP Study Region, we took the highest count within a count-cycle for each species and treated this as the minimum count of that species that migration period. This enabled us to compare numbers for each species among the three wetlands and between years (Moore et al. 2008; Moore 2012). This approach was considered reasonable in view of evidence that most shorebird species in the study area staged for several weeks, with numbers at the site building gradually until departures began (see Figure 2 and discussion). Spring tide series occurred at two-week intervals in the study area, numbers for each species were likely to be at or near peak levels during at least one of the spring tides in which the surveys were conducted. In longer spring tide series, when the height of high tides within daylight hours exceeded 6m on four or more consecutive dates, it was twice possible to conduct complete counts twice during a single tide series. Saemangeum totals in the first and second counts within these tide series were strongly correlated ($r = 0.995$, $n = 20$ species in the second tide series in 2007; $r = 0.994$, $n = 30$ species in the first tide series of 2008) and we present the second count for each of these tide series in this paper as it corresponded more closely to the dates of the highest tides.

For pre-seawall closure counts, we selected the higher of two counts (one labelled April, the other labelled May) in KARICO (2004). These counts are included in Table 1, which includes scientific names of species mentioned hereafter. The dates of surveys conducted by the Shorebird Network Korea (starting in 2011) were selected to coincide with the periods in which numbers of shorebirds were expected to peak, based on experience from previous surveys in ROK. With the Shorebird Network Korea data we therefore selected maximum counts by site, species or year in order to capture the highest numbers recorded of each tidal-flat dependent shorebird species.

Results

Saemangeum and the SSMP Study Region

In the three sites combined of the SSMP Study Region from 2006-2008, a total of 45 species of shorebird and a minimum 264,567 shorebirds were recorded. The highest shorebird count during a single count cycle was 244,348 (May 13th-17th, 2006). The highest shorebird counts during a single count cycle per wetland were 176,954 within Saemangeum, 97,670 at the Geum Estuary and 9,457 at Gomso Bay. Nineteen shorebird species were found within the SSMP Study Region in internationally important concentrations of 1% or more of flyway population as listed in Wetlands International (2006).

Counts within each season of the SSMP in Saemangeum and at the Geum Estuary and at Gomso Bay in 2007 and 2008 followed the expected pattern for sites where birds stage for several weeks: totals gradually increased through the study period until migratory departures began (Figure 2, top panel; Supplement Figure 1; Rogers et al. 2006). In each of the three seasons, substantial visible migration was first observed in mid-May, and was thereafter seen through much of the remainder of May on those days when teams were suitably positioned in the late afternoon or evening. Plots for each species of the dates of the count series when peak numbers were recorded (Figure 2, lower panel) show that most species departed in mid-May or late May in all three seasons. There were some noteworthy exceptions. The highest counts of Eurasian Curlew, Far Eastern Curlew, Eurasian Oystercatcher and Kentish Plover were observed in early to mid-April in at least some years of the study and it is possible that their numbers may have peaked before the field season began. Numbers of Great Knot and Bar-tailed Godwit peaked in mid-May in 2006, but in 2007 their numbers peaked a month earlier in mid-April. In Great Knot this difference was particularly striking in 2007, with numbers declining from 83,403 in mid-April to 44,384 at the start of May when peak numbers were expected. The decline was most marked in Saemangeum (where the early May count was 23,608 lower than in mid-April), but also occurred in the Geum Estuary and Gomso Bay.

Between 2006 and 2008 and subsequently, counts of almost all tidal-flat dependent shorebird species declined substantially at Saemangeum (Table 1), with populations of nearly all species in 2011 and 2014 only 0-30% of their levels in 2006. The only exception was Kentish Plover. Since sea-wall closure in 2006, this species has nested on sandy islands in Saemangeum temporarily created by the reclamation process.

In the SSMP Study Region, numbers of 18 of the 20 most numerous tidal-flat dependent shorebird species declined substantially or at best remained near-stable between 2006 and 2008 (Table 2). By 2011-2013, 13 of these 20 species had declined to less than 55% of their numbers in 2006. Declines were apparently more modest in five other species. In 2011-2013, counts were 63-72% of 2006 counts for Dunlin, Eurasian Oystercatcher, Far Eastern Curlew, Red-necked Stint and Whimbrel (Table 2). The increase in the counts of Kentish Plover was driven in large part by increased numbers within Saemangeum; the only other species that may have increased was Grey Plover.

Shorebird numbers counted at the Geum Estuary and Gomso Bay increased in 2007 and 2008 (Figure 3). However, the increases recorded at these two sites do not account for the majority of shorebirds lost from Saemangeum since 2006 and some of these increases were subsequently reversed, especially at the Geum Estuary. Spoon-billed Sandpiper at Saemangeum decreased from 34 in 2006 to three in 2008, and

increased at the Geum Estuary from one in 2006 to eight in 2008. None were recorded at Gomso Bay in any year. Great Knot declined by almost 55,000 at Saemangeum and increased by 20,000 at the Geum Estuary between 2006 and 2007. However, the peak count at the Geum Estuary in 2007 was made on only one early date (April 17th), with that number not then increasing as expected, but instead falling back by early May to almost the same number as recorded there in 2006. In 2008, the maximum number of Great Knot recorded at the Geum Estuary was less than half that recorded in 2006.

Counts made by the Shorebird Network Korea in 2011-2014 (Shorebird Network Korea 2013; 2014; 2016) confirm that the steep declines recorded during the SSMP continued as potential foraging habitat at Saemangeum continued to reduce in area and quality (Table 1). At Saemangeum, there was a decline of more than 90% in shorebird numbers between 2006 and 2013 with at least 19 species declining by more than 50%. Five species were unrecorded from 2011-2013, including Spoon-billed Sandpiper. In 2014, the Shorebird Network Korea recorded less than 5,000 shorebirds at Saemangeum including only 463 Great Knot and no Spoon-billed Sandpiper. Rapid declines also continued within the SSMP Study Region as a whole until at least 2011 (Table 2).

National Counts

In total, the 2008 ROK survey, recorded about 291,000 shorebirds during early-mid May at 17 sites (with almost 10% of these at Song Do, including 8,000 Great Knot), but no Spoon-billed Sandpiper. We found 147,577 shorebirds outside of the SSMP Study Region and 143,990 shorebirds within it. A total of 119,549 shorebirds were counted at the ten most important sites outside of the SSMP Study Region as identified in 1998 (Moores 1999): Yeongjong Island, Ganghwa Island, Namyang Bay, Asan Bay, Cheonsu Bay Hampyeong Bay and Muan (including Jido), Aphae Island, Haenam Hwangsan, Suncheon Bay and the Nakdong Estuary.

The improvement in knowledge and team size during the 2008 ROK survey should have meant that a greater proportion of birds were detected in 2008 than in a similar survey effort in 1998, when almost all counts were made by a single counter. In 1998, based on peak counts made during 2-3 surveys during northward migration, Moores (1999) counted a total of 192,211 shorebirds at these ten sites, with 127,728 shorebirds counted during a single count cycle between late April and mid-May (Table 3). National surveys conducted by the Shorebird Network Korea at the same ten sites during the whole of northward migration in 2011-2013 found fewer shorebirds in total than in 1998 or 2008, with 95,368 counted in

2013 (Shorebird Network Korea 2013; 2014) including 28,005 Great Knot and just one Spoon-billed Sandpiper (Table 3).

All ten of these most important sites outside of the SSMP Study Region have been affected directly by either small-scale or large-scale reclamation or infrastructural development since the 1990s. In general, declines in the numbers of shorebirds counted appear to have been steepest at sites that were largely-reclaimed during the past decade (e.g. Namyang Bay impounded in 2006 and Asan Bay with several impoundments in the 1990s and 2000s), with reduced numbers then persisting in remaining areas within each site. Declines were also substantial and ongoing at sites affected by ongoing reclamation and increased pressures in the hinterland (e.g. Yeongjong Island and Song Do). In contrast, shorebird declines did not appear to be as substantial at Hampyeong Bay / Muan and Suncheon Bay, where there has been less reclamation (Table 4).

Combining the maximum site-counts at each of the 35 sites made by the Shorebird Network Korea in 2011-2013 provides a national estimate of approximately 300,000 shorebirds during northward migration. The vast majority of these shorebirds were at sites covered by the 2008 ROK survey, with only between 4% and 11% of the annual total recorded at the additional 12 minor sites in any one year.

Discussion

Reclamation effects

Our study is the first in the ROK and along the EAAF to investigate the impacts of a major reclamation project on the number of tidal-flat dependent shorebirds at both the site and the national level (i.e. in all major shorebird sites in the ROK). We demonstrate several lines of evidence that are consistent with reclamation at Saemangeum causing declines in many species of migratory shorebirds at the site level and in the ROK overall, and in Great Knot and Spoon-billed Sandpiper at the species population level.

First, during northward migration we recorded a minimum of 128,000 shorebirds lost to Saemangeum between 2006 and 2008, in the two years after the sea-wall was closed. Further declines have occurred at Saemangeum since then and the site now supports fewer than 5,000 shorebirds.

Second, we found no evidence that the majority of affected shorebirds were able to relocate successfully either to adjacent sites or to other internationally important shorebird sites in the ROK. In total, more than 92,000 Great Knot, or 24% of the estimated global population at that time (Wetlands International 2006), were lost to the SSMP Study Region within only two years of seawall closure. These declines continued

at a slower rate after 2008 so that more than 104,000 were lost by 2013 (Shorebird Network Korea 2014). Spoon-billed Sandpiper also declined abruptly in the SSMP region, and the species has not been recorded during northward migration at Saemangeum since 2008. In addition, nearly all tidal-flat dependent shorebird species have also declined on an ROK-wide scale since 2006 and at the ten most important ROK shorebird sites outside Saemangeum and the SSMP Study region total shorebird numbers declined between 1998 and 2008 and again between 2008 and 2013, despite increased survey effort in later years.

Third, the SSMP detected a change in the timing of departure of Great Knot from Saemangeum and the SSMP Study Region between years, with early departures during northward migration in 2007 suggesting that that conditions post-reclamation could no longer support large numbers of Great Knot for their final staging before departure to the breeding grounds.

Fourth, national surveys in the ROK (e.g. Yi 2003, 2004; KARICO 2004; Moores 2012; Shorebird Network Korea 2014) suggest that several of the site-level declines have been largest and steepest at sites most directly affected by reclamation (e.g. Saemangeum, Namyang and Asan Bay) and less marked at sites that have been largely unaffected by reclamation (e.g. Suncheon Bay), even when most of the affected species are undergoing long-term declines at the flyway population level (e.g. Wilson et al. 2011; Clemens et al. 2016).

Fifth, substantially more than 300,000 shorebirds have been lost from the ROK during northward migration between 1997-2001 and 2013. This is consistent with the loss of the number of shorebirds previously estimated to stage at Saemangeum during northward migration by Yi (2003, 2004).

Sixth, the declines that we recorded in the ROK are consistent with declines in numbers and adult survival detected in Great Knot in North-western Australia between 2001 and 2008 (Rogers et al. 2009; Clemens et al. 2016; Piersma et al. 2016) and with the extremely rapid rate of decline of the Spoon-billed Sandpiper in the 2000s (Zöckler et al. 2010). Although there are many variables that need to be considered in determining population trends in long-range migrants (Wilson et al. 2011), the accelerated rate of global population decline in Great Knot and Spoon-billed Sandpiper experienced in the late 2000s followed by a less rapid rate of decline so far detected in the present decade is consistent with the reclamation of Saemangeum – a site of especial importance to both species during northward and southward migration – and perhaps of other important sites.

Our study did not capture the full extent of shorebird declines at Saemangeum. The reclamation process at Saemangeum has taken several decades. Patchy older data, including KARICO (2003), KARICO (2004) and KARICO (2005) suggest that shorebird numbers already began to decline in Saemangeum in

the early 2000's. The declines are probably not yet complete. Even in 2015 construction was continuing on inner sea-dykes (Moore 2015), and there were still a few relict areas of degraded tidal-flat and reclamation lagoons available to foraging shorebirds that will likely be lost as the reclamation process continues. Moreover, there are fewer data for the southward migration period when the largest number of Spoon-billed Sandpiper and some other species were previously recorded. Massive declines in many species during southward migration are strongly suggested by Shorebird Network Korea data, with for example fewer than 6,700 Great Knot and only four Spoon-billed Sandpiper recorded in the ROK in 2013 (Shorebird Network Korea 2013).

Alternative explanations

Before seawall closure in 2006, the adjacent Mangyeong and Dongjin estuaries were extensive and complex tidal systems. Local tide-related movements of shorebirds between roosts, within and between both estuaries and also between Saemangeum and the Geum estuary, made these sites difficult to count well (Rogers et al. 2006; Moore 2012). The SSMP (2006-2008) conducted extensive counts within Saemangeum and at the adjacent Geum Estuary and Gomso Bay with a large number of experienced counters on multiple survey dates, across three or four high-tide cycles per season, using boats to access otherwise inaccessible roost sites. The extensive survey effort during the SSMP, while finding fewer shorebirds at Saemangeum than earlier estimated to stage there during northward migration by Yi (2003; 2004) nonetheless made higher counts during northward migration of several species than previously recorded during previous survey effort, including Broad-billed Sandpiper and Grey-tailed Tattler (both of which peaked within the SSMP Study Region later in May) and in species like Nordmann's Greenshank which are often difficult to count well at high tide roosts.

The SSMP results therefore provide a reasonable baseline against which to measure the impacts of the rapid loss of foraging at Saemangeum caused by the closure of the seawall in late April 2006. Seawall closure led to the death of enormous numbers of shellfish on the former tidal flats of Saemangeum. They came to the surface and gaped open as they died, providing a ready source of carrion which was exploited by thousands of shorebirds, especially Great Knot (Rogers et al. 2006). These birds were unlikely to have been an influx from elsewhere, as similar numbers of Great Knot had been present at Saemangeum before the sea-wall was closed in late April (late April count just before sea-wall closure was 83,404, building to a peak post-closure of 86,288; Rogers et al. 2006). Moreover, counts in 2006 were lower than or consistent with counts that had been made in the previous few years. Counts in 2006 (the baseline for our comparisons in future years) are therefore unlikely to have been inflated by carrion-seeking birds.

The results are unlikely to have been confounded by survey timing or migratory turnover, with the exception of potentially underestimating in 2006 numbers of some species which appear to peak in number in the last decade of May (Moore 2012). In theory maximum counts on a single day could underestimate the number of birds that use a staging area, especially if staging durations are short with numbers only peaking briefly or if migration strategies are asynchronous, with some individuals departing before all individuals have arrived. Examination of SSMP count data within-season indicated that counts followed the pattern that would be expected if birds staged for long periods with negligible overlaps between arrivals and departures: i.e. gradual increase through the early migration period followed by decreases once migratory departures began (Rogers et al. 2006; Figure 2; Supplement Figure 1). Moreover, modelling of phenology of some species in the SSMP region indicated that most species staged in the area for several weeks (Moore 2012), with timing similar to that documented at other sites in the northern Yellow Sea that are used for final staging before a direct flight to the breeding grounds, namely Bohai Bay (Rogers et al. 2010) and Yalu Jiang (Riegen et al. 2014; Choi 2015).

Gradual increases in abdominal profile (an index of the amount of migration fuel) in Great Knot also suggested prolonged staging and refuelling in Saemangeum in 2006 (Rogers et al. 2006), and the correspondence of departure dates in late May with arrival dates of Great Knots on the breeding grounds (Tomkovich 1997) suggests they had refuelled for a direct flight to the breeding grounds. A small number of tracking studies have also demonstrated prolonged staging of adult shorebirds in the northern Yellow Sea of some 3-5 weeks before a direct flight to the breeding grounds (e.g. Battley et al. 2012; Driscoll and Ueta 2002; Minton et al. 2013). Collectively these sources of information indicate that the maximum counts used in our study would have been close to the peak numbers of birds that used the sites on northward migration. They therefore help to confirm that Saemangeum was a staging site used by very large numbers of shorebirds before their departure to the breeding grounds, serving a similar ecological function to similar staging sites in the northern part of the Yellow Sea as identified by Ma et al. (2014).

Could birds displaced from Saemangeum have relocated to alternate staging areas that were not monitored? We are confident that there were no major relocations to other sites within the ROK. There has been extensive exploration for shorebird sites on the coast of the ROK (Long et al. 1998; Moore 1999; Yi 2003, 2004); there is excellent satellite imagery to identify tidal flat areas that could potentially support shorebirds; and as coastal access in ROK is relatively easy, all ROK sites that could realistically support substantial shorebird numbers have been surveyed. The 2008 ROK survey and the Korea Shorebird Network surveys covered all major shorebird sites known in the ROK.

Outside the ROK, there are areas of Yellow Sea coastline in China and especially in the DPR Korea that have been not been monitored intensively enough to detect influxes of birds displaced from Saemangeum. In Bohai Bay, China, widespread reclamation led to Red Knots concentrating in one small section of coastline that had not been reclaimed (Yang et al. 2011). However we doubt that a similar scenario applies to birds displaced from Saemangeum. It is likely that the Red Knots that concentrated in the Bohai Bay site originated from other sites within Bohai Bay, no more than 100 km away, where almost no shorebird habitat now remains (Yang et al. 2011). In contrast, in the ROK all major shorebird sites within 250 km of Saemangeum were monitored, with no evidence to suggest substantial influxes of numbers of displaced shorebirds. Instead, at most sites shorebird numbers decreased rather than increased between 2008 and 2013. Moreover, we are not aware of any reports of increases in numbers of Great Knot (the species lost in greatest numbers from Saemangeum) in any of their known staging sites in the Yellow Sea – even in sites such as Yalu Jiang. Yalu Jiang, China, is now the most important staging site for Great Knot in the Yellow Sea and has been monitored extensively during northward migration including in years before and after the seawall closure at Saemangeum (Riegen et al. 2014, Choi et al. 2015).

Finally, if Saemangeum birds successfully relocated to alternate staging grounds, they should be able to continue migrating to the non-breeding grounds, where monitoring is more intensive. There is, however, strong evidence of declines in both numbers and adult survival of shorebirds on Australasian non-breeding grounds coinciding with the reclamation of Saemangeum and other sites in the Yellow Sea (Wilson et al. 2011; Clemens et al. 2016; Piersma et al. 2016).

Conservation implications

In the early 2000's reclamation proponents argued in public media, including websites of government bodies, that the reclamation of Saemangeum would simply cause shorebirds to stage elsewhere, including the Geum Estuary and Gomso Bay (Moores 2003; Rogers et al. 2006). More than twenty years later, there is still no published evidence to support this argument and many independent studies have instead documented serious shorebird declines in the EAAF which are thought to be driven by tidal flat reclamation (Amano et al. 2010; Wilson et al. 2011; Conklin et al. 2014; Piersma et al. 2016; Clemens et al. 2016). Our study supports this interpretation. Importantly, we found no evidence of large numbers of birds relocating successfully from Saemangeum to other shorebird sites in the ROK. It seems that the remaining shorebird sites in ROK (many of which have already been partially reclaimed or are affected by major infrastructural development) do not have the capacity to support large numbers of shorebirds displaced from other staging sites.

We predict that unless rates of reclamation are greatly reduced in East Asia, tidal-flat dependent shorebird species will continue to decline rapidly in the ROK and at the flyway population level. Reclamation has already resulted in the loss of approximately two-thirds of tidal-flat area in the Yellow Sea (Murray et al. 2014). This habitat loss has coincided with declines in the numbers of migratory shorebirds in their non-breeding grounds in Australia (e.g. Wilson et al. 2011; Clemens et al. 2016), and with recent decreases in adult survival in Australia and New Zealand that strongly suggest that further population declines can be expected (Piersma et al. 2016; Conklin et al. 2016). Within the ROK, several internationally important tidal wetlands are still undergoing large-scale reclamation (e.g. Song Do), or are being affected by construction in the hinterland (e.g. Yeongjong Island) leading to the loss of preferred roosting areas. The Geum Estuary, currently the nation's most important remaining shorebird site, still remains threatened by large-scale reclamation and major development in the hinterland. In addition, leg-flag re-sightings demonstrated that substantial numbers of Great Knot first staged in China before crossing to the SSMP Study Region (Rogers et al. 2006). Reclamation along much of the Chinese coast therefore also has the potential to affect the number of birds reaching the ROK, as do several other drivers of decline that include climate change, *Spartina* invasion, pollution and hunting (Barter 2002; Melville et al. 2016).

We are therefore in agreement with other studies and conservation initiatives that have called for an increase in international collaboration and research effort in order to improve understanding of the multifaceted impacts of reclamation in East Asia on shorebirds and other biodiversity; on ecosystem health; and on ecological and economic sustainability (see Barter 2002; Mackinnon et al. 2012). We emphasise that studies are needed to refine our understanding of the effects of reclamation on shorebirds because the broader impacts are no longer in serious doubt. Indeed, there is now plentiful evidence to suggest that tidal flat reclamation kills shorebirds and is driving flyway population declines in the EAAF; there is no evidence to the contrary.

Finally, we note that both the ROK and China are already signatories to the Ramsar Convention and to the Convention on Biological Diversity. Both nations have therefore already formally agreed to manage their wetlands wisely and to reduce rates of habitat and biodiversity loss. Moreover, as signatories to the United Nations, both have also accepted that the precautionary principle should be more fully incorporated into the national planning process by 2015. In accordance with the precautionary principle available evidence, including that provided by the present study, is now sufficient to help inform conservation planning and policies.

Acknowledgements

We thank past and present members of Birds Korea (especially Tyler Hicks, Geoff Styles, Park Meena, Andreas Kim and Ju Yong-Ki) and the Australian Wader Studies Group for their multiple contributions to the work. We are especially grateful to Dr. Phil Battley and Ken Gosbell for their various roles during the SSMP and to all the self-funded participants who made the SSMP and this study possible, volunteering a great deal of their time and collecting excellent data in difficult conditions. We also thank Lee Kyung Gyu and Ju Yong-Ki of the Shorebird Network Korea for generously sharing data, and all members of the Shorebird Network Korea for their research that enabled the publication of the Network's reports. We thank Seo Haemin for help with preparing figures and Alice Risely for analysis of data from Mokpo. We also thank Dr. Judit Szabo, Rob Clemens, Dr. Richard Fuller, Prof. Andrew Bennett and three anonymous reviewers for their substantial improvements to earlier drafts. This work was supported by funding from the University of Newcastle and the Packard Foundation.

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Table 1. Peak numbers of shorebirds observed at Saemangeum, 2004 and 2006 to 2013, for the 20 shorebird species that have occurred in the SSMP Study Region in internationally important numbers during northward migration since 2006. The 2004 totals are the higher of two counts (one in April, one in May) reported in KARICO (2004). Absolute counts are given for 2006, and totals in subsequent years are given as a % of the 2006 counts.

Vernacular Name	Scientific Name	Peak Saemangeum count during northward migration						
		2004	2006	2007	2008	2011	2013	2014
Great Knot	<i>Calidris tenuirostris</i>	78,900	86,288	37%	14%	1%	0%	1%
Dunlin	<i>Calidris alpina</i>	25,810	62,508	50%	42%	4%	12%	4%
Lesser Sand Plover	<i>Charadrius mongolus</i>	4,499	5,914	27%	12%	0%	2%	2%
Bar-tailed Godwit	<i>Limosa lapponica</i>	4,277	5,826	71%	57%	6%	10%	4%
Red-necked Stint	<i>Calidris ruficollis</i>	4,300	5,154	75%	77%	9%	31%	9%
Terek Sandpiper	<i>Xenus cinereus</i>	1,388	3,855	54%	42%	5%	1%	0%
Grey Plover	<i>Pluvialis squatarola</i>	5,899	3,488	84%	66%	3%	11%	11%
Far Eastern Curlew	<i>Numenius madagascariensis</i>	1,150	2,261	65%	22%	8%	12%	1%
Whimbrel	<i>Numenius phaeopus</i>	776	1,028	97%	54%	8%	5%	1%
Common Greenshank	<i>Tringa nebularia</i>	371	912	61%	24%	19%	10%	6%
Ruddy Turnstone	<i>Arenaria interpres</i>	339	744	56%	34%	0%	0%	1%
Sharp-tailed Sandpiper	<i>Calidris acuminata</i>	513	645	36%	6%	6%	1%	1%
Kentish Plover	<i>Charadrius alexandrinus</i>	957	486	99%	75%	89%	147%	59%
Grey-tailed Tattler	<i>Tringa brevipes</i>	0	430	40%	100%	3%	4%	0%
Broad-billed Sandpiper	<i>Limicola falcinellus</i>	0	338	37%	72%	0%	1%	0%
Eurasian Oystercatcher	<i>Haematopus ostralegus</i>	41	324	77%	75%	78%	15%	15%
Sanderling	<i>Calidris alba</i>	2	222	1%	4%	0%	0%	0%
Eurasian Curlew	<i>Numenius arquata</i>	339	213	101%	100%	0%	0%	0%
Spoon-billed Sandpiper	<i>Eurynorhynchus pygmeus</i>	0	31	100%	10%	0%	0%	0%
Nordmann's Greenshank	<i>Tringa guttifer</i>	0	14	50%	29%	0%	0%	0%
Other tidal-flat dependent shorebirds		397	715	1%	17%	10%	16%	30%
Total		129,958	181,534	48%	30%	3%	7%	3%

Table 2. Peak numbers of shorebirds observed in the SSMP Study Region (Saemangeum, Geum Estuary and Gomso Bay combined), 2006 to 2013, for the 20 shorebird species that have occurred in the SSMP Study Region in internationally important numbers since 2006. Absolute counts are given for 2006, and totals in subsequent years are given as a % of the 2006 counts.

Species	2006	2007	2008	2011	2013
Great Knot	116,126	72%	23%	7%	10%
Dunlin	82,718	86%	93%	7%	71%
Bar-tailed Godwit	18,305	40%	91%	49%	52%
Lesser Sand Plover	7,606	79%	70%	10%	31%
Red-necked Stint	5,873	119%	88%	16%	63%
Terek Sandpiper	5,633	78%	109%	24%	35%
Grey Plover	5,254	128%	122%	59%	155%
Far Eastern Curlew	4,843	66%	64%	48%	72%
Whimbrel	2,682	68%	100%	47%	69%
Common Greenshank	2,414	53%	38%	22%	29%
Sharp-tailed Sandpiper	1,659	58%	9%	4%	6%
Eastern Oystercatcher	1,483	69%	62%	34%	71%
Ruddy Turnstone	1,439	71%	61%	3%	10%
Eurasian Curlew	515	4%	257%	25%	44%
Kentish Plover	511	130%	84%	141%	227%
Sanderling	418	56%	138%	8%	43%
Broad-billed Sandpiper	349	93%	366%	2%	50%
Grey-tailed Tattler	302	135%	201%	59%	22%
Nordmann's Greenshank	84	69%	71%	7%	4%
Spoon-billed Sandpiper	35	111%	31%	0%	20%

Table 3. Numbers of the ten most numerous shorebird species counted at ten internationally important shorebird sites outside of the SSMP Study Region in 1998, 2008 and 2013

Totals are given for all years, and totals in 2008 and 2013 are also given (in parentheses) as a % of the 1998 counts.

	1998	2008	2013
Dunlin	49,537	57,439 (116%)	37,658 (76%)
Great Knot	33,881	18,135 (54%)	28,005 (83%)
Black-tailed Godwit	22,656	2,055 (9%)	913 (4%)
Bar-tailed Godwit	7,855	9,747 (124%)	9,763 (124%)
Grey Plover	3,293	3,978 (121%)	4,060 (123%)
Terek Sandpiper	2,915	3,571 (123%)	2,798 (96%)
Red-necked Stint	2,609	1,662 (64%)	814 (31%)
Lesser Sand Plover	2,780	2,183 (79%)	983 (35%)
Whimbrel	1,983	2,900 (146%)	2,495 (126%)
Far Eastern Curlew	1,365	2,032 (149%)	2,391 (175%)
Total	128,874	103,702 (80%)	89,880 (70%)

Note: The ten sites were surveyed between April 29th and May 11th, 1998 (Moores 1999); May 3rd to May 13th, 2008; and in late April and mid-May 2013.

Table 4. Ten most important shorebird sites in the ROK in May 2008 listed in order of the number of shorebirds, with their reclamation status and number of shorebirds at the same sites estimated or counted during northward migration

Shorebird Site	Reclamation Status (1997-2015)	Shorebird Estimate (1997-2001)	Shorebird Count 2008	Shorebird Count 2013
Geum Estuary	1, 2, 5	66,700	97,670	82,303
Saemangeum	1, 3, 4	316,000	39,557	11,895
Namyang Bay	1, 3, 4	74,000	33,389	34,746
Song Do	1, 3, 4, 5	N/A	28,028	8,768
Yeongjong Island	1, 2, 4	46,000	24,169	12,495
Ganghwa Island	1, 2, 5	29,700	11,894	3,520
Asan Bay	1, 3, 4, 5	45,000	9,570	15,505
Hampyeong & Muan	1	N/A	7,279	5,888
Aphae Island	1	N/A	8,835	2,627
Suncheon Bay	1	9,300	6,201	8,422

Note: N/A denotes that estimates are not available for these sites. 1= Partial or small-scale reclamation in 1990s; 2 = Partial or small-scale reclamation in 2000s; 3= Reclamation of >50% of tidal-flat by 2010; 4= Large-scale reclamation ongoing; 5 = Further large-scale reclamation has been proposed. Estimates and counts are by Yi (2003, 2004), the SSMP (2008) and Shorebird Network Korea for 2013 (Shorebird Network Korea 2014).