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Analysis of forty years long changes in coastal land use and land cover of the Yellow Sea: The gains or losses in ecosystem services

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ABSTRACT

The drastic land cover change and its impacts in the Yellow Sea have long been significant issues in terms of coastal vulnerabilities, but holistic data analysis is limited. The present study first reports 40 years long geographical changes of the Yellow Sea coasts including all three neighboring countries of China, North Korea, and South Korea. We delineated tidal flats by analysis of Landsat series satellite imageries (662 scenes) between 1981 and 2016. A total area of the Yellow Sea tidal flats has been considerably reducing for the past 36 years, from ~10,500 km^2 (1980s) to ~6700 km^2 (2010s), say ~1% annual loss. A majority loss of tidal flats was mainly due to the grand reclamations that conducted in almost entire coast of the Yellow Sea, particularly concentrated in the 1990s-2000s. Coastal reclaimed area during the past four decades reached ~9700 km^2, including ongoing and planned projects, which corresponds to over half the area of precedent natural tidal flats of the Yellow Sea. The potential carbon stocks in the eight representative regions with large scale reclamation indicated significant loss in carbon sink capacity in the South Korea's coast (~99%), while evidenced a lesser loss from the China's coast (~31%). It was noteworthy that the progradation of tidal flats after the reclamation in China's coast significantly reduced the loss of carbon sequestration. According to the ecosystem services valuation for the Yellow Sea, a total loss was estimated as ~8 billion USD yr^{-1} with relatively high proportional loss (up to 25%) of climate regulating services (viz., carbon sequestration). Overall, huge losses in ecosystem services being provided by the Yellow Sea natural tidal flats need immediate action to prevent or at least alleviate accelerating ecological deteriorations. Finally, future conservative policy direction on coastal wetlands management has been proposed towards enhancement of marine ecosystem services.

1. Introduction

Tidal flats play essential roles in maintaining various ecosystem services being recognized as one of the most important coastal habitats (Barter, 2002; Costanza et al., 1997; Hassan et al., 2005). Among the regions with globally recognized tidal flats, such as the Yellow Sea (~10,486 km^2), the Wadden Sea (~4000 km^2), and the Persian Gulf (~3000 km^2) (Deppe, 2000), however, the Yellow Sea might have experienced the worst ecosystem damages (MacKinnon et al., 2012). This is because of an increased societal demands for land-earning strategy in China and Korea during the past several decades, resulting in massive land reclamation of natural tidal flats in the Yellow Sea (Barter, 2002; Koh and de Jonge, 2014; Murray et al., 2014; Wang et al., 2014; Yang et al., 2011).

Land cover changes by the reclamation of natural tidal flats might brought both direct and indirect impact(s) on the coastal ecosystem services (de Jonge et al., 1993; Koh and Khim, 2014; Zhao et al., 2014). For instance, tidal flats widely developed on the frontline of the coasts of the Yellow Sea protect the hinterlands from the landward waves and tides, thus storm surge damages would increase without buffered tidal flats (Gedan et al., 2011). Coastal vegetation in the upper intertidal flat also play an important role in mitigating the climate changes by absorbing carbon up to 50

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times greater than terrestrial ecosystem (Chmura et al., 2003; McLeod et al., 2011). Thus, preservation of coastal wetlands is of great importance not only for maintaining coastal vulnerabilities but also increasing ecosystem services values (ESVs). While numerous ESVs have been considered and estimated for coastal wetlands (Camacho-Valdez et al., 2013; Cui et al., 2016; Shang et al., 2018; Sun et al., 2017; Xu et al., 2016; Ye et al., 2016; Yu and Zhang, 2011; Zhao et al., 2014), the value change by tidal flats reclamation with respect to coastal carbon sequestration has not been much emphasized.

In fact, the environmental and/or ecological impacts caused by the coastal reclamations have been consistently documented in China (An et al., 2007; Cui et al., 2016; Murray et al., 2012, 2014; Yang et al., 2011; Yu and Zhang, 2011) and Korea (Lee et al., 2014; Park et al., 2014; Ryu et al., 2014). However, the previous works mostly focused on specific region(s) and/or narrow time periods, accordingly a holistic analysis could not be given so far. While, the use of meta-data derived from individual studies would be benefit to address long-term analysis, but fundamental bias due to accuracy flaw would be another issue (An et al., 2007; Murray et al., 2012, 2014; Yang et al., 2011). Of note, the information of land cover change or historical coastal reclamations lacks in North Korea, particularly in recent 10 years. Finally, there has not been much work reporting the status and long-term changes of coastal ecosystem services in Korea (Ryu et al., 2014), of which aspect should be considered as part of the entire Yellow Sea ecosystem.

In the present study, we newly delineated the coastal wetlands, namely tidal flats, in the Yellow Sea, encompassing entire coasts of China, North Korea, and South Korea, in four decadal time periods; since the 1981 to present. The present work enabled us to describe spatio-temporal comparison cross all the coastal areas of the Yellow Sea in a consistent manner, which surely improved the its comparability between countries and/or regions. Areal loss of tidal flats due to land-reclamation and/or gain from regeneration of tidal flats could be identified in minimal dimension of 30 m × 30 m, thus net areal loss or gain in specific regions of interests was discussed. In addition, the comparative analysis of carbon stock changes in major reclaimed regions in China and Korea was provided to link long-term environmental impacts to historical reclamations in the study area.

2. Material and methods

2.1. Overall scoping and framework of the study

In the present study, we targeted the coastal areas of the Yellow Sea (Fig. 1) by adopting the geographical scope of the world's oceans, viz., the Large Marine Ecosystem (LME) (Sherman, 1994). Among the current 66 LMEs in the world, the Yellow Sea LME is regarded as one of the most significantly affected areas by human development, particularly threatened by extensive coastal reclamations (Koh and Khim, 2014). The coastal areas of the Yellow Sea encompass three countries of China, North Korea, and South Korea clockwise (Fig. 1).

To reflect the long-term historical changes in land use activities along the entire coastal areas of the Yellow Sea, time-series data of tidal flat delineation for the past 36 years was generated in this study. As part of the QA/QCs, the accuracy of tidal flat delineation results from the satellite image analysis has been verified and the proper interpretation and/or limitation were discussed (Figs. 2–3). Accordingly, areal loss or gain of the natural tidal flats along the Yellow Sea could be successfully identified and presented as decadal basis (Fig. 4). Of note, the tidal flats include the bare intertidal flats and salt marshes that situated within the intertidal zone of the study area. Net areal loss of the Yellow Sea tidal flats and/or ecological impacts due to the large-size coastal reclamations in the neighboring countries of China, North Korea, and South Korea were timely described (Table 1; Fig. 5).

2.2. Tidal flat delineation and updating reclaimed coastal areas

The Yellow Sea tidal flats were delineated by use of the remote sensing technique based on the Landsat satellite imageries, warranting advantages of spatial resolution, coverage, and availability (Hansen and Loveland, 2012). The study area consisted of 21 zones (#1-#21 in counterclockwise) of the Landsat satellite imagery (WRS-2; World Reference System 2) as shown in Fig. 1. The delineated tidal flats in each zone were merged by each country and presented as national basis.

The detailed procedures are as follows. First, we collected as many as available imageries of all zones, which have been captured for the low-tide landscapes from 1981 to 2016 from Landsat 4, 5, 7 and 8, resulting in a total of 662 scenes. Next, all the collected Landsat imageries were visually (say manually) reviewed to select representative imagery for each zone, showing the most extended area of tidal flat with least covered by clouds, ices, or fogs, within a decadal period (Fig. S1). Finally, from a total of 84 selected imageries (21 zones × 4 multi-decadal periods), tidal flats were identified and delineated by the Fuzzy K-mean unsupervised classification technique. Specifically, we subtracted coastal area before classification process and used visible, near-infrared, and mid-infrared spectral bands of the Landsat imagery in the classification process (Fig. S2; Burrough et al., 2000).

Finally, specific effort was given to collect and update the missing information of coastal reclamations within target areas and/or given time frame (viz., 4 decadal periods) for each country. In particular, we newly updated the aerial dimension of reclaimed coasts in North Korea in the 2010s (Table 1).

2.3. Verification of tidal flat delineation result

There has been debated on uncertainty in terms of accuracy in remote sensing technique, due to some possible errors in the process of acquisition followed by data analysis. Thus, the accuracy of tidal flat delineation results based on satellite imageries has been evaluated as part of the study. In this study, the delineation result of tidal flats was quantitatively compared with the most recently available data from the Ministry of Oceans and Fisheries (MOF), South Korea (Fig. 2), which was constructed from the aerial photographs and the aviation LiDAR (MOF, 2013).

Specifically, we constructed the confusion matrix between two data with randomly sampled 1000 points in coastal area of South Korea. In addition, for in-depth comparison, we constructed separate confusion matrices for points within 5, 10, 15, and 30 km, depending on the distance from the mainland of South Korea. In confusion matrix, the true positive (TP) or the true negative (TN) represents the point classified as same land cover classification between MOF data and ours (Table S1). Whilst, the false positive (FP) or the true negative (TN) indicates the point classified to be “discrepancy”, namely false-classifications or errors. The accuracy was calculated as below equation.

$$Accuracy = \frac{TP + TN}{Total\ number} \qquad \text{Eq (1)}$$

2.4. Analysis and calculation of coastal carbon stock

As for one aspect of ecological impacts caused by the reduction

Fig. 1. Map showing the study area of the Yellow Sea, satellite images analyzed by the 21 WRS-2 zones along the coasts of China, North Korea, and South Korea. Eight regions of the grand reclamations conducted, three in South Korea and five in China selected for the detailed analysis for the impacts of reclamations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of tidal flats, we attempted to estimate the gain or loss of carbon stocks in coastal sediment, viz., in terms of blue carbon (Chmura et al., 2003; McLeod et al., 2011). The total organic carbon (TOC) content in coastal sediment was used as a proxy of carbon sequestration in this study. The long-term changes in blue carbon between China and Korea was highlighted by a regional comparison of carbon stocks in 5 reclaimed areas of China (Yalu Jiang Estuary, Liadong Bay, Bohai Bay, Laizhou Bay, and Jiangsu) and in 3 reclaimed regions of Korea (Sihwa, Saemangeum, and Yeongsan) (Fig. 5). In order to estimate more reliable carbon stocks in sediments, the site (habitat)-specific assessment was made for bare intertidal flat and salt marsh, in a separate manner, for calculations of total coastal carbon stocks. To support this comparison being valid, the areas of bare intertidal flats and salt marshes were separately calculated for the eight reclaimed regions while assessment. Of note, we used a supervised classification method based on the NDVI (normalized difference vegetation index) for the classification of salt marshes. Meantime, pictures manually taken in the above three reclaimed regions of Korea were used for the training samples of the classification of salt marshes.

As part of the analysis, we obtained TOCs values in coastal zones of Ganghwa, Seosan, Boryeong, Seocheon, and Suncheon, in Korea. Ten sediment core samples (50–100 cm; subsamples at 5 cm intervals) were collected from bare intertidal flat and salt marsh zone, respectively, from the above five areas. TOCs were measured in each depth using an Elemental Analyzer (EA) - Isotope Ratio Mass Spectrometer (IRMS, Elementar, Hanau, Hesse). The mean TOC values from 10 to 20 subsamples were utilized to normalize TOC values for 1 m depth values in each zone, then these values were set for typical TOCs in bare intertidal flat (56 MgC ha^{-1}) and salt marsh (93 MgC ha^{-1}) in Korea, respectively (Table S3). Then, those two mean TOC values in bare intertidal flat and salt marsh were utilized

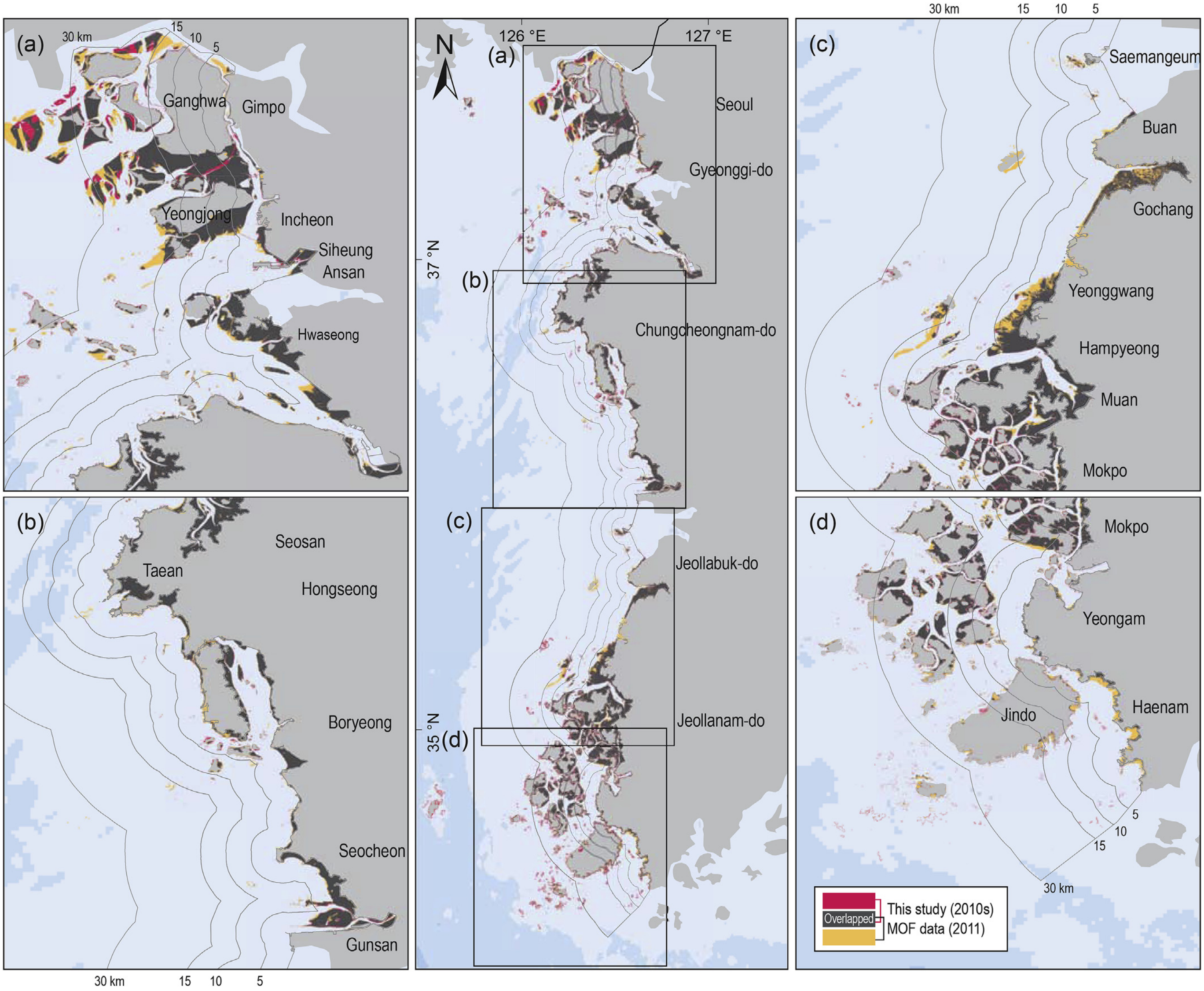


Fig. 2. The comparison of the delineation result of tidal flats between the present study (data of the 2010s) and the Ministry of Oceans and Fisheries (MOF), Korea (data of 2013), The identified area from each study presented in separate manner to show spatial comparability, with better spatial resolution; (a) Gyeonggi-Incheon, (b) Chungnam, (c) Jeonbuk, and (d) Jeonnam areas.

to calculate the coastal carbon stocks reflecting the zonal proportions in the above three target regions of Korea.

While, reliable TOC values in sediments of China's coastal areas were available from the literature (Tables S4 & S5), encompassing typical bare intertidal flat and salt marsh zone along the Yellow Sea; Liaohe delta, Liadong (Zhao et al., 2017a), Dongying port, Shandong (Zhao et al., 2017b), Yellow River Delta, Shandong (Zhao et al., 2018), Yancheng Natural Reserve, Jiangsu (Wang et al., 2013; Yang et al., 2013, 2015; 2017; Zhou et al., 2015), Sheyang, Jiangsu (Xiang et al., 2015), Xiayang estuary, Jiangsu (Liu et al., 2007; Zhou et al., 2008), Chongming Island, Shanghai (Zhang et al., 2017), and Jiudansha wetlands, Shanghai (Liao et al., 2007). A sediment depth for the reported TOC values varied with 20–100 cm in those studies, thus TOCs were normalized to the amount within 1 m depth for further calculation followed by a regional comparison. Finally, the typical TOCs in bare intertidal flat (45 MgC ha^{-1}) and salt marsh (91 MgC ha^{-1}) in China were used to estimate the coastal carbon stocks in 5 target areas of China (Tables S4 & S5).

3. Results and discussions

3.1. Validation and revision of the tidal flat delineation result

The present study revealed that area of tidal flats along the west coast of South Korea, which is eastern part of the Yellow Sea, reached about 1715 km^2 in the 2010s. The very area is estimated ~1980 km^2 based on the 2013 National Tidal Flat Area Survey of Korea (MOF, 2013), thus a slight variation (~13%) was noted between two estimates. The spatial distributions of tidal flats seemed to be very similar between two data sets (Fig. 2), but it should be noted that the noticeable difference prevailed in offshore islands areas of Incheon (Fig. 3a). This result could be explained by the recent report, indicating more dynamic sedimentological and morphological changes in an open-coast macrotidal (~9 m) environment of northern Gyeonggi Bay (Choi and Kim, 2016).

Whilst, the spatial accuracy in distributions of tidal flats in Jeonnam coastal region (Fig. 3b) far increased up to 98% between two data sets, even these areas represent a macrotidal (~5 m)

Table 1
Statistics of coastal reclamation in the three neighboring countries of China, North Korea, and South Korea along the coasts of the Yellow Sea from the 1980s to the 2010s; accumulated area from the 1980s given in parenthesis.

Region	Area of coastal reclamation (km^2)						
	1980s	1990s		2000s		2010s	
China	[a]2361	[b]1178	(3539)	[b]2723	(6262)	[c,*]1105	(7367)
Liaoning	573	235	(808)	656	(1464)	253	(1717)
Hebei	170	86	(256)	431	(687)	150	(837)
Tianjin	19	17	(36)	272	(308)	92	(400)
Shandong	1284	231	(1515)	797	(2312)	345	(2657)
Jiangsu	315	609	(924)	567	(1491)	265	(1756)
South Korea	[d]368	[d]539	(907)	[d]523	(1430)	[e, **]150	(1580)
Incheon	–	46	(46)	–	(46)	–	(46)
Gyeonggi	–	211	(211)	62	(273)	–	(273)
Chungnam	230	56	(286)	14	(300)	–	(390)
Jeonbuk	–	–		401	(401)	–	(461)
Jeonnam	138	226	(364)	46	(410)	–	(410)
North Korea	[f]155	[f]218	(373)	[g]376	(749)	[***]31	(780)
Yellow Sea	2884	1935	(4819)	3622	(8441)	1286	(9727)

[a] Meng et al., 2017, [b] Tian et al., 2016, [c] Wang et al., 2014, [d] MAFRA, 2015, [e] Koh and Khim, 2014, [f] Noh et al., 2001, [g] MLIT and NGII, 2014.
[*]Ongoing projects.
[**]Planned but not on the construction.
[***]Newly analyzed in this study.

environment similar to Gyeonggi Bay (Fig. 3a) with many islands. However, the difference would come from oceanographic condition in that islands developed in Jeonnam are more densely situated, say pronounced the embayment tidal flat, being lesser influenced by offshore tide- or wave-effects (Choi, 2014a). Overall, the accuracy between two data sets was ~86% (viz., proportions of TP & TN only; refer to Table S1), which might be within the reasonable ranges considering the short-term spatial variations in tide-dominated areas (Choi, 2014a; Choi and Dalrymple, 2004).

Further, to verify the (di)similarity between present work and MOF data, confusion matrix of the tidal flat detection was generated by 4 zones of isobathymetric line, say along the distance from the coastline (viz. mainland) of South Korea. The result indicated that the observed difference was primarily due to the spatial variability and/or temporal bias in the expansion of tidal flats. The latter temporal bias could not be surprising as the exposed area might be different depending on the captured date in tidal cycle, and even the area between the spring or neap tides might influence such variations (Murray et al., 2012). In the meantime, the former spatial variability could be explained by the vigorous changes in offshore sedimentary dynamics, particularly in remote islands due to increased tidal and wave effects (Choi, 2014a; Green and Coco, 2007). Our confusion matrix supported the above observations, as accuracy between two data sets much decreased up to 10%, i.e., ~81% in open coast of >10 km from the coastline and >91% within 10 km offshore (Table S1).

Whilst some salt marsh area or densely vegetated upper intertidal flat could not be automatically classified as tidal flat in processing satellite imagery data. Of note, the non-detected area (32 km^2) situated in the upper intertidal zone of Yangkou, Jiangsu, China, was comparable to the area of identified tidal flat (56 km^2), thus this underestimation, if any, was manually revised to increase the accuracy of tidal flat delineation (Fig. 3c). The present data employed strict QA/QC but inherent temporal bias or technical limitation such as spectral bias might remain for further revision.

3.2. *Spatiotemporal changes of the Yellow Sea tidal flats*

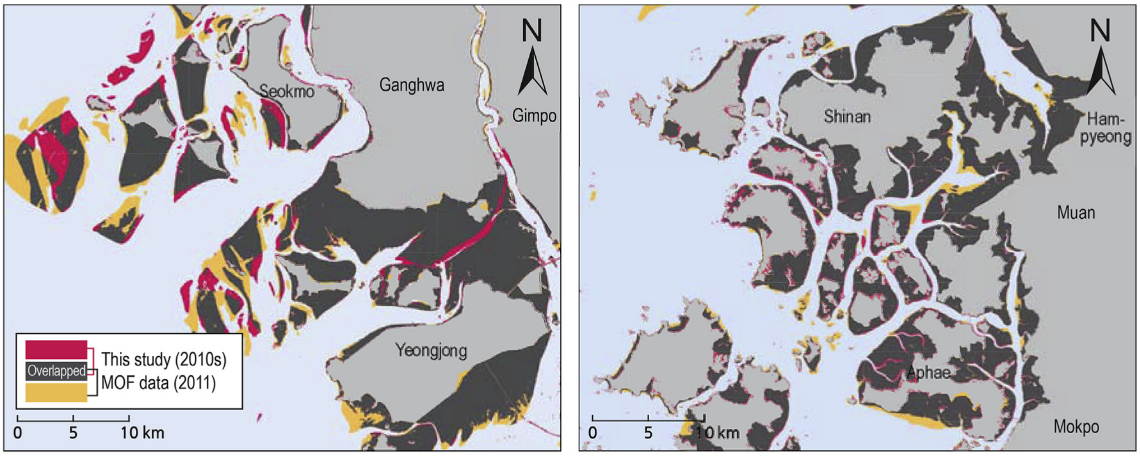
The present work provides the first comprehensive analysis, which reports the long-term changes in area of tidal flats along the entire coasts of the Yellow Sea in a time period of 36 years (Table S2). Back to the 1980s, the total area of Yellow Sea tidal flats reached ~10,500 km^2, where China's tidal flats (5830 km^2) occupied >50% in total, followed by South Korea (2680 km^2) and North Korea (1980 km^2) (Fig. 4). The Yellow Sea tidal flats decreased over 10% on a decadal basis and presently reached 6668 km^2, which is about 60% of the total area in the 1980s. It was noteworthy that about 1% of tidal flats annually disappeared and the reduction rate even increased for the past 36 years (Fig. 4b). The loss of tidal flats in South Korea greatly increased in the 1990s due to couple of large scale reclamation projects (Choi, 2014b; Koh and de Jonge, 2014) while China lost significant portion (~1500 km^2) of tidal flats more recently in the 2010s (Wang et al., 2014). While North Korea exhibited least decrease of tidal flats for the past 36 years, with a total loss of ~560 km^2. Of note, areal gain in several regions was identified in North Korea (Fig. 4), which might influence the lesser degree of areal loss in the given coastal areas.

Spatiotemporal change of the Yellow Sea tidal flats identified in the present study was similar to that of previous studies, although the reported values and trends were slightly different. Of note, Murray et al. (2014) first reported the total area of the Yellow Sea tidal flats in long-term aspect, but the values reached about half, compared to the present study, i.e., 11,220 km^2 in the 1950s, 5450 km^2 in the 1980s, and 3890 km^2 in the 2000s, respectively. Also, the very work indicated the areal gain in North Korea from the 1980s to the 2000s, but that was not evidenced in our study, thus careful interpretation should be given. The large areal reduction in China, particularly in the late 2000s, was consistent with the report by Yang et al. (2011), for example, tidal flats in Bohai Bay were reduced from 800 km^2 in 1989 to 350 km^2 in 2010.

The various (in)direct impacts of tidal flat reduction have been addressed in many studies during the past decade, but the continuing loss of tidal flats in the Yellow Sea, particularly even increasing recent loss in China, was evidenced in the present study. Earlier several studies indicated that reduction of tidal flats would badly influence biodiversity itself as well as fishery production in the given area (MacKinnon et al., 2012; Yang et al., 2011; Zhang et al., 2005). In fact, the lesser recognition of ecosystem services of coastal wetlands might be one reason back to support increased coastal reclamations in China and Korea during the past decades (Costanza et al., 1997). Fortunately, however, several recent case studies, mainly in China, re-brought our serious attention to the matter in the Yellow Sea LME (An et al., 2007; Shang et al., 2018; Sun et al., 2017; Ye et al., 2016). It should be noted that loss of ESV of coastal wetlands in the Yellow Sea might correspond to ~2 million USD km^{-2} y^{-1}, on average, from the several case studies conducted in China (Table S7), thus importance of protecting coastal wetlands is much recognized in recent years.

3.3. *Size and characteristics of coastal reclamations in the Yellow Sea*

Several previous studies collectively reported the historical data for coastal reclamations in the specific regions of interest along the coasts of the Yellow Sea in varying time frames (Choi, 2014b; Wang et al., 2014). We herein updated the historical data relating to the major coastal reclamations along the entire coasts of the Yellow Sea including North Korea for the past 36 years (Table 1). Not surprisingly, the area of coastal reclamation was the greatest in China, with total reclaimed area of 7367 km^2 (Meng et al., 2017; Tian et al., 2016), followed by South Korea (1580 km^2) and North Korea (780 km^2). In the 1980s, majority of coastal reclamation was concentrated in Shandong Province (1284 km^2), resulting in loss of >50% in total of China, then reclamation pressure seemed to move


(a) Incheon, Korea

(b) Jeollanam-do, Korea

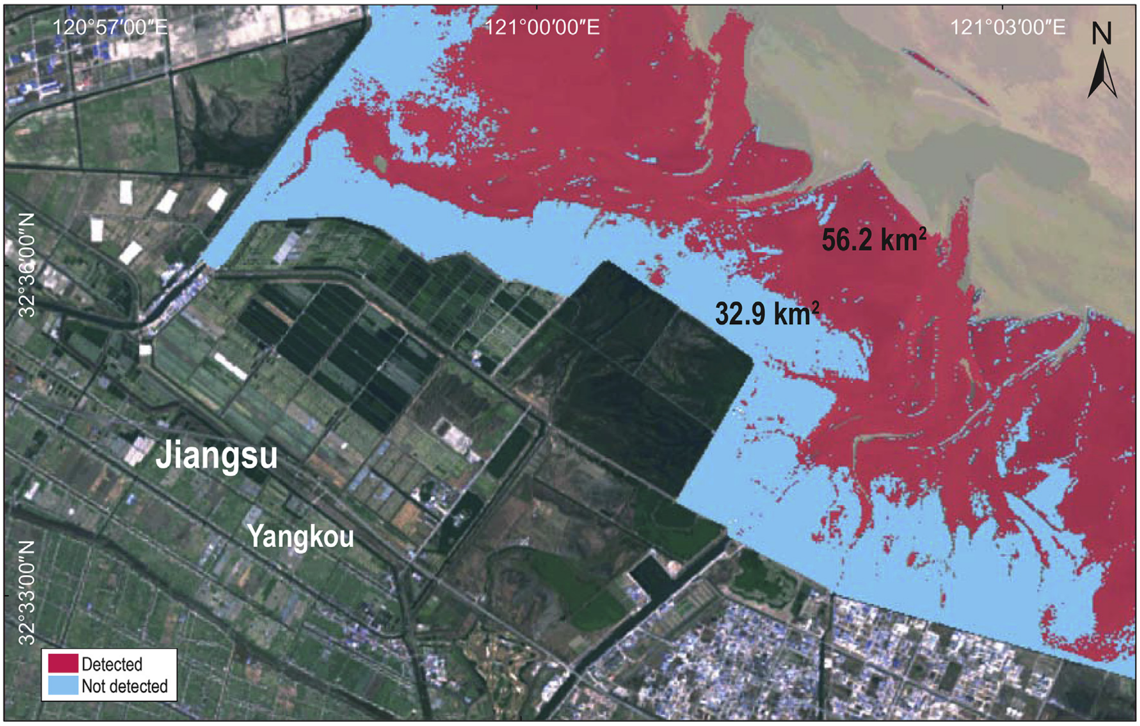

(c) Jiangsu, China

Fig. 3. Detailed comparisons of the spatial distributions of the three selected regions, by case, between the present study (data of the 2010s) and the Ministry of Oceans and Fisheries (MOF), Korea (data of 2013); (a) Incheon, Korea, (b) Jeonnam, Korea, and (c) Jiangsu, China.

to Jiangsu and Liaoning after the 1990s. Of note, the coastal reclamation pressure reached inflection point in the 2000s then decreased over half in the following decadal period of the 2010s.

Similarly, coastal reclamations much reduced in recent years in South Korea and North Korea after the booming of large scale coastal reclamations in the 1990s-2000s, such as Saemangeum project in South Korea. Saemangeum project was notorious with as the construction of world longest sea-wall (33.9 km) and the largest coastal reclaimed area (~400 km^2) in Korea, as a single project (Choi, 2014b). Serious environmental deterioration followed by long-term ecological effects on benthic community have been repeatedly documented during the past decade (Ryu et al., 2014), and the very issue brought high impact warning signal to the Korean society, turning back the management policy of coastal protection (Koh and Khim, 2014). Meanwhile, the reclaimed coastal area in North Korea has timely increased from the 1980s till the 2000s as accumulated area of 749 km^2 (Table 1), but relatively lesser pressure for coastal reclamation was evidenced in the 2010s (31 km^2), based on newly analyzed data in the present study (Fig. S3).

Anyways, as a result of the 40 years long coastal reclamations, the Yellow Sea lost ~9700 km^2 of the sea area (Table 1), where significant proportion was formerly natural tidal flats, say ~40% of the total. However, it should be noted that the coastline of China did not change much and even the degree of areal loss of tidal flats was much smaller compared to those in Korea (Fig. 5a). This is because of the difference in reclamation type between two countries followed by the varying degree of tidal flat recreation, which means the impact of reclamation might not be proportional to the area of the reclaimed land. For example, China builds a sea-wall that

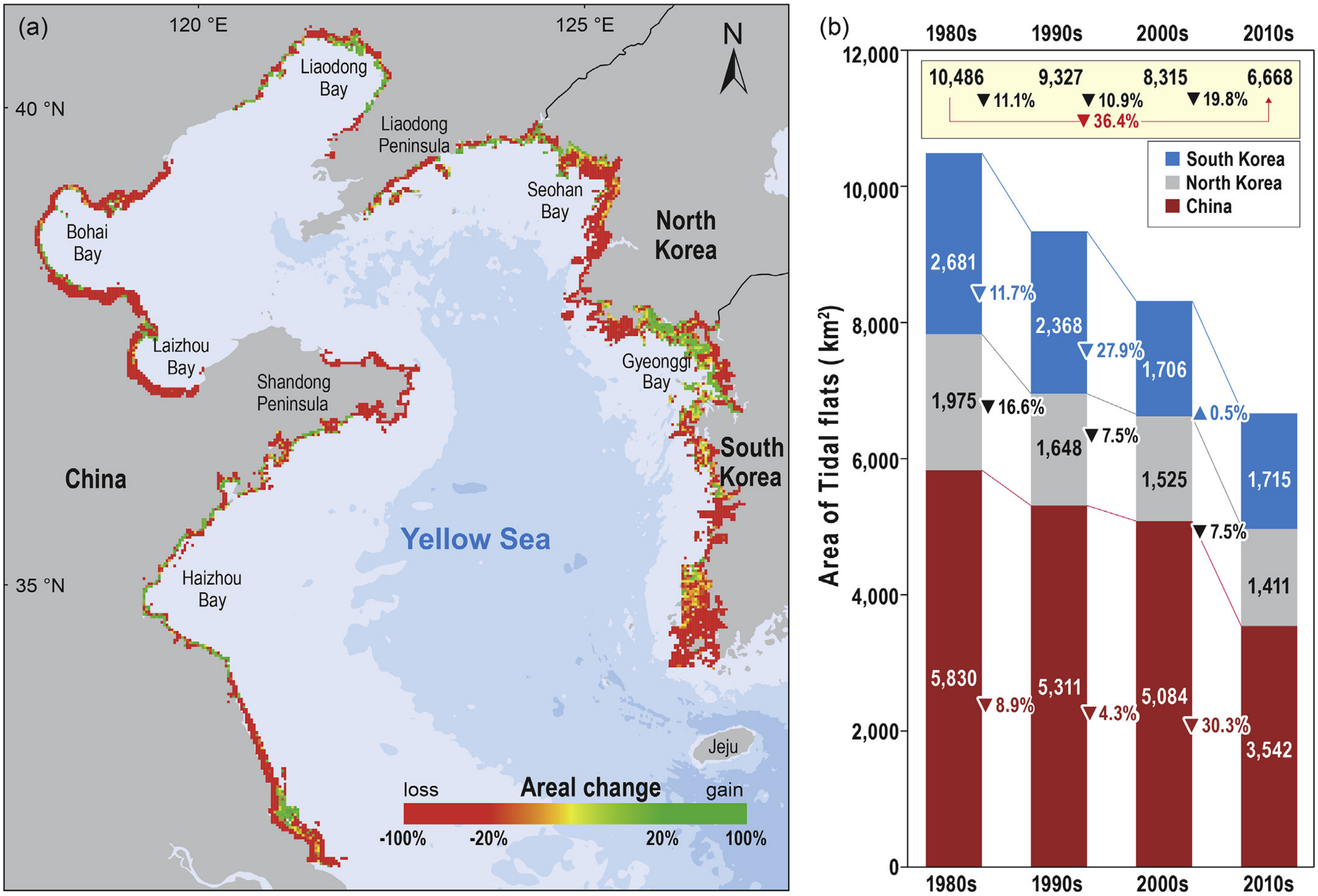


Fig. 4. Overview of the land cover and long-term spatiotemporal change of the tidal flats along the Yellow Sea from the 1980s and the 2010s; (a) areal loss or gain of the natural tidal flats, presented as net areal change of tidal flats (1 km^2 grid) on a color ramp from red (loss) to green (gain) and (b) historical change of the natural tidal flats, by country. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

parallels to the existing coastline (or former sea wall) in the middle of intertidal flat zone and only reclaims the upper zone, thus chances are high for the regeneration of tidal flats outside of the wall (Wang et al., 2014). This type of coastal reclamations was dominated in Jiangsu, Liadong, and Yalu Jiang, accordingly the areal loss due to reclamation could be minimized or even areal gain was observed in some places, most prevailing in Jiangsu (Fig. 4a). Korea utilized the method primarily securing more land–earning by blocking the entrance of a narrow bay as exampled in cases for Saemangeum, Sihwa, and Yeongsan (Fig. 5b), which resulted in significant shortening the coastline followed by smaller regeneration of new tidal flats.

3.4. Changes in carbon stocks and losses of ecosystem services

The quantitative analysis of carbon sequestration in eight reclaimed coastal regions along the Yellow Sea indicated that the impact on carbon sink capacity due to coastal reclamation varied greatly depending on the locality and/or countries (Fig. 5). The significant reduction of carbon stock could be evidenced (or expected) in three selected regions of South Korea, due to reclamation followed by entire loss of tidal flats. For example, the carbon stocks in Sihwa, Saemangeum, and Yeongsan were collectively estimated as 2.8×10^6 MgC in the 1980s but dramatically reduced to 0.024×10^6 MgC in the 2010s. Such a big loss in carbon stock capacity was mainly due to the great areal loss of tidal flats, collectively from 503 km^2 to 4.2 km^2 during the four decadal period. The areal reduction of ~26 km^2 of salt marshes in these three regions additionally accounted for the net loss of 0.2×10^6 MgC.

In the Meantime, the carbon stocks in the five selected reclaimed regions in China showed relatively lesser losses for Yalu Jiang Estuary, Bohai Bay, and Laizhou Bay or even increased in Liadong Bay and Jiangsu Province (Fig. 5a). Interestingly, in Liadong Bay, the area of tidal flats in the 2010s (273 km^2) decreased ~35% compared to that in the 1980s (417 km^2), but the carbon stock rather slightly increased. The expansion and/or recreation of large scale salt marshes developed along the Liadong Bay during the four decal periods might have increased the potential carbon sink capacity. Of note, Zhao et al. (2017a) reported the carbon stock capacity was about four times greater in salt marsh (9.75 kg m^{-2}) compared to bare intertidal flat (<2.55 kg m^{-2}). Anyways, the total loss of ~34% carbon stocks in these five reclaimed regions of China, from the 1980s (~17×10^6 MgC) to the 2010s (~11×10^6 MgC) was evidenced. Again, the big difference in potential carbon stock capacity and its change between China and Korea would be attributable to coastal reclamation type. The China's reclamation maintains the original shape of coastline which allows more chances for the progradation of tidal flats (Dalrymple and Choi, 2007), which was not the case in Korea (Koh and Khim, 2014). In addition, the proportion of salt marsh, which has generally greater carbon sink capacity in vegetated zone, would also be one

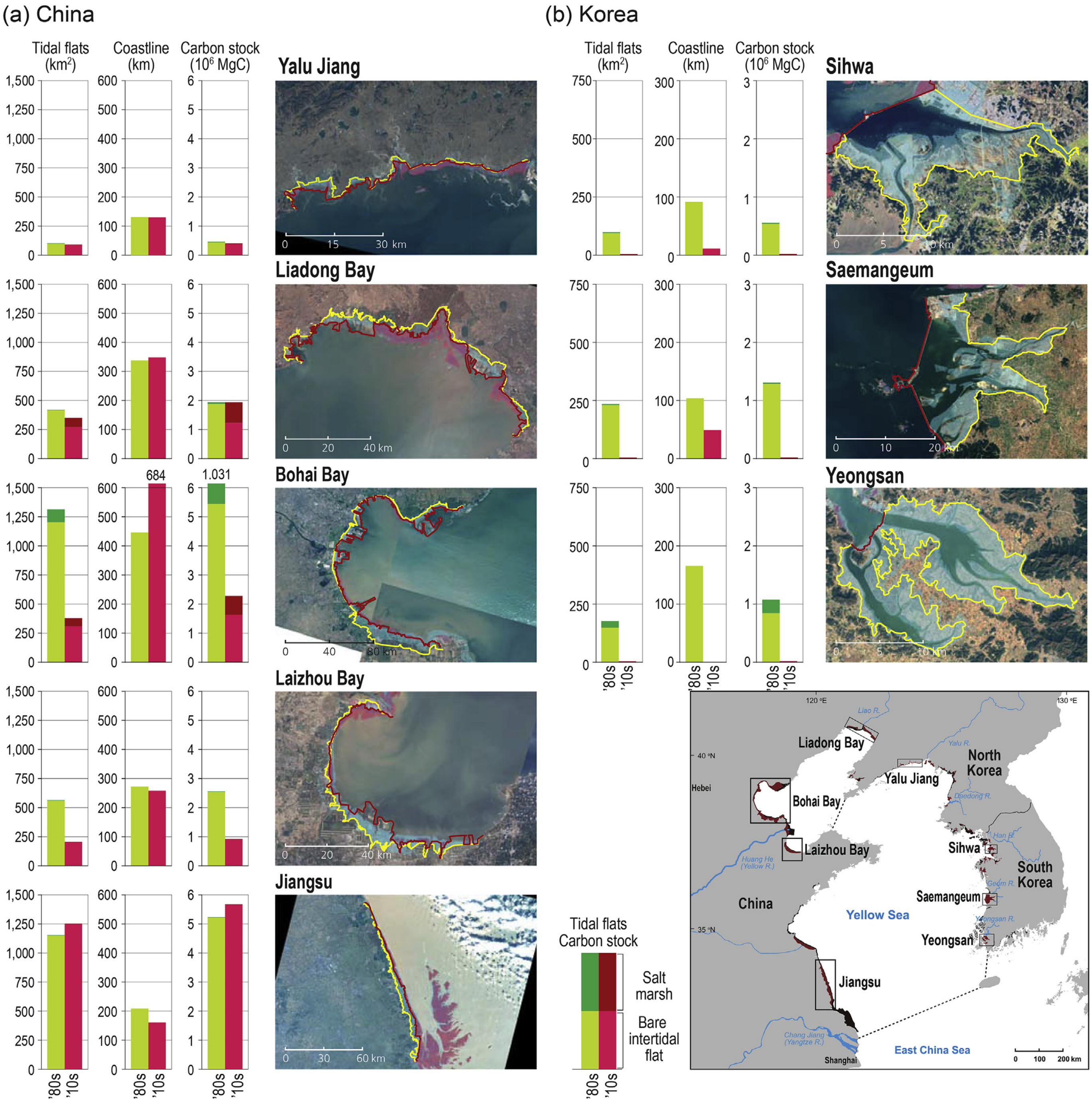


Fig. 5. The quantitative analysis of historical changes in selected areas of tidal flats, coastline, and carbon stock in the tidal flats of the Yellow Sea, (a) Yalu Jiang, Liadong Bay, Bohai Bay, Laizhou Bay, and Jiangsu, China and (b) Sihwa, Saemangeum, and Yeongsan, Korea; the proportional contributions to total values in each endpoint separately given for bare intertidal flat and salt marsh. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

important factor to alleviate the reduction of climate regulating services.

Recently, several studies repeatedly documented that a large loss in ecosystem services of coastal wetlands was directly linked to coastal reclamation (Tables S6 & S7), where reduction of climate regulating service such as blue carbon was highlighted. For example, Xu et al. (2016) insisted that the ESV of climate regulating (0.4 million USD km^{-2} y^{-1}), viz., carbon sequestration, would account for ~27% of total ESV in tidal flats of Jiangsu. Of note, several studies attempted to estimate the ESV for the Korean tidal flats, however, the climate regulating service targeting blue carbon has not been yet considered (Tables S6 & S7). Anyways, the ESV for the Yellow Sea tidal flats estimated by use of the reported values (Tables S6 & S7) decreased from 21 billion USD yr^{-1} in the 1980s to 14 billion USD yr^{-1} in the 2010s, reflecting great loss of ecosystem services (Table 2). Of note, the regulating services such as carbon sequestration and waste treatment were found to be the most important component among the four categories of ecosystem services (de Groot et al., 2012; Xu et al., 2016), accounting for over half (56%) of the total ESV in the Yellow Sea (Table 2).

Table 2
The expected ecosystem services value (ESV; 10^6 USD yr^{-1}) of the coastal wetlands (tidal flats) in the Yellow Sea in the 1980s and the 2010s, the estimated values given by region (country) adopting the reported country-based mean values from the literature (refer to Tables S6 & S7) for total ESV and four components of ecosystem services; provisioning, regulating, supporting, and cultural services.

Region	Total ecosystem services			Provisioning		Regulating		Supporting		Cultural	
	1980s	2010s		1980s	2010s	1980s	2010s	1980s	2010s	1980s	2010s
China	12416	7543	(▼39)	3104	1886	7419	4507	395	240	1498	910
South Korea	5156	3298	(▼36)	1475	943	2697	1725	652	417	332	212
North Korea	3798	2713	(▼29)	1086	776	1987	1419	480	343	245	175
Total	21370	13554	(▼37)	5665	3605	12103	7651	1527	1000	2075	1297

The present study emphasized a huge historical loss of tidal flats of the Yellow Sea, directly linked to coastal reclamation, but natural processes allowing areal gain of tidal flats are evidenced, particularly in coasts of China. The oceanographic settings that allow natural sediment supply from the major rivers such as Han River, Korea and Yellow River or Yangtze River, China to nearby estuaries might compensate the loss of ecosystem services (He et al., 2014; Koh and Khim, 2014; MacKinnon et al., 2012). Some natural factors such as precipitation and/or sea level rise might also influence the degree of gain and/or loss of coastal ecosystem services depending on the locality (Barbier et al., 2011). Anyways, the coastal developmental policy by the reclamation seems to be fading out in Korea as increasing public concern on natural conservation recently. China might follow the Korea's history in timely manner (Koh and de Jonge, 2014).

3.5. Implications for re-aligning of coastal wetland policy regimes

The present study reaffirmed existing but continuing environmental issues related to coastal developmental policy, say grand reclamation project, and exampled the degradation of ecological integrity of coastal ecosystem. High potential of further economic growth around the Yellow Sea and seemingly accelerated climate change impact (IPCC, 2014; NASEM, 2017; Pecl et al., 2017; Qiu, 2017) might increase ecosystem deterioration. Upon the given challenge, several regional management regimes such as Yellow Sea Large Marine Ecosystem Project (YSLME) (Chung, 2010), North-East Asian Marine Protected Areas Network, and East Asian-Australasian Flyway Partnership have been practiced.

In parallel with multilateral cooperation, China and South Korea have also evolved and fortified their own coastal ecosystem protection policy since the early 2000s, mainly led by expansion of marine protected areas (MPAs) designation and a more conservative approach to wetlands exploitation. There have been arguments, however, that the institutional and legal alignment on MPAs would not always guarantee desired outcomes such as rehabilitation and restoration of the ecosystem (Chaigneau and Brown, 2016; Pendleton et al., 2017). Merits and faults on coastal exploitation for economic growth are likely to be continuing critical issues.

Policy implications towards healthy coastal wetlands and balanced regime of conservation and exploitation of the YSLME would be appreciated as following, based on the findings of the present study. First, coastal developmental policy needs to consider the concept of ecological and physical linkages between river basins and wetlands. Second, despite controversial argument of MPA effectiveness, expansion of coastal MPAs could contribute to fortifying current policy regimes and raising public awareness on the wetlands conservation and their wise use. Third, innovative approach to MPAs designation is essential to witness conservation and rehabilitation of coastal wetlands ecosystems. Fourth, involvement of North Korea is one of integral part to establish fully functional regional governance for the Yellow Sea ecosystem. Finally, implication comes from incorporation of ecosystem services into marine and coastal spatial management regime.

4. Conclusions

The present study first attempted to address the 40 years long changes in coastal cover along the entire coast of the Yellow Sea including three countries of China, North Korea, and South Korea. The area of tidal flats in the Yellow Sea has been drastically reduced by 36% as of the 2010s compared to the 1980s, from ~10,500 to 6670 km^2, say annual decrease of 1%. The long-term continuing losses of tidal flats along the coasts of three countries were found to be directly related to the localized reclamations in major estuaries or bays, particularly in Korea. The cumulative area of reclamation in the three countries reached ~9700 km^2 for the past 40 years including ongoing and planned projects, mainly in China, in the 2010s, which was quite close to the area of natural tidal flats in the 1980s, indicating half of the original natural habitats disappeared. Of note, the net loss of Yellow Sea tidal flats during the same period was ~3800 km^2, accordingly the loss of estimated ESV of the entire Yellow Sea tidal flats was 7.8 billion USD yr^{-1}. The almost complete destruction of carbon stock capacity (>99%) was estimated in reclaimed coastal wetlands of Korea, while its loss in China much weakened (~38%) owing to the recreation of tidal flats. In general, the present study successfully reconfirmed the long standing relationship between coastal development and ecological impact, with updated revised data and analysis of coastal cover in the Yellow Sea LME. In order to minimize coastal vulnerability and loss of ecosystem services in this region, science-based policy design toward coastal conservation should be strengthened in the near future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2018.05.058.

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