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Monitoring loss and recovery of mangrove forests during 42 years: The achievements of mangrove conservation in China

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ABSTRACT

Mangroves are valuable ecosystems that have been protected and restored for decades in China. However, little is known about achievements of China's mangrove conservation efforts. This study aims to analyze the effectiveness of these efforts by presenting long-term dynamics of mangrove forests areal extent at the national scale. To achieve this goal, 123 Landsat images, covering all the mangrove forests in China from 1973 to 2015, were interpreted. For the first time, we built a new dataset of China's mangrove forest changes during past 42 years called Chinese Academy of Sciences Mangroves (CAS_Mangroves). Based on this dataset, we conducted case studies in seven mangrove national nature reserves to show dramatic changes of mangrove forests before and after the establishment of the reserves. Results showed that: 1) on the national scale, mangrove forests declined from 48,801 ha to 18,702 ha between 1973 and 2000, then partially recovered to 22,419 ha in 2015; 2) in each reserve, the areal extent of mangrove forests increased immediately after the reserve was established. Depending on our analysis, in the early time, agricultural reclamation caused the loss of mangrove forests; in contrast, recently, protection and reforestation actions prompt to mangrove forest restoration greatly. Because of China's conservation efforts, since 2000, direct destruction by human beings has rarely happened, and natural disasters and the existing artificial seawalls have become major threats to mangrove forest in China. This study is an application of remote sensing technologies in evaluating effectiveness of conserving natural resources. And the experiences and achievements of China's mangrove conservation efforts presented in this study will facilitate the development of applicable coastal management strategies globally, especially in developing countries.

1. Introduction

Mangroves are rated amidst the most productive natural ecosystems on the Earth (Lee et al., 2014; Liu et al., 2018). These forests are ecologically and socioeconomically important because of their crucial roles in coastal ecosystem protection (Giri et al., 2011; Jia et al., 2015). However, about 35% of world's mangrove forests disappeared during the last two decades of twenty century (Valiela et al., 2001). Even diligently protected after the 2004 tsunami, mangrove forests in most South and Southeast Asian countries still decreased significantly (Giri et al., 2015; Richards and Friess, 2016; Veettil et al., 2018). In China, according to survey results by State Forestry Administration (SFA), only 44% of the original mangrove forests in the 1950s left in 2002. The serious losses have been noticed by Chinese governments, since the 1990s the China State Council has launched a series of projects to protect and restore mangrove forests. Yet, there are few studies focused on the results of these efforts, failure or success, especially on a national scale (Jia et al., 2014a, 2016).

A report about long-term holistic views of China's mangrove forests dynamics could support as fundamental information to evaluate mangrove conservation efforts, however, such reports do not exist in China. Satellite remote sensing has great potential to provide history and current status of natural resources for the assessment of the effect of conservation policies, especially in monitoring inaccessible mangrove ecosystem, in addition, the method is accurate, rapid, and cost effective (Spalding et al., 1997; Seto and Fragkias, 2007; Zhang et al., 2018). Currently, several global mangrove maps generated by remote sensing methodology are published, but due to the small area of China's

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mangroves, there are minor descriptions and no specific spatial dynamic analysis (Spalding et al., 1997, 2010; Giri et al., 2011; Hamilton and Casey, 2016). Additionally, the long-term national scale overview of mangrove forests is vital to various applications, such as evaluation of national protection plans, identification of mangroves response to climate change, understanding the driving forces of mangrove changes (natural and anthropogenic factors), etc.

Therefore, the objectives of this study are: (1) to apply a systematic remote sensing method across the entire coast of China, and build a new dataset of long-term China's mangrove forest distribution called CAS_Mangroves; (2) to quantify the changes of mangroves forests at the decadal scale from 1973 to 2015, and focus on the dynamics of mangrove forests in and around mangrove national nature reserves (NNRs), then discuss the effectiveness of conservation actions. The dataset (CAS_Mangroves) generated in this study will be freely distributed through the Google Earth Engine cloud platform, so that it could be used for other studies of mangrove conservation and management in China and globally.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) encompassed six coastal provinces (Guangxi, Guangdong, Fujian, Zhejiang, Hainan, and Taiwan), Hong Kong Special Administrative Region and Macao Special Administrative Region. The geographical range of the study area is between 18°12′–28°25′ N and 108°03′–122°00′ E. The climates in this area vary from tropical monsoon to subtropical monsoon climate. Sanya (Hainan Province) is the southernmost city that mangrove forests grow in China. Fuding (Fujian Province) is the northern boundary of natural grown mangroves in China, with the lowest monthly mean temperature of 8.4 °C. Tides across the coastlines varied in type and amplitude (Fig. 1).

Fig. 1 also shows locations of the 37 mangrove reserves, including seven NNRs, five provincial nature reserves, and twenty-five local nature reserves. Approved by the State Council, China's NNRs receive priority financial and political supports. Detail information about the mangrove NNRs' establishment and development are listed in Table 1.

2.2. Landsat imagery and reference datasets

In this study, cloud-free Landsat images (resolution 30 m/60 m) were used to monitor China's mangrove forests changes from 1973 to 2015 (downloaded from http://glovis.usgs.gov). As an example, a complete list of the images used in 2015 is shown in Table 2. In total, 123 Landsat images were obtained, including Multi-spectral Scanner (MSS), Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) images, most of

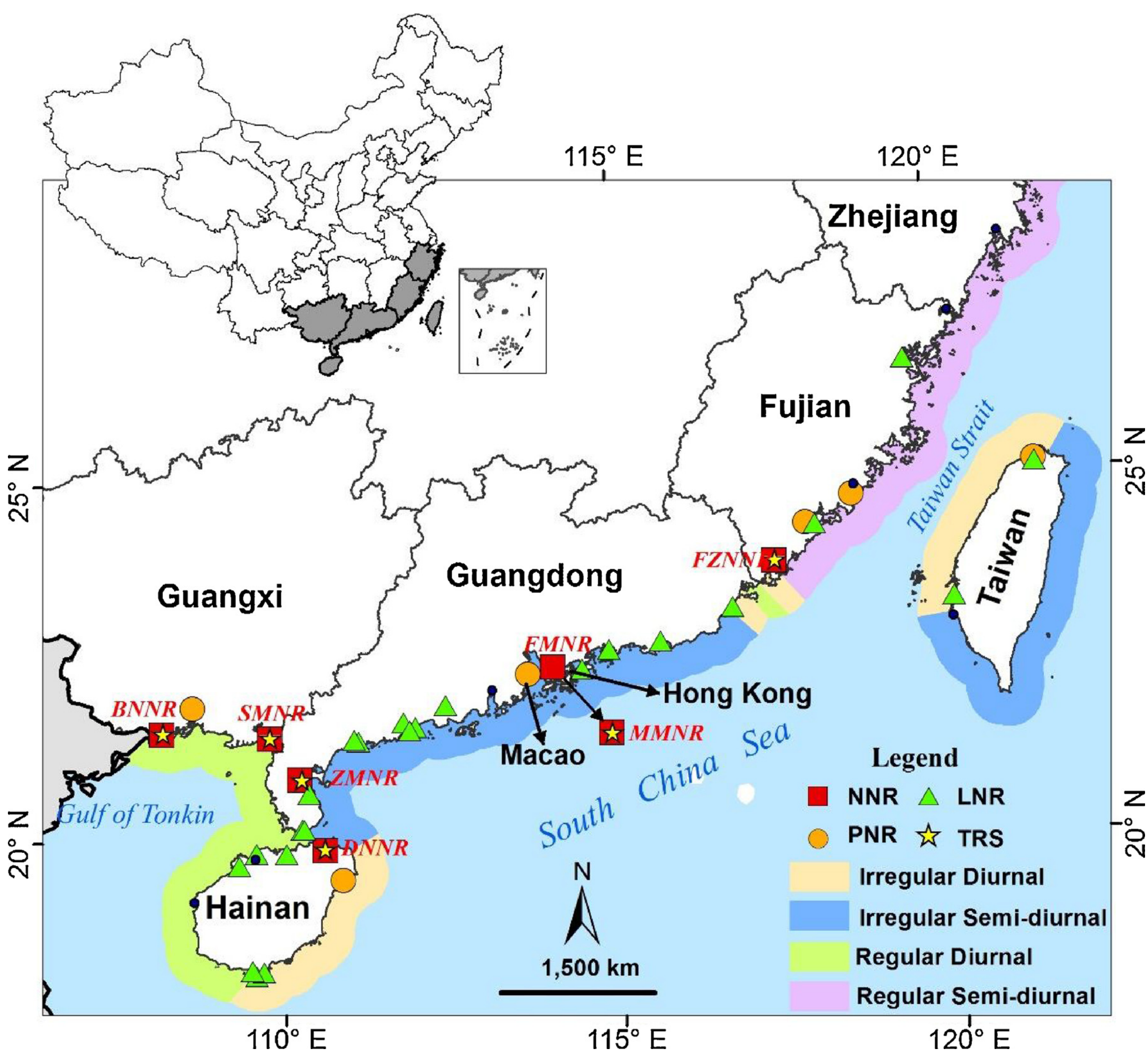

Fig. 1. Location of the study area, distribution of mangrove reserves, and the types of tide along the coasts of China. (NNR: national nature reserve; PNR: provincial nature reserve; LNR: local nature reserve; TRS: The Ramsar Site).

Table 1
The establishment and developments of mangrove NNRs, China.

National Nature Reserve	Abbreviation	Location	Year of			
			Establish	Provincial	National	Ramsar
Dongzhaigang National Nature Reserve	DNNR	Hainan	1980	1980	1986	1992
Guangxi Beilun Estuary National Nature Reserve	BNNR	Guangxi	1985	1995	2000	2002
Shankou Mangrove Nature Reserve	SMNR	Guangxi	1990	–	1990	2002
Zhanjiang Mangrove National Nature Reserve	ZMNR	Guangdong	1990	1990	1997	2002
Futian Mangrove National Nature Reserve	FMNR	Guangdong	1984	–	1988	–
Mai Po Marshes & Inner Deep Bay	MMNR	Hong Hong	1976	1983	1983	1995
Fujian Zhangjiangkou National Mangrove Nature Reserve.	FZNNR	Fujian	1992	1997	2003	2008

Table 2
Landsat images used in 2015 including the time of acquisition, tide status, and location.

Path/Row	Time (mm:ss)	Tidal height (m)	Location	Station
125/47	11:00	−0.05	Hainan	Sanya
125/45	11:03	−1.5	Guangxi	Fangchenggang
124/47	10:59	0.2	Hainan	Sanya
124/46	10:58	0.05	Guangdong, Hainan	Haikou
124/45	10:56	0.35	Guangxi, Guangdong	Beihai
123/47	10:52	0.15	Hainan	Sanya
123/46	10:52	−0.7	Hainan	Haikou
123/45	10:48	0.7	Guangdong	Zhanjiang
122/45	10:46	−0.05	Guangdong, Macao	Macon, Zhuhai
122/44	10:45	0.1	Guangdong, Hong Kong	Zhuhai, Hong Kong
121/45	10:38	−0.7	Hong Kong	Hong Kong
121/44	10:37	−1	Guangdong	Huizhou
120/44	10:32	0.85/1.25	Guangdong, Fujian	Xiamen/Shantou
120/43	10:31	1.25	Fujian	Quanzhou
119/43	10:26	−0.4	Fujian	Quanzhou
119/42	10:25	−0.4	Fujian	Quanzhou
119/41	10:24	1.8	Fujian, Zhejiang	Quanzhou
118/44	10:20	−0.05	Taiwan	Gaoxiong
118/43	10:19	0.15	Taiwan	Jilong
118/42	10:19	1.8	Fujian	Quanzhou
118/41	10:18	1.8	Fujian, Zhejiang	Quanzhou
118/40	10:18	2	Zhejiang	Ningbo
117/45	10:14	−0.05	Taiwan	Gaoxiong
117/44	10:13	−0.05	Taiwan	Gaoxiong
117/43	10:03	0.15	Taiwan	Jilong

which were acquired in dry season with low tidal heights (less than 0.5 m), so that all mangrove canopies were exposed above the seawater. Unfortunately, we cannot acquire cloud-free images in some region during a specific period, the regions and periods are listed as follows. (1) Parts of Zhejiang Province in 1973 and 1980; (2) Parts of Taiwan in 1973 and 1980; (3) Small parts of Hainan in 1980; (4) Parts of Hong Kong in 1980; (5) Parts of Macao in 1980 and 1990.

Firstly, satellite images obtained in 2010 and 2015 were geo-rectify by 1:50,000 topographic map. Then, based on the images of 2010 and 2015, Landsat images in 1973, 1980, 1990, and 1980 were resampled and rectified, the average root mean square error (RMSE) was maintained as less than 0.5 pixels, the pixel size was resampled to 30 m by 30 m in a universal transverse Mercator (UTM) system. In this study, we used Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) model to do the atmospheric correction, and the geo-rectification and atmospheric correction were completed by ENVI software (ITT 2010).

In order to collect ground-truth samples, two rounds of ground survey were conducted by three teams from June to November 2011 and October 2015 to January 2016, respectively. The observations collected in the surveys of 2011 contained 386 non-mangrove points and 457 mangrove points, and the survey in 2015–2016 contained 839 mangrove points and 672 non-mangrove points. We also collected samples via visual inspection of free access high resolution images, such as Google Earth. Various data, such as field data, historic maps, e-mails from local experts, interviews with local people, and photos were collected as ground truth samples in the estimation of classification accuracies. Finally, the reference data gained in 1973, 1980, 1990, and 2000, 2010, and 2015 consisted of 873, 990, 967, 1032, 1052, and 1808 samples, respectively.

Besides validations using ground-truth samples, we also conducted comparisons between our mapping results with other peer-reviewed references which contained China's mangrove forest information at national scale. Four global scale mangrove mapping or reporting results (Spalding et al., 1997; FAO, 2007; Spalding et al., 2010; Hamilton and Casey, 2016) and three national scale results (Chen and Huang, 1995; Chen et al., 2009, 2017) were selected. A brief summary of the reference data is presented in Table 3.

2.3. Methodology of building CAS_Mangroves dataset

An object-based classification approach, which has been proven to be more accurate and effective than the pixel-based approaches, was used for mangrove forests interpretation (Aguirre-Gutiérrez et al., 2012). The advantages of the object-based method are widely described, such as the faster processing is suitable for large scale image classification, overcoming 'salt-and-pepper effects', and providing geo-information that can be directly stored into geographical databases (Yu et al., 2006; Johnsson, 1994; Jensen, 1986). Thus, object-based classification is appropriate to the goals of our classification, and it has been successfully used in mapping mangrove forests of Thailand (Myint et al., 2008), Vietnam (Vo et al., 2013), and so on.

In this study, eCognition Developer 8.64 (Definiens, 2011) was used to process object-based classification. The following steps were performed in our classification:

(1) Homogeneous objects were obtained by segmenting images based on three parameters: scale, compactness, and shape. The scale parameter rules the maximum size of the object being created; users apply weights range 0–1 for the shape parameter to adjusts the shape (the regularity of an object) and the spectral homogeneity of an object;

Table 3
A brief summary of the selected reference datasets.

Publisher	Abbreviation	Data source	Reference year
Spalding et al. (1997)	WAM97	Sketch maps	1989
FAO (2007)	FAO	Reports	1980-2005
Spalding et al. (2010)	WAM10	Remote sensing	1999-2003
Hamilton and Casey (2016)	CGMFC-21	Remote sensing	2000-2012
Chen and Huang (1995)	CCL	Field survey	1986
Chen et al. (2009)	SFA	Remote sensing and field survey	2002
Chen et al. (2017)	MFM	Remote sensing	2015

at the same time, users apply weights range 0–1 for the compactness parameter to adjusts the smoothness and compactness of an object (the formula of shape and compactness factor can be found in Definiens (2011)). In this study, the shape of mangrove object is irregular, but the spectral of the object is homogeneous, hence, the shape parameter were set at 0.1, so that the shape and spectral factor of an object were 0.1 and 0.9. respectively. Because the compactness of a mangrove object is a little more remarkable then smoothness, this study gave more weight on compactness than smoothness (0.6 and 0.4, respectively). After a number of tests, the scale parameter was determined as 8, so that the image objects and mangrove forests spatial characteristics were matched to each other.

(2) To classify objects into specific categories by applying the nearest neighbor classifier (NN classifier). The NN classifier not only effective in classifying mangrove forests, but also the quickest method in large scale classification. When processing the NN classifier, training samples (at least 20 mangrove samples and 80 non-mangrove samples) were selected from the image which is going to be classified and inputted to the following classification procedure. So that the spectral differences caused by different sensors could be avoided. Typical spectra of mangrove forests and other coastal vegetation obtained by Landsat TM are shown in Jia et al. (2015). Between the spectral regions of 1550 and 1750 nm, the reflectance of mangrove forest is different from other coastal vegetation. An initial classification result was formed using eCongnition software based on NN classifier.

(3) To inspect the initial classification results and modify the incorrect objects. In order to obtain the best interpretation, the misclassified objects were manually modified by a remote sensing expert. Firstly, to facilitate the manual interpretation, a false color composite of the OLI bands 6 (red), 5 (green), and 4 (blue) was generated (mangrove forests are dark green in the combination images (Spalding et al., 1997)). Then, a remote sensing expert who has extensive knowledge of coastal field survey inspected each image along the coasts, and manually remove or add misclassified objects.

At last, a new dataset named CAS_Mangroves was built, which contains multi-temporal spatial distribution of China's mangrove forests from 1973 to 2015.

3. Results

3.1. Accuracy assessment

The overall accuracies and the Kappa coefficients of the classification results in the CAS_Mangroves dataset was presented in Table 4. Independent reference data defined in Section 2.2 were used to generate the confusion matrices. Classification errors were mainly observed between mangrove forests and water surfaces. The uncertainty of instantaneous tidal conditions contributed to this confusion. The results of our accuracy assessments demonstrated that the classification maps are mainly agreed with ground truth.

Table 4
The overall accuracies and Kappa coefficients for CAS_Mangroves dataset.

Year	Mangroves		Accuracy	
	Ground thruth	Classification results	Overall accuracy	Kappa coefficients
1973	320	250	78%	0.71
1980	380	300	79%	0.75
1990	427	371	87%	0.78
2000	461	415	89%	0.85
2010	472	435	92%	0.88
2015	531	498	94%	0.91

Table 5
Areal extent of mangrove forest in different provinces (districts) from 1973 to 2015.

Province(district)	Areal extent (ha)					
	1973	1980	1990	2000	2010	2015
Guangdong	32,830	16,197	11,016	7,343	9,289	9,855
Guangxi	5,305	2,306	2,683	5,937	5,813	6,621
Fujian	3,810	3,624	1,216	698	1,023	957
Zhejiang	53†	53†	53	25	293	56
Hainan	5,991	5,254†	4,809	3,978	3,576	4,017
Taiwan	388†	388†	388	320	382	412
Hong Kong	404	404†	270	286	389	560
Macao	20	20†	15†	15	11	16
Total	48,801	28,246	20,450	18,702	20,776	22,419

Note: † represents entirely or partially lacks of available images.

3.2. Spatial and temporal dynamics of China's mangrove forests

Temporal changes of mangrove forests in each province or district are shown in Table 5. The sites where no available Landsat data were acquired at the specific year were filled using the areal extent of the nearest available year's, in order to complete the comparability of mangrove extent in each period. For example, because of the lack of cloud-free Landsat images, no areal extents of mangroves in Macao were acquired in the years of 1980 and 1990, so we assumed mangrove area in 1980 was proximate to 1973's, and area in 1990 was similar to 2000's. In Table 6, data followed by the symbol of '†' were entirely or partially obtained based on this principle.

According to Table 5, in the past 42 years, the net decrease of China's mangrove forests was almost 27,000 ha, while the change patterns and rates were inconsistent in different periods. From 1973 to 2000, approximately 62% of the original mangrove forests have been lost (the areal extent decreased from 48,801 ha to 18,702 ha). Fortunately, in the following 15 years, mangrove forests increased to 21,899 ha, showing a rise of 17%. Among eight provinces (districts), the most dramatic turnover was observed in Guangdong province, where over three-fourths of mangrove forests disappeared from 1973 to 2000, and then from 2000 to 2015, 34% of mangrove forests were restored.

The spatial distributions of mangrove forests in China from 1973 to 2015 are illustrated in Fig. 2. Results showed that, in 1973, mangroves along the coasts of Guangdong and Guangxi were relatively dense, especially in Qinzhou Bay (Guangxi), Zhanjiang and Zhujiang Estuary (Guangdong). However, in 1980, a large area of these mangroves disappeared. From 1980 to 1990, the trend of shrinkage continued, for instance, mangrove forests along the coasts of northern Fujian faded away dramatically. Between 1990 and 2000, although mangroves in Guangxi increased noticeably, the other mangroves in Guangdong, Fujian, and Hainan continuously decreased. From 2000 to 2015, the most significant restoration was observed in Zhujiang Estuary, Guangdong.

Table 6
Temporal changes of mangrove forests in and around DNNR, BNNR, and SMNR.

Year	DNNR Area (ha)			BNNR Area (ha)			SMNR Area (ha)		
	In	Out	Total	In	Out	Total	In	Out	Total
1973	1,069	1,158	2227	1,039	9	1048	744	22	766
1980	–	–	–	747	0	747	584	12	596
1990	1,227	447	1,674	440	4	444	193	0	193
2000	1,220	386	1,606	720	6	726	598	35	633
2010	1,234	427	1,661	873	65	938	702	48	750
2015	1,426	635	2,061	838	70	908	800	68	868

Note: "–" represents to no data.

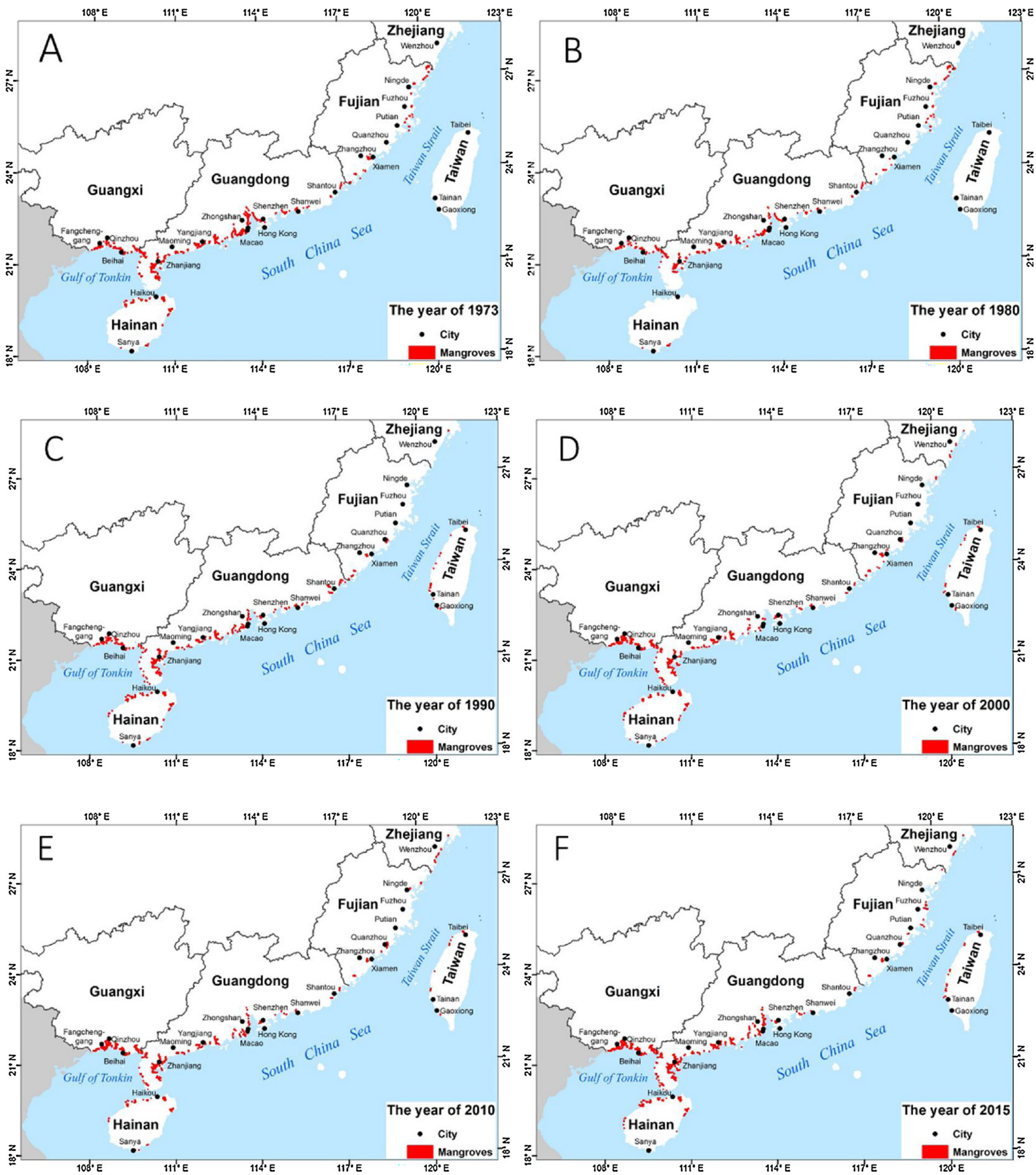

Fig. 2. Distribution of mangrove forests along the coast of China from 1973 to 2015.

3.3. Mangrove forest changes in and close to each NNR

Fig. 3A–F show the spatial distribution of mangrove forests in and close to DNNR, BNNR, SMNR, ZMNR, FMNR and MMNR, and FZNNR, respectively, in the year of 1973 (beginning), 1990 or 2000 (smallest areal extent), and 2015 (ending). Table 6 and 7 show temporal changes of mangrove forests in and close to these reserves.

Since no cloud free images covering the DNNR were obtained around the year of 1980, the areal extents were not calculated during that time. From 1973 to 2015, mangrove forests in DNNR decreased by 7% (from 2227 to 2046 ha). According to Table 6, changes of the areal extent of mangrove forest in and close to reserve are obviously different, even though these mangroves were adjacent to each other. Mangrove forests in the reserve generally increased during the study periods, however, mangrove forests out of the reserve declined drastically (approximately 67% disappeared) from 1973 to 2000, and then increased slightly.

From 1973 to 1990, mangrove forests in BNNR reduced from 1048 to 444 ha, indicating that approximately 58% of mangroves disappeared. From 1990 to 2010, the area of mangrove forest increased from 444 to 938 ha, showed a raise of 111%. From 2010 to 2015, the area of mangrove forests slightly decreased (from 938 to 908 ha).

In SMNR, during 1973 to 1990, the total area of these mangrove forests seriously decreased, as approximately 74% of these mangroves disappeared. During this period, all mangroves along the east coast of Dandou Bay faded away, and other mangrove patches shrank noticeably. Fortunately, from 1990 to 2015, the areal extent of mangrove forests increased from 193 to 800 ha, showing a rise of 314%. All

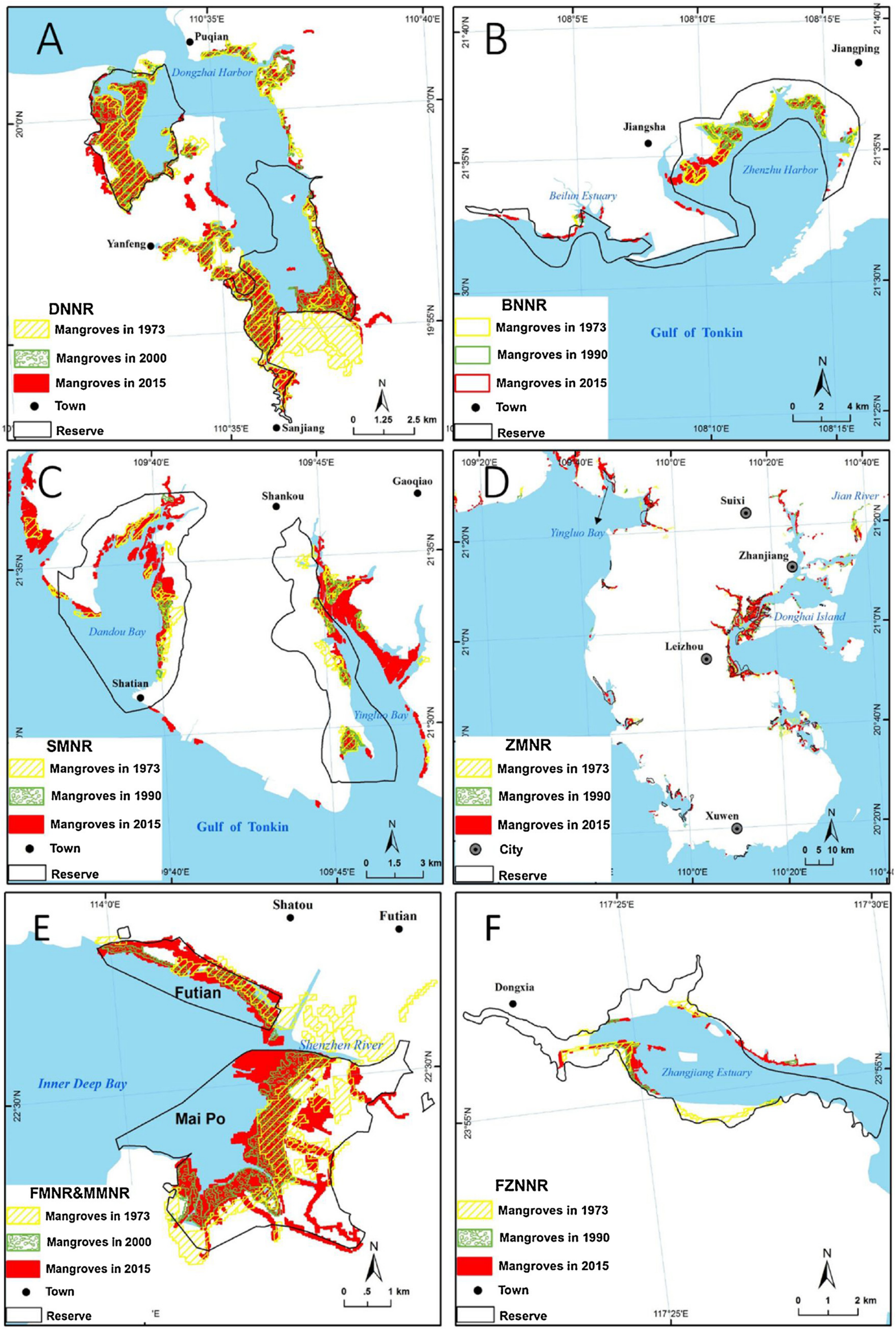

Fig. 3. Dynamics of mangrove forests along the coast of NNRs in the year of 1973 (beginning), 1990 or 2000 (smallest areal extent), and 2015 (ending).

Table 7
Temporal changes of mangrove forests in and around ZMNR, FMNR, MMNR, and FZNNR.

Year	ZMNR Area (ha)			FMNR Area (ha)			MMNR Area (ha)			FZNNR Area (ha)		
	In	Out	Total	In	Out	Total	In	Out	Total	In	Out	Total
1973	3,864	10,125	13,989	42	151	193	331	51	382	122	18	140
1980	–	–	–	28	88	116	237	14	251	64	7	71
1990	1,935	4,708	6,643	63	19	82	231	39	270	35	4	39
2000	1,979	3,164	5,143	69	2	71	277	0	277	90	9	99
2010	2254	3,999	6,253	113	10	123	368	1	369	101	25	126
2015	1,935	4,708	6,643	132	22	154	532	28	560	108	25	133

Note: "–" represents to no data.

mangrove forest patches expanded during this period.

ZMNR has more than 40 patches of conservation zone that distributed along the coasts of Leizhou Peninsula. From 1973 to 2015, mangrove forests along the entire coast decreased first and then increased, the inflection point is the year of 2000. Although significant increasing was observed, the net decrease during the last 42 years was remarkable: almost 55% of mangroves disappeared. The area of mangroves in the reserve started increasing from 1990, but declined from 2254 ha to 1984 ha between 2010 and 2015. These decreases mainly occurred along Jian River and Donghai Island.

FMNR and MMNR are both located along the Inner Deep Bay of Pearl River Delta. Since they are spatially close to each other, they were described together in this section. From 1973 to 2015, the total area of mangroves around MMNR decreased from 382 ha to 251 ha, and then sharply increased to 560 ha in 2015. In contrast, around the FMNR, the total area of mangroves decreased from 193 ha to 71 ha, during 1973 to 2000, then increased to 154 ha in 2015.

From 1973 to 1990, mangrove forests in and around the FZNNR all decreased sharply, totally decreased from 140 to 35 ha, indicating a loss of 75%. By the year of 2015, these mangroves had increased from 39 to 133 ha, nearly recovering to the extent of mangrove forests in 1973.

3.4. Comparison between CAS_Mangroves and reference datasets

Table 8 depicts the area extent of mangrove forests in CAS_Mangroves and reference datasets. In 1980, 1990, and 2000, areal extents of mangrove forest in CAS_Mangroves were all much smaller than FAO's reports. In 1986, the CCL dataset calculated the areal extent of mangrove forests in China as 23,000 ha, which is just between CAS_Mangroves' estimations of 1980 and 1990. There are four comparable references of mangrove forests extent in 2000. Among these datasets, the CGMFC-21's estimation is much larger than the others, the FAO and SFA are very similar to each other (because the FAO's report was based on SFA's survey; FAO, 2007), in contrast, the areal extent of mangrove forests in CAS_Mangroves is close to WAM10's which was also estimated by remote sensing methods. In 2010, the CAS_Mangroves detected a significantly lower value than CGMFC-21's. In 2015, the CAS_Mangroves interpreted less mangrove forests than MFM.

Table 8
Area comparison of mangrove forests in China between CAS_Mangroves and reference datasets.

Year	CAS_Mangroves (ha)	Reference	
		Dataset	Area (ha)
1980	28,246	FAO	34,157
		CCL	23,000
		FAO	28,344
1990	20,450	CCL	23,000
		WAM97	36,882
2000	18,702	FAO	22,955
		WAM10	19,788
		SFA	22,025
		CGMFC-21	31,390
2010	20,776	CGMFC-21	30,910
2015	22,419	MFM	20,303

4. Discussion

4.1. Mangrove forests conservation efforts in China

In China, the important ecological and economic values of mangrove ecosystem were not recognized by publics until the early 1990s (Chen et al., 2009). Before this time, over 60% of China's mangroves had been lost (Table 2; from 48,801 ha to 20,450 ha), and most mangrove forests were converted to paddy fields or aquaculture ponds (Jia et al., 2015). Our results demonstrate that mangrove forests in all NNRs have a tendency of loss first and recovery later. According to our literature reviews and field surveys, losses of mangrove forests were mainly caused by human-made destructions, and the recoveries were strongly associated with conservation actions. Since the early 1990s, China's government has formulated a number of laws and regulations to protect mangrove ecosystems, including the Action Plan for China Biodiversity Protection (State Environmental Protection Agency, 1994), the Forestry Action Plan for China's Agenda of the 21 st Century (State Forestry Administration, 1995; 1996), the Plan for China Ecological Environment Conservation (The State Council, 1998), and the Action Plan for China Wetland Protection (State Forestry Administration, 2000), etc. Ultimately, two very beneficial consequences were directly caused by these laws and regulations, one is the boom of establishing mangrove reserves, and the other is large-scale mangrove forest reforestation.

According to the National Natural Wetland Protection Directory (2016), twenty-eight of thirty-four mangrove reserves along the coasts of mainland China have been established since the early 1990s. In terms of CAS_Mangroves, mangrove forests in all the NNRs increased right after the establishment of the reserves (Tables 1,6, and 7). Furthermore, with the increasing awareness of the significance of protecting mangrove ecosystems and forbidding illegal logging, mangrove forests around these reserves were also recovered along with the mangrove forests in the reserves. In Shenzhen, the fastest growing city in China, mangroves near FMNR were under great pressure of population explosion (in 1980 there were only 30,000 residents, by the year of 2008 the city had 12 million inhabitants; Jia et al., 2016). Therefore, even though FMNR was approved to be a national reserve in 1988, the mangrove forests close FMNR did not increased until 2000.

Besides establish mangrove reserves, Chinese central and local governments have been made great efforts to afforest mangrove forests since the early 1980s (Li et al., 1991; Zheng et al., 2003). Fig. 4 are photos we took during field surveys, local residents were planting mangroves in slack time. However, at the beginning, the survival rates of newly planted mangroves were quite low, in most regions it was only 20% to 30% (Liao and Zhen, 1996). Successful replantation program started from the early 1990s along the east coast of Guangxi, as reported, 71% of the planted mangrove forests in SMNR survived which

Fig. 4. Reforestation of mangrove forests in DNNR.
A. Local residents were planting mangrove seedlings; B. Mangrove seedlings; C&D. Newly planted mangrove seedlings.

accounted for the highest survival rate of mangrove forests in China (Chen et al., 2009). By 2002, about 2678 ha mangrove forests have been replanted with 57% successfully restored in Hainan (60 ha), Guangdong (298 ha), Guangxi (783 ha), Fujian (369 ha) and Zhejiang Provinces (21 ha) (Chen et al., 2009). The afforestation efforts mainly contributed to the increases of mangrove forests along the coasts of Guangxi and Fujian, during 1990–2000 and 2000–2010, respectively (Chen et al., 2012; Jia et al., 2015). Reported by SFA and State Oceanic Administration (2006), China has great potential for mangrove afforestation, because there is over 65,600 ha of intertidal area suitable for mangrove planting. In May 2017, SFA and National Development and Reform Commission released a 10-year plan called the Planning of Constructing National Coastal Shelter Forests (2016 to 2025). In this plan, mangrove afforestation was listed as a key project with an aim to plant 48,650 ha mangrove forests in 62 counties.

4.2. Comparisons of China's conservation effectiveness with that in other Asian Countries

Asia accounts for 42% of the world's mangroves and contains the greatest diversity of mangrove species (Giri et al., 2011; Spalding et al., 2010). There is a long history of mangrove conservation and management in some Asian countries (Kairo et al., 2001). For example, the oldest records of mangrove management can be traced back to the beginning of the twentieth century, with the creation of Sundarbans Reserved Forest, Bangladesh (FAO, 2007). Mangrove conservation efforts in Asia mainly focused on implementing replantation and afforestation programs, issuing laws and regulations to protect remaining mangroves, and establishing nature reserves or national parks. However, in the past, conservation and management of mangroves in South and Southeast Asia hampered by a lack of financial and human resources, resulting in a large proportion of mangroves were converted to aquaculture ponds for direct economic benefits (Primavera, 1995; Seto and Fragkias, 2007).

After the 2004 tsunami, in the order to give security against ocean hazards, Asian national and local governments pay the great attention to mangrove forest conservation (Macintosh et al., 2012). Both international funding agencies and governmental agencies offered extensive financial support for various mangrove restoration programs (Upadhyay et al., 2015). To date, numerous districts in the country of India, Pakistan, Sri Lanka, Bangladesh, Malaysia, and Indonesia etc. have recorded successful restoration of mangrove forests (Giri et al., 2015; Upadhyay et al., 2015; Macintosh et al., 2012; Richards and Friess, 2016). However, many projects have yielded disappointing results, even worth, the rapid expansion of aquaculture, rice agriculture, and oil palm plantations are still threatening and invading mangrove ecosystems (Macintosh et al., 2012; Richards and Friess, 2016). As a result, mangrove forests in most countries of South and Southeast Asia have been decreasing from 2000 to 2012 (Giri et al., 2015; Richards and Friess, 2016). Unlike these countries, China's mangrove forests have been continuously increasing since 2000 (Figs. 2 and 3, Tables 5,6, and 7), which indicates that China's mangrove forests conservation is more effective than other South and Southeast Asian countries.

4.3. Potential threats to China's mangroves

Although Chinese governments invested billions of dollars to restore mangrove forests, there is a lack of comprehensive ecological and social economic insights when taken developing restoration and conservation policies (Ren et al., 2004). Actually, in China, restoration in most regions means simply planting or replanting mangrove seedlings that consisted of just a few species, which could cause reduction of regional biodiversity (Lewis, 2005). It has been admitted that regions with decreased biodiversity provide less ecosystem services and are very sensitive to insect attacks. However, in most of China's mangrove replanting projects, several native mangrove species, such as *Rhizophora stylosa*, *Kandelia obovata*, and *Sonneratia caseolaris*, were still frequently planted as monocultures (Chen et al., 2009; Jia et al., 2014b). Even worse, in order to restore mangrove forests in a short time, a fast-growing exotic mangrove species called *Sonneratia apetala*, which can break the integrity of natural mangrove landscape, was widely planted (occupies about 95% of the reforestation regions) (Ren et al., 2009; Chen et al., 2012). Besides the potential threats from planting mono-species or exotic species mangroves, China's mangrove forests are under pressures from natural disasters, such as extreme low temperature, hurricanes, biological invasion, and insect outbreaks. Since illegal logging is strictly prohibited and the awareness of protecting mangrove ecosystem has been increased continuously, losses of mangroves in some areas were mainly caused by natural disasters (Li et al., 2013; Jia et al., 2015).

Another serious threat to China's mangroves is the existing artificial seawalls. In China, currently, more than 60% of coastlines were converted to artificial seawalls (Ma et al., 2014), and more than 80% of mangroves are located outside these seawalls (Wang and Wang, 2007). Constructing seawalls have destroyed large areas of mangrove forests, and the remaining mangrove forests outside these seawalls are under great threats in the following ways. Firstly, seawalls obstructed the exchange of matter and energy between terrestrial ecosystems and marine ecosystems, especially blocked the flow of freshwater to mangrove swamps. Scientists agree that freshwater plays an important role in creating optimal salinity conditions for mangroves, limited freshwater is a significant factor contributing to mangrove forests slowly dying off and subsequent coastal erosion (Nijbroek, 2014). Secondly, seawalls are usually built on the middle intertidal zone where the most prosperous mangroves live, the narrow mangrove fringe with barren pioneer species left outside the seawalls are extremely sensitive to natural and anthropogenic factors. Thirdly, mangrove forests migrate landward is a natural response to rising sea levels, however, this landward migration would be obstructed by seawalls, so some coasts will experience extirpation of the mangrove forests with the sea-level rising (Gilman et al., 2006) (Fig. 5).

4.4. Inter-comparison of different mangrove forests datasets

Datasets of FAO, WAM97, WAM10, and CGMFC-21 provide information on global mangroves, and describe China's mangroves in brief. However, we noted that the China's mangrove forests estimated by these datasets were highly variable (Table 8). The CCL, SFA, and MFM datasets focus on China's mangrove forests, but none of these datasets provide multi- temporal estimations (Table 8).

The FAO dataset contains long-term information of mangrove forests in China which could be utilized as a comparison to our dataset (CAS_Mangroves) in 1980, 1990, and 2000. According to Table 8, the areal extents calculated by FAO are all much higher (4,000–8,000 ha) than CAS_Mangroves' 1980, 1990, and 2000 data, meanwhile it is notable that mangrove forest changing tendencies of these two datasets are coincident. The CCL dataset may be more accurate than FAO dataset in 1980 and 1990, because in 1980 and 1990 China's mangrove information provided by FAO is only based on SFA's statistical results, no field surveys were carried out, yet the CCL dataset was acquired from field surveys by the Geological Survey team of Guangdong Province. As reported, in 1986, areal extent by CCL's estimation was about 23,000 ha, this number is just between CAS_Mangroves' 1980 and 1990 data; based on this CAS_Mangroves' result is similar to CCL's surveys. WAM97 also provides information of mangroves in 1990, but the estimation is much higher (8,000–16,000 ha) than others it is categorized as an inaccurate dataset. Therefore, the data provided by CAS_Mangroves in 1980, 1990, and 2000 are considered to be more accurate than the others at the same time. As shown in Table 8, estimations of 2000's mangrove forest are quite variable. Among datasets of FAO, WAM10, SFA, CGMFC-21, and CAS_Mangroves, CGMFC-21's 2000 data is significantly higher than others, thus we assumed that the dataset of CAS_Mangroves is more accurate than CGMFC-21 in the estimation results of 2000 and 2010.

Datasets of WAM10, MFM, and CAS_Mangroves were all generated based on Landsat images. Compared with the WAM10, the total area of China's mangrove forests in 2000 from CAS_Mangroves is very close to that of WAM10 (only 5% lower). Compare with MFM's 2015 data, the value in CAS_Mangroves is a little higher (about 10% higher). The difference between CAS_Mangroves and MFM was mainly caused by the different classification methods adopted in interpreting remote sensing images. The MFM used a pixel based classification method which extracts mangrove forests at pixel level, the CAS_Mangroves used an object-oriented method which identifies mangrove forests at object level. Compared with pixel based methods, the object-oriented method has the advantage in extraction of sparse, lower, and newly planted mangrove forests. In this case, the CAS_Mangroves presents more mangrove forests than MFM.

4.5. Uncertainties of remote sensing

Our analysis focused on multi-temporal China's mangrove forests dynamics over 40 years. Therefore, it is very important to keep spatial coherence of classification maps interpreted from various images. However, unbiased maps are difficult to produce, owing to the uncertainties from scanning system, angular affect, and over-pass time. In addition, the most significant limitation is the different spatial resolution of various remote sensing data, which causes the spatial inconsistency of initial classification. Although these images were unified to 30 m × 30 m per pixel, the MSS images with coarser spatial resolution

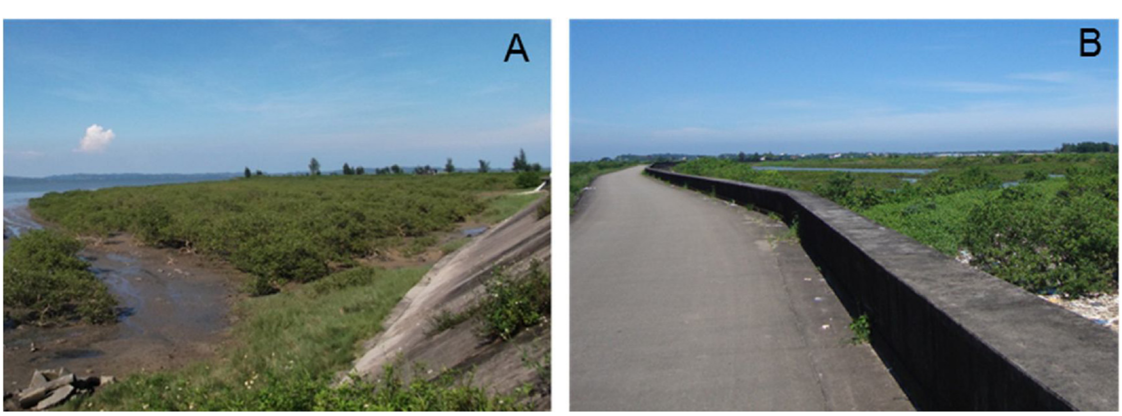

Fig. 5. Seawall neighborhood with mangrove forests.
A. Dongxing City, Guangxi Province; B. Fangchenggang City, Guangxi Province.

(60 m × 60 m per pixel) in 1973 indeed cannot be resampled to higher spatial resolution. Furthermore, classification errors existed in each of produced maps increased the uncertainties of identifying the changes in mangrove forests in China. Although there are uncertainties, CAS_Mangroves is the first dataset built on consistent data sources and methodology, which contains long-term (over 40 years) multi-temporal mangrove forests distribution and dynamics information for the whole of China.

5. Conclusions

In China, mangrove conservation and restoration efforts started in the early 1980s, and were widely adopted after the central government issued China's Biodiversity Conservation Action Plan in 1995. According to our remote sensing analyses, the most serious mangrove deforestation happened from 1973 to 1980, with a decrease rate of 2936 ha/year, fortunately, the areal extent of mangroves began to increase from the year 2000. In order to evaluate the effectiveness of mangrove conservation, seven NNRs were presented and discussed in precise details. In general, mangrove forests located in these NNRs, all expanded immediately after the establishment of the reserves. Furthermore, mangrove forests located close to the reserves, were recovered following the expanding of mangrove forests in the reserves. Although the series of conservation efforts were effective in protecting mangroves from human destruction, in some regions mangroves are still shrinking because of extreme weather events, biological invasion, insect outbreaks, as well as the existing artificial seawalls. As we discussed, China's mangrove conservation results are better than other Asian countries', in spite of this, further studies focusing on the biological diversity and ecological processes of the restored mangrove forests are required to give a comprehensive judgment of the restoration efforts. This study provides the first long-term multi-temporal China's mangrove forest distribution dataset (CAS_Mangroves), and presents the achievement of China's mangrove conservation and restoration strategies. The CAS_Mangroves dataset provides a preferable understanding of the implementation of mangrove forest conservation actions to China's government and publics. And the practical experiences of China's mangrove conservation can assist worldwide governments in making policies for maintaining both development opportunities and natural environments on coastal areas.

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