Front Matter

Title
Remote observations in China’s Ramsar sites: wetland dynamics, anthropogenic threats, and implications for Sustainable Development Goals

Observations in China’s Ramsar wetlands

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Abstract
The Ramsar Convention on Wetlands is an international framework through which countries identify and protect important wetlands. Yet Ramsar wetlands are under substantial anthropogenic pressure worldwide, and tracking ecological change relies on multitemporal datasets. Here, we evaluated the spatial extent, temporal change, and anthropogenic threat to Ramsar wetlands at a national scale across China to determine whether their management is currently sustainable. We analyzed Landsat data to examine wetland dynamics and anthropogenic threats at the 57 Ramsar wetlands in China between 1980 and 2018. Results reveal that Ramsar sites play important roles in preventing wetland loss compared to the dramatic decline of wetlands in the surrounding areas. However, there are declines in wetland area at 18 Ramsar sites. Among those six lost a wetland area greater than 100 km², primarily caused by agricultural activities. Consistent expansion of anthropogenic land covers occurred within 43 (75%) Ramsar sites, and anthropogenic threats from land cover change were particularly notable in eastern China. Aquaculture pond expansion and Spartina alterniflora invasion were prominent threats to coastal Ramsar wetlands. The observations within China’s Ramsar sites, which in management regulations have higher levels of protection than other wetlands, can help track progress towards achieving United Nations...
Sustainable Development Goals (SDGs). The study findings suggest that further and timely actions are required to control the loss and degradation of wetland ecosystems.

1. Introduction

Wetlands are among the most fragile ecosystems, vulnerable to climate change and human disturbances, and have experienced striking loss and degradation worldwide [1-3]. Understanding the spatial extents, temporal changes, and ecosystem threats of wetlands is important in achieving the United Nations Sustainable Development Goals (SDGs) which highlights the protection of wetlands [4, 5]. However, due to the difficulty in accurately delineating wetland boundaries caused by complex composition and spectral features, there are few reliable assessments of wetland change at global or national scales [6]. This deficiency may result in unsustainable wetland ecosystem management, and hinder policy improvement.

China has the fourth largest wetland coverage in the world. Its wetlands account for 5% of the nation’s territorial area [7]. However, wetland loss has occurred rapidly in China despite the value of these ecosystems being recognized [8, 9]. Multiple studies have reported on wetland changes and their driving factors [5, 10]. For example, it was estimated that the total wetland area in China declined by more than 50,000 km$^2$ between 1990 and 2000, and 33% of China’s wetlands were lost between 1978 and 2008 [11, 12]. Cropland expansion contributed 60% to the loss of vegetated wetlands in China between 1990 and 2010 [13]. Yet little is known about the anthropogenic processes driving those losses, hampering sustainable management and long-term conservation of wetlands. China has established a large number of wetland protected areas [9], but it is unclear whether the actions have stopped wetland losses within these protected areas.

The Ramsar Convention on Wetlands, established in 1971, was the first globally coordinated institutional framework for wetland conservation and wise use [14]. Currently, 2,354 Ramsar sites are designated and distributed among 170 countries, protecting 13–18% of global wetlands [3]. Since the adoption of the Ramsar Convention in 1992, China had designated 57 Ramsar wetland sites by 2019 with a total area of 69,486 km$^2$ aimed at protection of the principal ecological characteristics and biodiversity of those areas (www.ramsar.org). The protection of Ramsar wetlands has strong governmental commitment through domestic legislation in China, and a systematic evaluation of Ramsar sites is critical for informing their management and indicative for wetland protection across the country [15].

Ecological change in Ramsar wetlands can be assessed through multiple indicators including widely used spectral vegetation indices (e.g. normalized difference vegetation index, NDVI), landscape metrics, and directly-measured ecosystem parameters [16, 17]. Although wetland loss and degradation have been documented to some degree using those methods in several Ramsar sites in China, specific anthropogenic threats such as agricultural cultivation, industrial footprint, aquaculture development, and biological invasions, have not been quantitatively investigated. A systematic understanding of spatial extents, temporal changes, and major threats to Ramsar wetlands is required for wetland management and policy improvement to achieve ecological sustainability.
In this study we evaluated the effects that Ramsar designation has had on wetland conservation in China, with the aim of informing wetland management and protection measures at the national scale. To achieve this goal, we mapped land cover changes within and adjacent to the 57 Ramsar sites between 1980 and 2018 at decadal intervals. We compared wetland change within and adjacent to the Ramsar sites before and after their designation and investigated the coverage proportion and temporal changes in anthropogenic land covers including cropland and built-up land. Finally, we examined the expansion of aquaculture ponds, and damaging invasive species, *Spartina alterniflora* (*S. alterniflora*) introduced into China’s coastal Ramsar wetlands. Our evaluation of wetland protection efficacy across China’s Ramsar sites will provide valuable insights into management and policy priorities for wetlands to promote the protection of wetlands and biodiversity worldwide.

2. Materials and Methods

2.1 Study area

Ramsar sites protect habitat for a large number of endangered migratory waterbirds, aquatic animals, and natural plants or ecosystems and are an important component of the wetland protection system in China. The 57 Ramsar sites (Figure 1A) designated by 2019 occur from the Grand Khingan Hanma Wetlands in the north (51° 35'N, Site No. 1,976) to the Dongzhaigang in Hainan in the south (19° 59'N, Site No. 553). According to the National Wetlands Conservation Program (NWCP), the largest number of sites (16) occur in the Coastal Region (CRC), while the fewest (1) are found in the lower and middle reaches of the Yellow River (YER; Figure 1A, 1C). The largest Ramsar site, the Selincuo Wetlands in Tibet (Site No. 2,352), has an area of 19,836 km$^2$, while the Hangzhou Xixi Wetlands in Zhejiang (Site No. 1,867) has the smallest area (3 km$^2$). China’s Ramsar sites include multiple natural wetland types including inland swamp, marsh, lake, river, coastal mangrove, bare tidal flat, estuary, and shallow marine water. Detailed designation number, name, and date for each Ramsar site is provided in supplementary Table S1.
Figure 1 Locations of China’s Ramsar sites. A: distribution of Ramsar sites and division of the National Wetlands Conservation Program (NWCP); B: number of Ramsar sites designated in different years; C: number of Ramsar sites located in each NWCP region.

2.2 Landsat satellite images

Although the widely used national land use data product has advantages such as a five-year interval and 30 m spatial resolution, we performed our image classification for a finer wetland classification with reliable data accuracy and consistency for each Ramsar site. We selected 5 time periods at approximately decadal intervals (1980, 1990, 2000, 2010, and 2018) to evaluate the effects of the Ramsar Convention on Wetlands in China. Due to the scarcity of available images in 1980, images in adjacent years were supplemented to classify land cover in 1980. Sixty-four Landsat scenes were required to cover the entire extent of all Ramsar sites (Figure 2). Multi-seasonal images characterizing phenological features could support the identification of different land cover types. Therefore, for obtaining the land cover datasets for each the five years, we collected a total of 768 images (with cloud cover < 10%) from the open access source by the United States Geological Survey (USGS). Prior to image classification, data preprocessing including geometric, topographic, and radiometric corrections was performed for all images using the ENVI 5.1 software package.
2.3 Land cover classification

To reduce seasonal variation in land cover, images in the months from June to September were primarily used, while images from other months were used as auxiliary data. A hybrid approach combining object-based image analysis and hierarchical decision-tree classification (HOHC) performed in the eCognition software (version 9.2) was used due to its advantages in segmenting images into homogeneous objects and semi-automated distinguishing of these objects ensuring both classification accuracy and efficiency [7, 18]. The classification accuracies of final datasets were evaluated using independent ground reference samples, which were acquired from field surveys, public databases, and high-resolution images from Google Earth [19-21]. An outline of the process used for Landsat image classification is adopted from Mao et al. [7] and illustrated in Figure 3.
Figure 3 General flowchart of Landsat data processing and data analysis.

We determined and adapted a classification by referencing the level of Class I of the National Land Cover Database of China (ChinaCover) [18] and considering the classification potential of the Landsat images (Table 1). We were able to categorize land cover classes into natural (woodland, grassland, wetland, and barren land) and anthropogenic (cropland and built-up land) types according to Table 1. To permit a detailed assessment of anthropogenic land cover, cropland was further divided into dry farmland and paddy field, while built-up land was classified into residential land, industrial land, transportation land, and mining land. The classification at second level (Class II) for wetlands was derived from our proposed wetland classification system for national wetland mapping [7]. According the Ramsar wetland definition, we classified all waterbodies in the Ramsar site were as wetlands. Although paddy field is an important human-made wetland type, we nonetheless classified it into cropland to reflect its limited ecosystem function and the high intensity of human management. In this study, classifications were performed to the level of Class II for the inland Ramsar wetland sites and Class III for coastal Ramsar wetland sites. To investigate conversions among wetland categories, we separated human-made wetlands including reservoirs/artificial ponds and canals/channels from natural wetlands. Moreover, to examine the impacts of aquaculture development on natural wetlands, the expansion of aquaculture ponds in the coastal Ramsar sites was assessed using the methods described in Ren et al. [22]. Exotic plant invasion is also impacting a number of Ramsar sites in China. S. alterniflora, native to the Atlantic coastal America, has been the most invasive species in coastal wetlands. In our study, data on the distribution of S. alterniflora were obtained from the study of Liu et al. [23] and Mao et al. [24] to evaluate exotic plant invasion on natural wetlands.

For evaluating the classification results, accuracies were assessed by field wetland samples which were provided by the Wetland Science Data Centre of China.
These samples were investigated with the support of several national research projects [7]. All classifications achieved consistency with validation samples characterized by overall accuracies for both Class II and Class III larger than 85%.

Table 1 Land covers at different levels classified in this study

<table>
<thead>
<tr>
<th>Land covers</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodland</td>
<td></td>
<td>Human-made wetland (reservoir/artificial pond, canal/channel, and salt pan)</td>
<td>Coastal aquaculture pond</td>
</tr>
<tr>
<td>Grassland</td>
<td></td>
<td>Natural waterbody (lake, river, estuary, lagoon, and shallow marine water)</td>
<td></td>
</tr>
<tr>
<td>Barren land</td>
<td></td>
<td>Other wetlands (swamp, marsh, and mudflat)</td>
<td>S. alterniflora</td>
</tr>
<tr>
<td>Wetland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropogenic</td>
<td>Cropland</td>
<td>Dry farmland</td>
<td></td>
</tr>
<tr>
<td>Built-up land</td>
<td></td>
<td>Paddy field</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Statistical Analysis

We compared areal changes in wetlands from 1980 to 2018 within and around (10-km buffer) China’s Ramsar sites. We also used datasets in the four time periods to investigate changes in wetland area and anthropogenic threats before and after their Ramsar designation. The areal proportion of anthropogenic land covers within the Ramsar site was used to represent the direct anthropogenic threats in corresponding sites [25] (equation 1). Considering the evident human disturbances from human activities on coastal wetlands, areal changes in aquaculture ponds were quantified during the investigated different periods. Moreover, expansion of artificially introduced exotic species from North America, S. alterniflora, was estimated in major coastal Ramsar sites from 1990. Therefore, the top four anthropogenic threats to Ramsar wetlands considered in this study were agricultural cultivation, built-up land expansion including urbanization and industrial footprint, aquaculture development, and exotic species invasion.

For a Ramsar site with two different anthropogenic threats (e.g. cropland and built-up land), the direct anthropogenic threat was calculated as

\[ \text{Direct anthropogenic threat} = \frac{A_1 + A_2}{A_{total}} \]  

where \( A_1 \) represents the area of cropland in a Ramsar site, \( A_2 \) represents the area of built-up land in a Ramsar site, and \( A_{total} \) represents the total area of a Ramsar site.

3. Results

3.1 Spatial extents and temporal changes of wetlands within and adjacent to Ramsar sites
Landsat-based observations revealed that there were 32,692 km² of wetlands protected in the 57 Ramsar sites in 2018. Among these, 19 sites (33%) had wetland coverage larger than 90% and 14 sites had wetland coverage (including all water bodies) ranging between 50% and 90% (Figure 4A). Sites with high wetland coverage mostly occurred in eastern China (Figure 4B), especially in the CRC. The Ramsar sites in Inner Mongolia-Xinjiang Plateau (MXP) and Yunnan-Guizhou Plateau (YGP) had lower wetland coverages than that in other geographic regions. Three sites in shallow marine waters, i.e. the Yangtze Estuarine Wetland Nature Reserve for Chinese Sturgeon (Site No. 1,730) in Shanghai, the Nanpeng Archipelago Wetlands (Site No. 2,249) in Guangdong, and the Dalian National Spotted Seal Nature Reserve (Site No. 1,147) in Liaoning, had wetland coverages of 100%. However, 11 sites (19%) had wetland coverages of only 30%–50%, while another 13 sites (23%) had wetland coverage lower than 30%. The Selincuo Wetlands in Tibet (Site No. 2,352) contained the largest total wetland area of 6,094 km², dominated by lakes. The Daju Lake Wetland (Site No. 2,186) in Hubei had the smallest wetland area (1.4 km²) and coverage (1%) among all the sites, being covered mainly by woodland. Spatial patterns of land cover in each Ramsar site were provided in supplementary Figure S1.

Figure 4. Statistics of wetland coverage and direct anthropogenic threats in Ramsar sites in 2018. A, number of Ramsar sites with various wetland coverage classes; B, mean value of Ramsar wetland coverages in different geographic regions of the National Wetland Conservation Program (NWCP); C, number of Ramsar sites with various classes of direct anthropogenic threats; D, mean value of direct anthropogenic threats in different Ramsar sites over the geographic regions of NWCP: Coastal region (CRC), Northeast China (NEC), Lower and middle reaches of the Yangtze River (YAR), Qinghai-Tibet Plateau (QTP), Yunnan-Guizhou Plateau (YGP), Inner Mongolia-Xinjiang Plateau (IXP), and Lower and middle reaches of the Yellow River (YER); Error bars show standard deviations.

Total wetland area across the Ramsar estate decreased by an estimated 6.6% from 1980 to 2018, while wetland area in the 10 km buffer adjacent to the Ramsar sites declined by 22.5% in the same period. Natural wetlands in the Ramsar sites lost 12.3% of their total area, while natural wetlands in the 10 km buffer adjacent to the Ramsar sites lost 26.1%. Wetland loss primarily occurred in the Ramsar sites of Northeast China (NEC) and CRC. However, human-made wetlands in the Ramsar sites expanded by 246% and in the 10 km buffer adjacent to the Ramsar sites by 31%. The expanded human-made wetlands were
mostly identified in Ramsar sites in the CRC (70%). Ramsar sites appear to have played an important role in reducing wetland loss and protecting wetlands.

From 1980 to 2018, wetland areas in 41 of the 57 Ramsar sites (72%) showed changes (Figure 5). Specifically, wetland area in 18 sites (32%) appeared to decline consistently despite these wetlands having been designated as Ramsar sites. Another 6 sites showed an initial wetland increase followed by decrease. In particular, more than 100 km$^2$ was lost from each of 6 sites between 1980 and 2018. The San Jiang National Nature Reserve in Heilongjiang (Site No. 1,152) had a most remarkable net loss of wetland (693 km$^2$), mostly resulting from agricultural cultivation. After the designation of Ramsar site, 21 km$^2$ of wetlands were converted into cropland. In contrast, 7 sites (12%) showed consistent wetland increase, with the largest wetland increase (61 km$^2$) being dominated by marsh and swamp expansion occurring in the Nanweng River National Nature Reserve in Heilongjiang (Site No. 1,976). Another 10 sites had an initial decrease in wetland area followed by increase after being formally designated as Ramsar sites. For example, the decreased wetland area in Xianghai (Site No. 548) designated as a Ramsar site in 1992 has been reversed.

![Figure 5. Various wetland changes from 1980 to 2018 over different Ramsar sites (time points are 1980, 1990, 2000, 2010, and 2018).](image)

3.2 Direct anthropogenic threats and their dynamics in the Ramsar sites
Only 8 Ramsar sites had no sign of anthropogenic land covers in 2018, while wetlands in the other 49 sites (86%) had been subject to various extents by anthropogenic threats over the past four decades (Figure 4C). Specifically, 10 sites (17%) had an areal proportion of anthropogenic land cover larger than 30%. Agricultural activities imposed the largest influences on wetlands, which were identified as the most severe in the San Jiang National Nature Reserve in Heilongjiang (Site No. 1,152). In this site, 64% of the whole area (2,232 km²) was covered by cropland in 2018. In addition to agricultural encroachment into wetlands, the largest proportion (13%) of built-up land area dominated by residential land was found for the Shengjin Lake National Nature Reserve in Anhui (Site No. 2,248), and significant industrial footprints occurred in the Liaohe Estuary in Liaoning (Site No. 1,441). Particularly acute anthropogenic threats were observed in sites in the Lower and middle reaches of the Yangtze River (YAR) and NEC compared to other geographic regions (Figure 4D), with the former having 24.4% of its area subject to anthropogenic threats.

From 1980 to 2018, increases in direct anthropogenic threats occurred in 40 sites, with an initial decrease followed by an increase for 3 sites (supplementary Figure S2). The San Jiang National Nature Reserve in Heilongjiang (Site No. 1,152) had the largest areal increase of anthropogenic land covers (692 km²), with 95% of the increase resulting from cropland expansion. However, the rate of increase of direct anthropogenic threats slowed markedly after its designation as a Ramsar site (Figure 6). The greatest expansion area of built-up land was observed in the Dong Dongting Hu in Hunan (Site No. 551) with an area increase of 98.5 km², with the increase occurring mostly after its designation as Ramsar site.

Only the Haifeng Wetlands site in Guangdong (Site No. 1,727) had a consistent decrease of anthropogenic land covers (Figure 6), while another 5 sites experienced an increase followed by a decrease of direct anthropogenic threats. The Wang Lake site in Hubei (Site No. 2,349) experienced the most striking decrease in direct anthropogenic threats from 25% to 12%, while the Zhanjiang Mangrove National Nature Reserve (Site No. 1,157) in Guangdong had the largest areal decline of anthropogenic land covers (38 km²) after its Ramsar designation. However, built-up lands in all these 6 sites showed consistent expansion during the study period.
Figure 6 Anthropogenic land cover (ALC) changes from 1980 to 2018 in Ramsar sites (the gray dotted line denotes its Ramsar designation time, different colors in the line charts denote different change trends of direct anthropogenic threats).

3.3 Aquaculture pond expansion and exotic *S. alterniflora* invasion in coastal Ramsar sites

A striking expansion of aquaculture ponds at the expense of natural wetlands occurred in 8 coastal sites, including 4 sites where aquaculture ponds expanded by more than 100 km$^2$. 
with expansion continuing beyond the date of Ramsar site designation (Table 2). The most obvious expansion occurred in the Yancheng National Nature Reserve with an areal increase of 752 km$^2$. Liaohe Estuary experienced a marked expansion (106 km$^2$) between 2010 and 2018 after its Ramsar designation in 2004. A rapid expansion of aquaculture pond in the Zhanjiang Mangrove National Nature Reserve was identified between 1990 and 2000, but slowed after Ramsar designation in 2002.

Table 2 Aquaculture pond expansion (km$^2$) in selected Ramsar sites from 1980 to 2018

<table>
<thead>
<tr>
<th>Site number</th>
<th>Site name</th>
<th>Aquaculture pond expansion in different periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,441</td>
<td>Liaohe Estuary</td>
<td>0</td>
</tr>
<tr>
<td>2,187</td>
<td>Yellow River Delta Wetland</td>
<td>13</td>
</tr>
<tr>
<td>1,156</td>
<td>Yancheng National Nature Reserve</td>
<td>145.4</td>
</tr>
<tr>
<td>1,145</td>
<td>Dafeng National Nature Reserve</td>
<td>53</td>
</tr>
<tr>
<td>1,157</td>
<td>Zhanjiang Mangrove National Reserve</td>
<td>25.3</td>
</tr>
<tr>
<td>1.726</td>
<td>Zhangjiangkou National Mangrove</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Reserve</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>Mai Po Marshes and Inner Deep Bay</td>
<td>0</td>
</tr>
<tr>
<td>1,728</td>
<td>Beilun Estuary National Reserve</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*S. alterniflora* invaded several coastal areas (Figure 7). Notable *S. alterniflora* invasions of areas larger than 10 km$^2$ occurred in 4 Ramsar sites (Table 3). The Yancheng National Nature Reserve in Jiangsu had the most evident invasion of *S. alterniflora* with the largest and consistent areal increase from 3.2 km$^2$ in 1990 to 111.2 km$^2$ in 2018. The Dafeng National Nature Reserve in Jiangsu (Site No. 1,145) had an increase in *S. alterniflora* coverage of 49.4 km$^2$ between 1990 and 2000, but a slightly decreasing trend after 2000. The Chongming Dongtan Nature Reserve in Shanghai (Site No. 1,144) had *S. alterniflora* coverage of 15.3 km$^2$ in 2018 and *S. alterniflora* expansion of 10.4 km$^2$ during 2000–2010. It is noteworthy that *S. alterniflora* invasion from 2010 to 2018 also occurred in a northern site, the Yellow River Delta Wetland in Shandong (Site No. 2,187), with an areal increase of 11.9 km$^2$. 
Figure 7 Expansion of *S. alterniflora* invaded into the coastal Ramsar sites

Table 3 *S. alterniflora* changes in different coastal Ramsar sites (positive values denote areal increase and negative values denote areal decline)

<table>
<thead>
<tr>
<th>Site number</th>
<th>Site name</th>
<th>S. alterniflora areal changes in different periods (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,187</td>
<td>Yellow River Delta Wetland</td>
<td>0</td>
</tr>
<tr>
<td>1,156</td>
<td>Yancheng National Nature Reserve</td>
<td>100.4</td>
</tr>
<tr>
<td>1,145</td>
<td>Dafeng National Nature Reserve</td>
<td>49.4</td>
</tr>
<tr>
<td>1,144</td>
<td>Chongming Dongtan Nature Reserve</td>
<td>3.9</td>
</tr>
<tr>
<td>1,726</td>
<td>Zhangjiangkou National Mangrove Nature Reserve</td>
<td>0.4</td>
</tr>
<tr>
<td>1,153</td>
<td>Shankou Mangrove Nature Reserve</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4. **Discussion**

In this study, we compared wetland areal changes within and adjacent to Ramsar sites in China through Landsat observations and highlighted diverse anthropogenic threats to wetlands in these sites. China is to host the 15th UN Conference of the Parities to the Convention on Biological Diversity and 14th Meeting of the Conference of the Contracting Parties to the Ramsar Convention on Wetlands in 2021. The findings will beneficial to understanding the achievements and challenges in conserving China’s wetlands. Considering the striking loss of natural wetlands across the whole country [10], the Ramsar sites have contributed substantially to protecting natural wetlands and halting the downward trend of wetland area. However, as revealed in our analysis, although wetland conservation has expanded significantly under the Ramsar Convention on
Wetlands, anthropogenic impacts, including agricultural reclamation, urbanization, industrialization, and aquaculture and tourism development are pervasive in many Ramsar sites [26-28]. Anthropogenic threats to wetlands are also intensified in several China’s Ramsar sites (Figures 6 and 7). According to the report of Second National Wetland Inventory (2009–2013) of China, the major threats to wetlands are pollution, agricultural encroachment, built-up land expansion, overfishing and harvesting, and exotic species invasion (www.forestry.gov.cn). Almost all these threat types could be detected in the Chinese Ramsar estate. Although pollution, overfishing and harvesting were not directly monitored using remote sensing in this study, we can infer that non-point source pollution related to agricultural and industrial activities and aquatic product acquisition from aquaculture pond expansion also imposed considerable threats to wetland ecosystems in the Ramsar sites.

In terms of evident wetland loss and diverse anthropogenic threats (Figure 4), protection efficacy for most Ramsar sites in China could be improved. Even after the designation of Ramsar sites, agricultural activities still encroached into large areas of Ramsar wetlands, especially in NEC [18, 29], while infrastructure construction with urbanization and industrialization occurred in areas such as the YAR [30, 31]. Moreover, aquaculture development and invasive S. alterniflora had encroached upon large areas of natural wetlands in coastal Ramsar sites that are known to be important for migratory waterbirds [32, 33]. While the preservation of natural wetlands is of primary importance for migratory waterbirds, enhanced management of existing human-made wetlands including aquaculture ponds and paddy fields can also be beneficial for biodiversity [34] and could be explored as a priority within Ramsar sites that already include aquaculture.

Wetlands provide important ecosystem services including aquatic food provision, water retention and purification, climate and flood regulation, carbon sequestration, and biodiversity conservation, and healthy wetlands thus contribute towards achieving the SDGs [27, 28]. Besides the dramatic wetland loss, wetland gain occurred in many Ramsar sites due to effective protection and wetland restoration efforts (Table 5). On the one hand, improved hydrology caused by increased precipitation or melting glaciers can facilitate the formation of new wetlands. On the other hand, wetland restoration from cropland was enhanced especially in the protected areas from the National Wetland Conservation Project [13]. To date, China has established 602 wetland protected areas and 1,699 wetland parks. Of these, 898 parks and more than 100 protected areas were designated at the national level (www.forestry.gov.cn). China’s protected areas for wetlands have been and will be increased continuously [9, 35]. Although large areas of wetlands have been protected, the effectiveness of these reserves or parks could be greatly improved through careful management and in particular through stopping expansion of anthropogenic land covers and wetland conversion [17]. Anthropogenic land covers, especially illegal agricultural cultivation, excessive tourism development, and industrial footprints, should be rehabilitated into natural ecosystems as much as possible to reduce the direct disturbance to wetlands [10, 25]. Ecological migration, compensation mechanism, and alternative livelihoods for native peoples in the Ramsar sites or national nature reserves should be enhanced for implementing returning cropland and aquaculture pond to natural wetlands [36]. The utilization of wetland resources, e.g. tourism, should be controlled, even prohibited when necessary, in the core area of Ramsar sites by legislation [37]. Ecological water supplement from reservoirs or rivers to wetlands with obvious degradation, especially the wetlands in arid and semiarid zones, is necessary for maintaining vulnerable ecosystems and biodiversity [38]. More scientific evidence is
needed to evaluated methods for the prevention and eradication of exotic *S. alterniflora* [24]. For example, the Yancheng National Nature Reserve in Jiangsu experienced marked natural wetland loss to agricultural cultivation and *S. alterniflora* invasion before its Ramsar designation in 2002. However, after its Ramsar designation, the encroachment of cropland and *S. alterniflora* into tidal flats was well controlled, but the expansion of aquaculture ponds increased (Tables 2-3). Therefore, place-based polices and responsive decision-making are required for the sustainable management of China’s Ramsar sites, as well as other protected areas.

We found that boundaries of the Yancheng and Dafeng national nature reserves overlap (Figure 7). Some national nature reserve boundaries have been changed due to the re-valuation of wetlands and biodiversity impacted by regional socio-economic development need [25, 39]. Therefore, managers could re-evaluate boundaries of the important reserves and confirm the optimal boundaries using remote sensing and geographic information system technology. At present, a new protection system comprising national parks is being established for protecting China’s natural heritage [5]. Boundaries of wetland protected areas should be carefully placed to represent biodiversity and include all relevant ecological processes [40, 41]. For example, a national park was suggested to be established in the Songnen Plain to combine the 3 Ramsar sites and more than 10 wetland protected areas at different levels. In short, key priorities would appear to be (i) improving the effectiveness of existing protected areas, (ii) expanding protected areas, (iii) upgrading the protection level at some sites, (iv) optimizing the management efforts, and (v) communicating with the public on wetland conservation [17].

The evaluation of China’s Ramsar wetlands is informative for other wetland protected areas and Ramsar wetlands in other countries by providing methods based on an open data source (Landsat). Consistent datasets with long time series, such as used in this study, are beneficial to studying ecosystem processes, but accurate observations on diverse anthropogenic threats to wetlands in Ramsar sites and other protected areas are also important to deliver sustainable wetland management. High-resolution images could be more easily acquired from satellite or airborne platforms [42]. Therefore, mapping of land covers with high accuracy using finer-resolution images covering the whole Ramsar sites is necessary. The current system of reporting and monitoring Ramsar wetland status has room for improvement. Besides land cover, remote sensing could characterize other ecosystem variables such as the fractional vegetation cover, leaf area index, and vegetation productivity to assess ecosystem quality [38, 43]. The assessments from perspectives of ecosystem functions and services also are still necessary for sustainable wetland conservation and management practice [44-46].

In this study, Landsat series images from 1980 to 2018 were used to examine wetland extents, temporal changes, and anthropogenic threats in China’s 57 Ramsar wetland sites. This study presents the first systematic assessment of the effectiveness of conserving Ramsar sites in China on a national scale and provides a framework to inform sustainable wetland management and policy improvement in other countries or even for global wetlands. Our results reveal that although Ramsar designation played important roles in halting wetland loss, natural wetland loss caused by anthropogenic encroachment remain striking in many Ramsar sites. Agricultural activities are the dominated anthropogenic threats to Ramsar wetlands in China, while built-up land expansion, coastal aquaculture development, and exotic species invasion are key threats in most coastal Ramsar wetlands. Protective efficacy for most of Ramsar wetlands in China thus requires improvements
given the evident wetland loss and diverse anthropogenic threats detected in the Ramsar sites, despite these wetlands having been designated for their international importance. These observations suggest that China needs to continue its efforts to control the loss and degradation of wetland ecosystems to achieve sustainable development and ecological civilization.

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References


ecosystem services in Colombia. Global Environmental Change, 44, 158–169,

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull, V., Wang, Z., Zheng, H., Liu, J.,
Z., 2017. Strengthening protected areas for biodiversity and ecosystem services in China.
Proceedings of the National Academy of Sciences, 114(7), 1601–1606,
https://doi.org/10.1073/pnas.1620503114