

Tidal flats of the Yellow Sea: A review of ecosystem status and anthropogenic threats

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Abstract Tidal flats provide ecosystem services to billions of people worldwide, yet their changing status is largely unknown. In the Yellow Sea region of East Asia, tidal flats are the principal coastal ecosystem fringing more than 4000 km of the coastlines of China, North Korea and South Korea. However, widespread loss of areal extent, increasing frequency of algal blooms, hypoxic dead zones and jellyfish blooms, and declines of commercial fisheries and migratory bird populations suggest that this ecosystem is degraded and declining. Here, we apply the International Union for Conservation of Nature Red List of Ecosystems criteria to the Yellow Sea tidal flat ecosystem and determine that its status is endangered. Comparison of standardized remotely sensed habitat data and historic topographic map data indicated that in the last 50 years, a decline of more than 50% but less than 80% of tidal flat extent has occurred (criterion A1). Although restricted to a narrow band along the coastline, Yellow Sea tidal flats are sufficiently broadly distributed to be classified as least concern under criterion B. However, widespread pollution, algal blooms and declines of invertebrate and vertebrate fauna across the region result in a classification of endangered (C1, D1). Owing to the lack of long-term monitoring data and the unknown impacts of severe biotic and abiotic change, the ecosystem was scored as data deficient for Criterion E and several subcriteria. Our assessment demonstrates an urgent need to arrest the decline of the Yellow Sea tidal flat ecosystem, which could be achieved by (i) improved coastal planning and management at regional and national levels, (ii) expansion of the coastal protected area network, and (iii) improved managed of existing protected areas to reduce illegal land reclamation and coastal exploitation.

Key words: coastal wetland, ecosystem decline, IUCN Red List of Ecosystem, risk assessment habitat loss, wetland status.

INTRODUCTION

Tidal flats provide ecosystem services to billions of people worldwide, yet their changing status is largely unknown (Millennium Ecosystem Assessment 2005). Tidal flats are classified by the International Union for Conservation of Nature (IUCN) within marine intertidal habitats as mud shoreline and intertidal mud flats (12.4) and are defined as a coastal wetland ecosystem characterized by fine-grained sedimentary deposits within a broad, low-sloping intertidal zone, where they undergo regular inundation during the tidal cycle (Healy *et al.* 2002; IUCN 2012b). In the Yellow Sea region of East Asia, tidal flats occur in association with a variety of coastal landforms across a latitudinal range of about 8° and constitute the principal coastal

ecosystem fringing more than 4000 km of the coastlines of China, North Korea and South Korea (Fig. 1). Owing to a wide extent of occurrence (EOO) and very high productivity, the Yellow Sea tidal flat supports a diverse biota, including more than three million migratory shorebirds that use the ecosystem as stopover sites to feed on abundant benthic invertebrates during their annual migration (Barter 2002; UNDP/GEF 2007). In addition, Yellow Sea tidal flats provide important ecosystem services including storm protection, coastline stabilization and food production for a coastal population of more than 150 million people (MacKinnon *et al.* 2012; Murray *et al.* 2014).

Several sources of information suggest that a large, ongoing decline of the Yellow Sea tidal flat ecosystem is occurring, and the remaining tidal flats are estimated to account for less than half of their historical extent (Yu 1994; Cho & Olsen 2003; An *et al.* 2007b; CCICED 2010; Murray *et al.* 2014). Some of the key threatening processes to tidal flats include (i) rapid growth of urban, agricultural and industrial developments in the coastal zone, (ii) widespread damming

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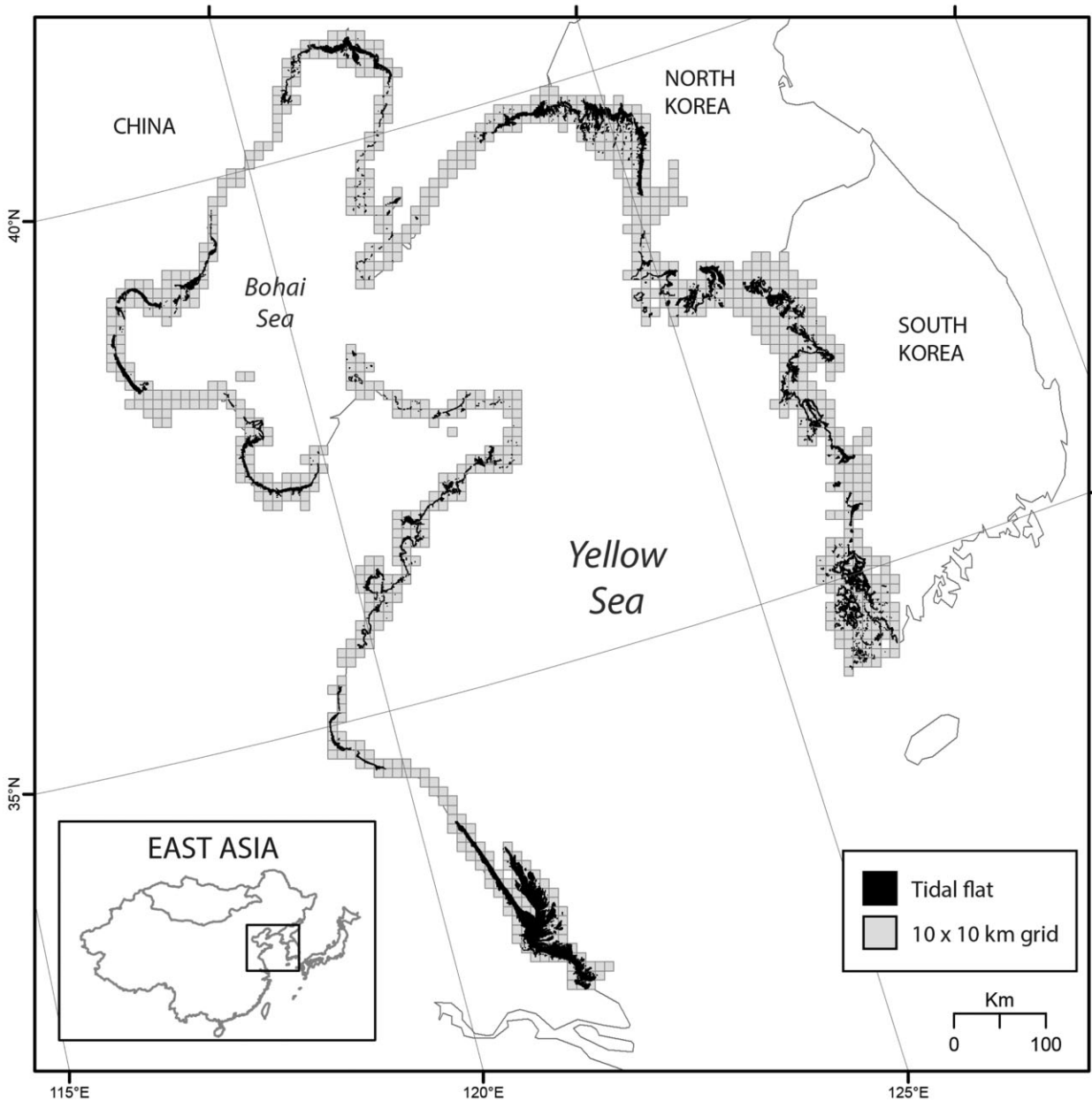


Fig. 1. Distribution of the Yellow Sea tidal flat ecosystem. Note that in some areas, such as the south-west coast of the Bohai Sea, no spatial data of tidal flat extent are available. Data from Murray *et al.* (2012, 2014).

and modification of the large river systems that supply sediment to the system, (iii) the swift emergence of large-scale tide and wind power generation facilities, (iv) invasion of exotic flora, (v) extensive pollution in coastal areas, (vi) overharvesting of fin fish and shellfish populations, (vii) ongoing erosion, compaction and subsidence of tidal flat sediments and (viii) sea-level rise (Sato & Koh 2004; MacKinnon *et al.* 2012; Iwamura *et al.* 2013; He *et al.* 2014; Murray *et al.* 2014). These processes have led to widespread degradation, fragmentation and decline in the areal extent of tidal flats, which has increased the extinction risk of

much of the ecosystem's characteristic biodiversity (Sato & Koh 2004; UNDP/GEF 2007; Murray *et al.* 2014). Although much of the degradation has occurred in recent decades, there is evidence that river damming, channel engineering, catchment modification and coastal reclamation have been occurring for more than 1000 years (Wang & Aubrey 1987; Zhang *et al.* 2004; Yang *et al.* 2005).

The alarming rates of loss and degradation of the ecosystem, the prevalence and diversity of threatening processes and the irreplaceability of the Yellow Sea tidal flat ecosystem necessitate an urgent assessment of

its conservation status. Here, we apply the IUCN Red List of Ecosystems criteria (Keith *et al.* 2013; Rodríguez *et al.* 2015) to determine that the current status of tidal flats in the Yellow Sea is endangered.

ECOSYSTEM DESCRIPTION

Tidal flats are the principal coastal ecosystem across the Yellow Sea coastline (Fig 1, Appendix S1). For the purposes of this assessment, we define tidal flat as the area inundated between the spring high and low tide waterlines that includes sand flat, silt flat and mudflat (Murray *et al.* 2012). Owing to large tidal ranges, highly turbid water, extensive reworking of sediments during tidal inundation and cold winter temperatures, tidal flats in the Yellow Sea are predominantly unvegetated and are often devoid of supra-tidal saltmarsh habitats (Healy *et al.* 2002). We restrict our assessment to the tidal flats within the Yellow Sea marine ecoregion, which is a regional centre for endemism that comprises the semi-enclosed Yellow Sea bounded to the south-west by the Yangtze River (Spalding *et al.* 2007; UNDP/GEF 2007). Our assessment thus encompasses the northern coastline of China from Jiangsu province (32°06'N, 121°30'E), the entire North Korean west coast and south to Jeollanam-do province, South Korea (34°18'N, 126°30'E; Fig. 1).

Characteristic native biota

Terrestrial, marine and freshwater biota are associated with the Yellow Sea tidal flat ecosystem, forming a complex ecological community that is dominated by micro- and macro-invertebrates, fish and predatory birds (Bird 2010; Choi *et al.* 2010; Kuwae *et al.* 2012). The key feature of tidal flats – regular tidal inundation – is fundamental to the ongoing functioning of the intertidal food web; when the tidal flat is inundated, it provides important foraging and nursery habitat to marine organisms such as fin fish and crustacea whereas at low tide, the tidal flat becomes accessible to other fauna, including predatory birds (Beck *et al.* 2001; Healy *et al.* 2002). In general, the Yellow Sea tidal flat ecosystem is dominated by tube-building polychaetes and suspension-feeding bivalves (Ahn *et al.* 1995), and supports very high biomass, with molluscs accounting for up to 50% of the benthic biomass at some sites (UNDP/GEF 2007; Choi *et al.* 2010). Detailed information on benthic diversity, abundance and community composition is limited (Choi *et al.* 2014), although it is estimated that the Yellow Sea marine ecoregion contains 464 endemic species, many of which occur only in the tidal flat ecosystem (UNDP/GEF 2007). Bivalve species from

the genus *Potamocorbula* are particularly common across the Yellow Sea, perhaps due to their ability to exploit disturbed or polluted environments (Choi *et al.* 2014). Several endemic species, such as several subspecies of amphioxus (*Branchiotoma belcheri* ssp.), have become identified as threatened in recent years (UNDP/GEF 2007; Hao *et al.* 2014). Similarly, the Chinese shrimp (*Fenneropenaeus chinensis*), an economically important species that inhabits the northern Yellow Sea and was formerly relatively abundant (in 1979 production was 40 000 tons), was listed as endangered in 2005 due to overfishing (Liu 2013).

A key feature of the Yellow Sea ecoregion is the yearly influx of about three million migratory shorebirds that utilize tidal flats during their annual migration between their breeding grounds in the Arctic and non-breeding areas throughout Asia and Oceania (Barter 2002). The Yellow Sea contains 27 sites that support important numbers (over 1% of the flyway population) of 36 species of migratory shorebirds, accounting for almost 40% of all migratory shorebirds that migrate through the East Asian–Australasian Flyway (Barter 2002). Eighteen species are estimated to occur in numbers that account for more than 30% of the total breeding populations; for six of these, almost the entire breeding population relies on tidal flat habitat within the Yellow Sea ecoregion during migration (Barter 2002). Four migratory shorebirds that depend heavily on the Yellow Sea's tidal flats are currently considered globally threatened: Nordmann's greenshank *Tringa guttifer*, far eastern curlew *Numenius madagascariensis*, spoon-billed sandpiper *Eurynorhynchus pygmeus* and great knot *Calidris tenuirostris*. Tidal flats also provide foraging habitat and non-breeding grounds for several other globally threatened waterbirds, such as the Saunders's gull (*Larus saundersi*), red-crowned crane (*Grus japonensis*) and hooded crane (*Grus monacha*; Ma *et al.* 2003; Ma *et al.* 2009).

Key abiotic features

The Yellow Sea is a shallow (mean depth c. 45 m), semi-enclosed sea with surrounding geography varying from mountain ranges in South Korea to low-elevation coastal plains across much of the northern and western regions. As such, tidal flats in the Yellow Sea are among the largest on earth; in areas with high tidal amplitude (macrotidal, > 4 m), they may attain a width of nearly 20 km when exposed at low tide (Healy *et al.* 2002). A key feature of the Yellow Sea tidal flats is the seasonal switching from an erosion- to accretion-dominated system in some areas, depending on the occurrence of the monsoon (Healy *et al.* 2002).

Table 1. Summary of the IUCN Red List of Ecosystems assessment of the Yellow Sea tidal flat ecosystem

Time scale of assessment	Red List of Ecosystems Assessment Criteria					Overall
	A	B	C	D	E	
Subcriterion 1 Past 50-year period	E	LC	E	E	DD	E
Subcriterion 2 Present and future 50-year period	DD	LC	DD	DD		
Subcriterion 3 Historic change since 1750	DD	LC	DD	DD		

Criteria relate to the decline in ecosystem extent (A), its distribution (B); the relative severity of abiotic degradation (C) and biotic disruption (D). Criterion E is a category that allows for assessments of all of the above via a simulation model of ecosystem dynamics. The overall outcome of the assessment is determined by the highest level of risk in any single category. DD, data deficient; E, endangered; LC, least concern; IUCN, International Union for Conservation of Nature.

Characteristic processes and interactions

The Yellow Sea tidal flat ecosystem is dependent on the continuing operation of a suite of coastal processes that are focused on sediment transport and dynamics (Healy *et al.* 2002). Sediments are transported to tidal flats by coastal and tidal currents, where the deposition process is influenced by factors such as sediment texture and size, occurrence of vegetation, wave dynamics, rainfall and the composition of the benthic community, which facilitates local bioturbation, biodeposition and biotransportation (Healy *et al.* 2002; Wang *et al.* 2012). In addition to contributing to sediment transport, the benthic community is also a critical component of the intertidal food web, contributing to trophic interactions between primary producers and intertidal predators (Kuwaie *et al.* 2012). Storms, wind and wave action cause seaward erosion of tidal flats, and compaction and subsidence reduce their elevation, so sediment trapping and replenishment are required to offset these processes and maintain tidal flat extent (Healy *et al.* 2002). However, a feature that distinguishes tidal flats in the Yellow Sea from adjacent regions is that the tidal flat ecosystem is largely erosion dominated (Healy *et al.* 2002), requiring ongoing sediment replenishment and transport to persist (Wang *et al.* 2014). Therefore, disruption of sediment provision via reduced supply from sources such as rivers, and interruption of sediment transport and deposition mechanisms are considered the primary processes that lead to degradation of the ecosystem (Appendix S2; Healy *et al.* 2002; Wang *et al.* 2012).

METHODS

We applied the IUCN Red List of Ecosystems criteria to the Yellow Sea tidal flat ecosystem. The IUCN Red List of Ecosystems is a newly developed system for assessing the risk of ecosystem collapse, which is considered to have occurred

when an ecosystem has lost its defining features (Keith *et al.* 2013). Through the application of five rule-based criteria, which are designed to evaluate four symptoms of ecosystem degradation (declining distribution, restricted distribution, degradation of abiotic environment and altered biotic processes), the red list status of an ecosystem is determined by the highest level of risk returned by any of the criteria (Keith *et al.* 2013; Rodríguez *et al.* 2015). For the Yellow Sea tidal flat ecosystem, assessments of criteria A and B (Table 1), which assess declines of ecosystem extent (A; leading to reduced carrying capacity and niche diversity) and restricted distribution (B; increasing susceptibility to spatial threats), were based on a recently developed 100-m resolution spatio-temporal dataset of tidal flat extent from the 1950s to 2010. The dataset was developed from historical topographic maps (1950s) and remote sensing analyses of Landsat Multispectral Scanner and Thematic Mapper data (1980s) and Landsat Enhanced Thematic Mapper Plus data (2000s), providing three robust estimates of tidal flat extent suitable for the assessment (Murray *et al.* 2012, 2014). Assessments of criteria C and D, which assess the relative level of degradation to the ecosystem (C; leading to reduced habitat quality) and degree of biotic disruption (D; interference of key ecosystem processes), were completed by synthesizing available information and obtaining relevant data on key variables that could be used to assess the relative severity of degradation of the system (Appendix S2), including sources such as peer-reviewed publications, environmental assessments and government reports. The relative severity of biotic and abiotic degradation over a 50-year period was determined by estimating the ratio of observed change in key variables, estimated with linear regression, to variable-specific collapse thresholds (Keith *et al.* 2013).

RESULTS

Our assessment of the status of Yellow Sea tidal flats indicates that it is an endangered ecosystem under criteria A1, C1 and D1 (Table 1). Data were available for assessment under criterion B (least concern for B1, B2 and B3). There were insufficient data to robustly apply criteria C2, C3, D2, D3 and E, although we provide a qualitative assessment based on available information.

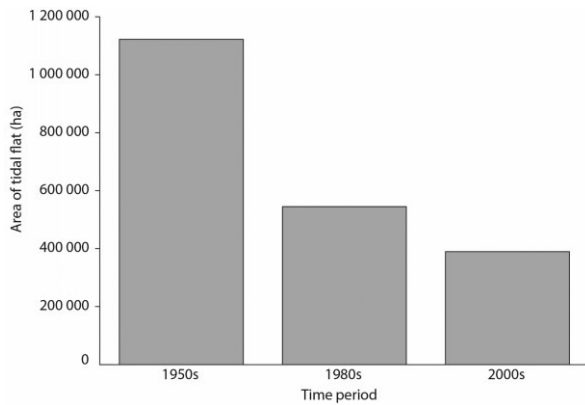


Fig. 2. Area of the Yellow Sea tidal flat ecosystem, 1950s–2000s. Data sourced from Murray *et al.* (2014).

Criterion A: Decline in distribution

Recent analyses combining historical topographical maps with remote sensing data from time series Landsat satellite imagery concluded that Yellow Sea tidal flats have declined in area by up to 65% between the mid-1950s and the early 2000s, a period of approximately 50 years (Murray *et al.* 2014). This quantitative estimate of decline exceeds the threshold for endangered under criterion A1 of 50%, but does not meet the threshold for critically endangered of 80%, which leads to a classification of this ecosystem as endangered (A1). Presently, no projections of future tidal flat change exist (A2), although continuing coastal development suggests that the current rate of loss of about 2% per year is likely to continue (Fig. 2; Murray *et al.* 2014; Ma *et al.* 2014). The historical extent of tidal flats prior to 1750 (A3) is unknown and hence it is not possible to put the recent declines into a long-term context. Some evidence suggests that long-term historical land clearing between about 1000 and 1950, particularly on the Loess Plateau in China, led to run-off and sediment flows to rivers that exceed natural rates (Wang & Aubrey 1987), potentially inflating the rate of delta progradations and the extent of tidal flats, as has been noted elsewhere (Kirwan *et al.* 2011). However, considerable uncertainty around this hypothesis remains and requires further investigation; therefore, the status of the Yellow Sea tidal flat ecosystem under criteria A2 and A3 is data deficient (A2a, A2b, A3).

Criterion B: Restricted distribution

The Yellow Sea tidal flat ecosystem fringes a coastline that is > 4000 km in length (Fig. 1). The EOO measured using a minimum convex polygon around the tidal flats shown in Figure 1 is 555 200 km² and the

ecosystem is assessed as least concern (B1). The ecosystem presently occupies more than 1% of at least 407 10 × 10 km grid cells (area of occupancy) and is also least concern (B2, B3).

Criterion C: Environmental degradation

Tidal flats in the Yellow Sea have been subject to sustained ‘coastal squeeze’ over several decades, driven by extensive coastal development, sea level rise, coastal subsidence, compaction and erosion (Murray *et al.* 2014). Sediment discharge from rivers, which is critical for tidal flat replenishment following seasonal erosion and enables tidal flats to persist with rising sea levels (Healy *et al.* 2002), has declined to a critical level over the past 50 years (Syvitski *et al.* 2005; Yang *et al.* 2006; Wang *et al.* 2010a). For example, sediment outflows from the two major rivers flowing into the Yellow Sea, the Yellow River (Huang He) and the Yangtze River (Chang Jiang) have declined by more than 90% and 70% respectively over the last 100 years (Fig. 3; Syvitski *et al.* 2009). When an ecosystem collapse threshold of zero sediment discharge is assumed, these declines represent a relative severity of 49% for the Yangtze (bounded estimate 59–41%) and 90% (21–256%) for the Yellow River (Fig. 3). The mean relative severity of sediment declines, weighted by sediment output from these two rivers at t_0 , provides an overall estimate of the relative severity of 77% over a 50-year period. The impacts of sediment decline will influence the entire Yellow Sea tidal flat ecosystem; thus, the ecosystem is classified as endangered (C1).

Several other factors are likely to influence the abiotic condition of the tidal flat system. Tidal flats will be among the first ecosystems to be significantly impacted by rising sea levels and intensifying storms under climate change (Murray *et al.* 2014). Given that the majority of tidal flats in the Yellow Sea are bounded by rock walls and coastal development, ecosystem migration in response to rising sea levels cannot occur, which will lead to inundation of the ecosystem, reducing the key process of regular tidal inundation, changes in distribution and declines in extent (Craft *et al.* 2008; Iwamura *et al.* 2013). In many places, relative sea level rise has already occurred due to subsidence and localized compaction of tidal flats from coastal development and oil, gas and ground water extraction (Bi *et al.* 2011, 2014; Higgins *et al.* 2013). Lastly, increased erosion of tidal flats from intensifying storms and scouring of tidal flat surfaces is expected as a result of climate change (Nicholls *et al.* 2007). However, despite an exhaustive literature review, no robust future projections (C2) or long-term historic data from 1750 (C3) that would allow abiotic degradation over these time periods were found; criteria C2 and C3 were data deficient.

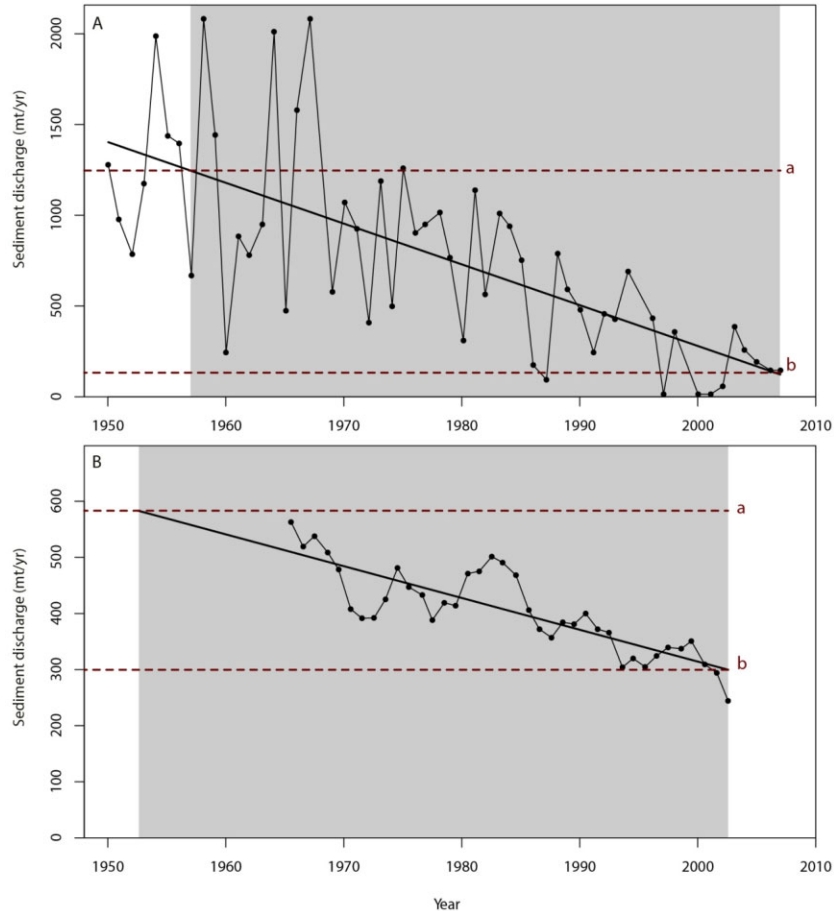


Fig. 3. Declines of sediment outflow from the two major rivers flowing into the Yellow Sea, Yellow River (A) and Yangtze River (B). Grey-shaded areas indicate the 50-yr period used to calculate the relative severity of the sediment decline, as estimated by a least-squares regression model in black, from the initial state (a) to final state (b). Data sourced from Yang *et al.* (2005) and Wang *et al.* (2010a).

Criterion D: Disruption of biotic processes and interactions

In the past few decades, several indicators of biotic disruption, including algal blooms, hypoxia, invasions of non-indigenous species, jellyfish blooms, and declines of commercial fisheries and migratory bird populations have occurred in the Yellow Sea (Liu & Diamond 2005; UNDP/GEF 2007; Diaz & Rosenberg 2008; Liu *et al.* 2009; Dong *et al.* 2010). The whole coastline is severely polluted by land and sea-based sources, as well as waste from aquaculture operations and oil spills (Liu & Diamond 2005; UNDP/GEF 2007; He *et al.* 2014). The magnitude, frequency and extent of harmful algal blooms in the Yellow Sea have increased considerably (Appendix S3), and have been implicated in large-scale mortality events of coastal fin fish and shellfish across the entire coastline (Liu & Diamond 2005; UNDP/GEF 2007; He *et al.* 2014). As a result, almost all the endemic species of fauna in the Yellow Sea region are undergoing population

declines due to extreme overharvesting by commercial and artisanal fisheries, habitat loss, disturbance and environmental degradation (UNDP/GEF 2007; Beck *et al.* 2011). Yet despite these broad observations, baseline information that would allow robust estimation of the relative severity of the decline of Yellow Sea tidal flats, such as changing trends in benthic community structure, abundance and variability, are lacking (Choi *et al.* 2014). As such, quantitatively assessing the severity of biotic degradation is difficult, although several sources of information suggest rapid degradation across much of the Yellow Sea tidal flat ecosystem.

Many local studies in the Yellow Sea have demonstrated declines in the diversity, variability and composition of benthic communities, which have generally been shifting towards polychaete-dominated communities as a result of increasing pollution and physical disturbance (Ahn *et al.* 1995; Choi *et al.* 2010; UNDP/GEF 2007; Choi *et al.* 2014). For example, according to a review by Liu (2013), at one site in the western Yellow Sea, the mollusc- and crustacean-

dominated benthic community declined from a maximum of 164 species in 1967 to 7 species in the 1980s, after which no living benthic animals were recorded in subsequent surveys, with the heavy industrial pollution after the 1970s cited as the key factor for the collapse of the benthic community. Indeed, nutrient pollution, which elevates phytoplankton biomass in the water column, generally leads to reduced benthic diversity through a complex pathway of oxygen reduction, hypoxia and organic enrichment, cascading across the ecosystem gradient (Choi *et al.* 2010). At a larger scale, regional populations of mobile predators (such as migratory shorebirds) appear a useful indicator of the stability of the tidal flat ecosystem, due to their higher position in the tidal flat food web (Kuwaie *et al.* 2012). Amano *et al.* (2010) reported that the migratory shorebird species in Japan that depend on the Yellow Sea tidal flat ecosystem during migration are declining at significantly faster rates than those that do not, and suggested the degradation of the Yellow Sea tidal flat ecosystem as the likely driver of the declines. This general trend has been corroborated in Australia, where some Yellow Sea-dependent species have declined by up to 70% in the last 20 years, with changes to the Yellow Sea tidal flat ecosystem again considered a likely cause of the declines (Wilson *et al.* 2011; Szabo *et al.* 2012; Iwamura *et al.* 2013).

Invasive species are an additional threat that has led to observed biotic and abiotic degradation of the tidal flat ecosystem. *Spartina alterniflora*, a cordgrass that occurs on tidal flats and was introduced in 1979 to southern China for sediment capture, reclamation of tidal flats for agriculture, biomass production and shore protection (Strong & Ayres 2013), is rapidly invading the west coast of the Yellow Sea. The invasion across South and Eastern China, considered the world's largest invasion of *S. alterniflora* (Strong & Ayres 2013), doubled about every 1.5 years between 1985 and 2001 and is now estimated to cover approximately 19 000 ha of tidal flat in the Yellow Sea provinces (Lu & Zhang 2013; Strong & Ayres 2013). *Spartina alterniflora* has been shown to substantially reduce macrobenthic diversity and alter community structure (Neira *et al.* 2006; Zhou *et al.* 2009), elevate the shoreline to a point where it is no longer tidally inundated (Dennis *et al.* 2011), and is disrupting natural coastal processes in the Yellow Sea, reducing the extent of exposed tidal flat, outcompeting native flora and negatively impacting bird communities (Zhang *et al.* 2004; Gan *et al.* 2009; Strong & Ayres 2013). Measures to control *S. alterniflora*, which include the construction of seawalls, dikes and ditches aimed at reducing tidal inundation and promote flooding of freshwater (An *et al.* 2007a), are likely lead to further degradation of key biotic and abiotic processes of the Yellow Sea tidal flat ecosystem.

Overall, given that aquaculture development, coastal pollution, decline of fisheries, decline of benthic fauna and harmful algal blooms have occurred across the entire Yellow Sea region, we assume greater than 80% of the Yellow Sea tidal flat ecosystem has undergone biotic disruption. Establishing the relative severity is more difficult, although the declines of several Yellow Sea-dependent migratory shorebird species (up to 70% in some Australian sites) and reported declines of endemic fauna (including extinction at some sites) allow a broad estimate of between 30% and 80%. Thus, the status of the ecosystem is assessed as endangered under criterion D1 (precautionary, the plausible range is vulnerable to endangered). Owing to a lack of future estimates (D2) or long-term historic data to 1750 (D3), criteria D2 and D3 are considered data deficient.

Criterion E: Quantitative estimates of risk of ecosystem collapse

There are no quantitative estimates of the risk of ecosystem collapse, and so we assess the ecosystem as data deficient with respect to criterion E.

DISCUSSION

Severe observed declines in the extent of the Yellow Sea tidal flat ecosystem over the past 50 years, as well as long-term declines in sediment delivery, considered a key abiotic process, enable its assessment as endangered (A1, C1, D1). Owing to the difficulty in finding useful, long-term datasets for biotic and abiotic factors across the region, further work to identify data sources would improve confidence in this assessment.

The current rate of loss, the vast scale of planned development activities and the high incidence of degrading processes suggest that the future for the Yellow Sea tidal flat ecosystem is grim. With coastal urbanization forecast to result in the formation of one of the largest urban areas on earth by 2030 (Seto *et al.* 2012), ongoing declines in the extent and condition of tidal flats in the Yellow Sea seem inevitable. Reclamation activities, particularly in China and South Korea, will continue to occur as a result of ongoing development of coastal regions, the increasing scarcity of vacant coastal land and the relatively low cost of developing the coastline (Wang *et al.* 2010b; Murray *et al.* 2014). The coastline of North Korea appears to have experienced relatively little coastal development in comparison with South Korea and China, and at this stage, it may harbour some of the few areas of intact tidal flats remaining in the Yellow Sea (Murray *et al.* 2014). However, damming of the Yellow and Yangtze Rivers has significantly reduced the amount of

sediment entering the Yellow Sea, and large-scale changes of the natural coastline are interrupting the natural coastal processes that govern this dynamic ecosystem (Yang *et al.* 2006; Wang *et al.* 2010a).

The final status assessment of this ecosystem as endangered relied on large-scale remote sensing data and historical topographic maps, and long-term data from river monitoring stations. However, to improve this assessment, a deeper understanding of the sources and trends of biotic and abiotic degradation is necessary. Information regarding these would reduce uncertainty in the listings under criteria C and D, and would allow the necessary work to be completed to quantitatively assess risk under criterion E. Thus, several research priorities remain including (i) achieving higher temporal resolution of tidal flat mapping, (ii) further consolidating data on the sources and ecosystem impacts of biotic and abiotic degradation, (iii) improving our understanding of the effects of sediment declines and coastal reclamation on the tidal flat system, and (iv) improving our knowledge of the status of tidal flats in North Korea.

The application of the IUCN Red List of Ecosystems criteria on the tidal flats of the Yellow Sea highlighted several challenges in the assessment of ecosystem status. Firstly, contemporary satellite imagery, the principal method for monitoring change of habitats at large (regional) scales, is only available from the early 1970s, necessitating comparisons with historical data such as topographic maps to achieve a suitably long-term assessment of ecosystem change (Murray *et al.* 2014). Until 2022, the point at which 50 years of standardized earth observation data will be available via Landsat, there will be no standard satellite data source for mapping change of ecosystems over regional scales (>100 km) for the 50 year time frame required. Nevertheless, cautious data processing and analysis allowed this long-term assessment (Murray *et al.* 2014). Secondly, the boundary of the ecosystem, which we defined as within the Yellow Sea marine ecoregion, was necessarily a somewhat subjective choice. Tidal flats exist for more than 600 km to the east around the southern coastline of South Korea as well as the entire China coastline and throughout South-east Asia (Healy *et al.* 2002). It may have been possible to assess tidal flats in several subgeographic units, such as 'South-west South Korean coastline' and 'Bohai Sea', but we chose to assess on the Yellow Sea marine ecoregion because the ecosystem processes that govern the system are likely to apply at the regional scale and because it is considered an ecoregion due to endemism and distinctness from adjacent regions (Spalding *et al.* 2007; IUCN 2012a).

There is an urgent need to arrest the decline of the Yellow Sea tidal flat ecosystem. Improved coastal planning and management at regional and national levels

to reduce aggressive coastal reclamation is a critical first step, as well as reducing deleterious influences such as pollution, overfishing, harmful algal blooms and eutrophication (MacKinnon *et al.* 2012). As an additional protective measure, protected areas should be expanded to ensure tidal flats are captured within the protected area network, as this ecosystem is often omitted from both terrestrial and marine conservation planning frameworks in the region. Lastly, management of protected areas must be improved to combat illegal development, resource use and extraction activities.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Examples of tidal flat ecosystems in the Yellow Sea. Tidal flat showing deep dendritic drainage channels, Gomso Bay, South Korea (top) and large flock of migratory shorebirds on tidal flats at Yalu Jiang, China (bottom). Photos by N. Murray.

Appendix S2. Conceptual model showing drivers of change to key ecosystem processes of the Yellow Sea tidal flat ecosystem. The simplified tidal flat ecosystem (right) responds to changes in key processes (middle), which are caused by deleterious anthropogenic influences (left).

Appendix S3. Occurrences of harmful algal blooms (HAB) in the Yellow Sea, 1984–2005. Data sourced from *The Yellow Sea: Analysis of Environmental Status and Trends* (UNDP/GEF 2007).