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Assessment of Spatiotemporal Dynamics of Mangrove in Five Typical Mangrove Reserve Wetlands in Asia, Africa and Oceania

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Abstract: Mangrove wetlands play a key role in global biodiversity conservation, though they have been damaged in recent decades. Therefore, mangrove habitats have been of great concern at the international level since the latter half of the 20th century. We focused on the key issue of the dynamics of mangrove habitats. A comprehensive review of their typicality and status from the global perspective was evaluated before the landscape dynamics of the mangrove habitats at the five sites were interpreted from Landsat satellite images covering 20 years, from 2000 to 2020. Ground-truthing was undertaken after comparing the results with the other published international mangrove datasets. We reached three conclusions: Firstly, within the period from 2000 to 2020, the mangrove area in Dongzhaigang increased by 414 ha, with an increase of 24.6%. In Sembilang NP, Sundarban, Kakadu NP, and RUMAKI, the mangrove area decreased by 1652 ha, 16,091 ha, 83 ha, and 2012 ha, with a decrease of 1.8%, 2.7%, 0.9%, and 3.9%, respectively. Secondly, other types of wetlands play a key role in degradating the mangrove wetlands in all of five protected areas. Thirdly, the rate of mangrove degradation has slowed dramatically based on the five sites over the past two decades, which are generally consistent with the findings of other researchers.

Keywords: mangrove conservation; wetland habitat; landscape changes; ecology & hydrology

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1. Introduction

Mangroves are distributed in tropical, subtropical, and some temperate coasts and often in regions with high population density and intensive human activities. Mangroves provide essential ecosystem services, such as coastal protection, pollution control, and cultural values to hundreds of millions of people [1,2]. However, mangrove habitats have been drastically degraded due to various factors over the past few decades, such as climate change, urban expansion, aquaculture, mining, and logging [3,4]. Global mangrove area has decreased by 35–50% in the past half-century (equivalent to an annual loss of 1% to 2%) [5].

International organizations and governments have taken actions to protect mangrove wetlands. In 2015, the United Nations included the mangrove ecosystem as an important factor in achieving sustainable development [6]. As early as 1996, India implemented a project to restore mangrove wetlands along the east coast through a partnership between the Environment Foundation and the government [7]. In 2002, the State Forestry Administration of China began a series of mangrove conservation and restoration projects. In 2020, the Chinese government again launched Special Action Plan for Mangrove Protection and Restoration (2020–2025)" [2]. To prevent the continued degradation of mangrove ecosystems, the Indonesian government has also focused on implementing a community-based mangrove management program [8].

Many researchers have investigated mangrove wetlands' long-term change. The FAO published the global status of mangrove degradation in 2007 and reported that the global mangrove wetland area decreased by 20% from 1980 to 2005. Goldberg et al. [9] showed an average annual loss rate of 0.13% (2000–2016) of the global mangrove area. Global Mangrove Watching Version 3.0 [10] showed a global average annual mangrove loss rate of 0.21% (1996–2010) and 0.04% (2010–2020), respectively, and that the mangrove area in Australia has been declining. However, Lymburner et al. [11] indicated that the mangrove area in Australia maintained an increasing trend between 2000 and 2010. Most studies reported that the rate of mangrove decline has started to decrease, but inconsistencies still existed in some of the results. In addition, the existing studies have mainly focused on the area change of mangrove ecosystems, while the change in landscape characteristics has been under-investigated.

Mangroves are one of the world's most threatened and vulnerable ecosystems, with climatic factors and human activities as the primary degradation factors [12]. Climatic factors include precipitation, temperature, sea levels rise, natural disasters, etc. Human activities can be divided into agricultural encroachment, urban expansion, environmental pollution, coastal aquaculture, etc. [13–15]. Friess et al. [16] suggested that the intertidal mangroves are a dynamic ecosystem, where the range and habitat quality were undergoing rapid changes. Since their first appearance in the geological record 75 million years ago, climate and sea level change have entirely changed the spatial distribution of mangroves. However, climate change contributes less to mangrove degradation [17]. With economic development, human activities have become the most important factor for mangrove degradation. Unplanned shrimp farms and urban development mainly cause mangrove deforestation, but the fundamental problem is inappropriate systems and regulations in the past [18,19]. Water pollution caused by offshore oil extraction may also impact the degradation of mangroves [20]. These studies suggest that the factors driving mangrove change are complex and vary from region to region.

The rapid development of remote sensing technology has provided technical support to realize mangrove monitoring on a large scale. Hamilton and Casey [21] established new global data sets of the 21st-century continuous mangrove coverage by integrating the World Forest Change Database, the World Mangrove Database, and the World Terrestrial Ecosystem Database. Giri et al. [22] obtained the global mangrove distribution dataset in 2000 from the Global Land Survey (GLS) dataset and Landsat images, which were interpreted by using a hybrid supervised classification and unsupervised classification method. Goldberg et al. [9] used a random forest classification approach to map the extent of global mangroves from 2000–2016 based on Landsat images. Bunting et al. [10] used synthetic aperture radar data to generate GMW version 3.0, which is valuable for analyzing global mangrove changes.

Despite international conservation policies and ambitious global restoration goals, deforestation is still occurring at a large scale, especially in Asia and Africa. At the same time, the rapid development of remote sensing technology provides support for the dynamic monitoring of mangroves [23,24]. Our objective is to select mangrove reserve wetlands within five continents over 20 years, use remote sensing and Geographic Information System (GIS) techniques to analyze and evaluate the loss/gain and landscape characteristics of mangrove wetlands, and compare current mainstream mangrove data to obtain actual mangrove change trends.

2. Materials and Methods

2.1. Selection of Study Sites

2.1.1. Principles for Selecting Study Sites of Mangrove Importance

There are 298 Ramsar-listed sites worldwide, playing key roles as international mangrove habitats. Among them, some sites also play additional key roles in UNESCO Biosphere Plan or in the UNESCO Natural Heritage. These mangrove habitats have different functions and regional features. The following principles were considered to select representative sites in our study.

(1) Site importance. To select those sites which are listed in the list of Ramsar wetlands of international importance, the UNESCO marine heritage list, and the UN biosphere list as much as possible;
(2) Geographical representativeness. The selected sites present different regional characteristics and cover wide geographical regions of mangrove spatial distribution as much as possible, and the site network should cover Asia, Oceania, and Africa, linking the Indian Ocean and the Pacific Ocean;
(3) Difference in functional roles of mangrove habitats. The selected sites can present different functional roles of mangrove habitats, such as Storing carbon, biodiversity protection, tsunami risk reduction, coastal line protection, and tourism service;
(4) Different challenges or problems on the sites. The selected sites are facing different challenges or national or international issues from economic development, environmental change, urbanization, etc.

2.1.2. The Final Scheme of the Study Sites of Mangrove Importance

The selected five sites are shown in Figure 1 and Table 1. The serial number was then finally fixed as A to E. The Sundarban mangrove, including Sundarbans Reserved Forest (Bangladesh) and Sundarban Wetland (India), is the largest mangrove wetland, while Bangladesh takes the largest protection ratio of the national mangrove area [25]. Indonesia has around 20% global mangrove and is one of the countries with the largest mangrove wetlands. However, it has lost nearly half mangrove area due to aquaculture development according to a research report from Richards and Friess [12].

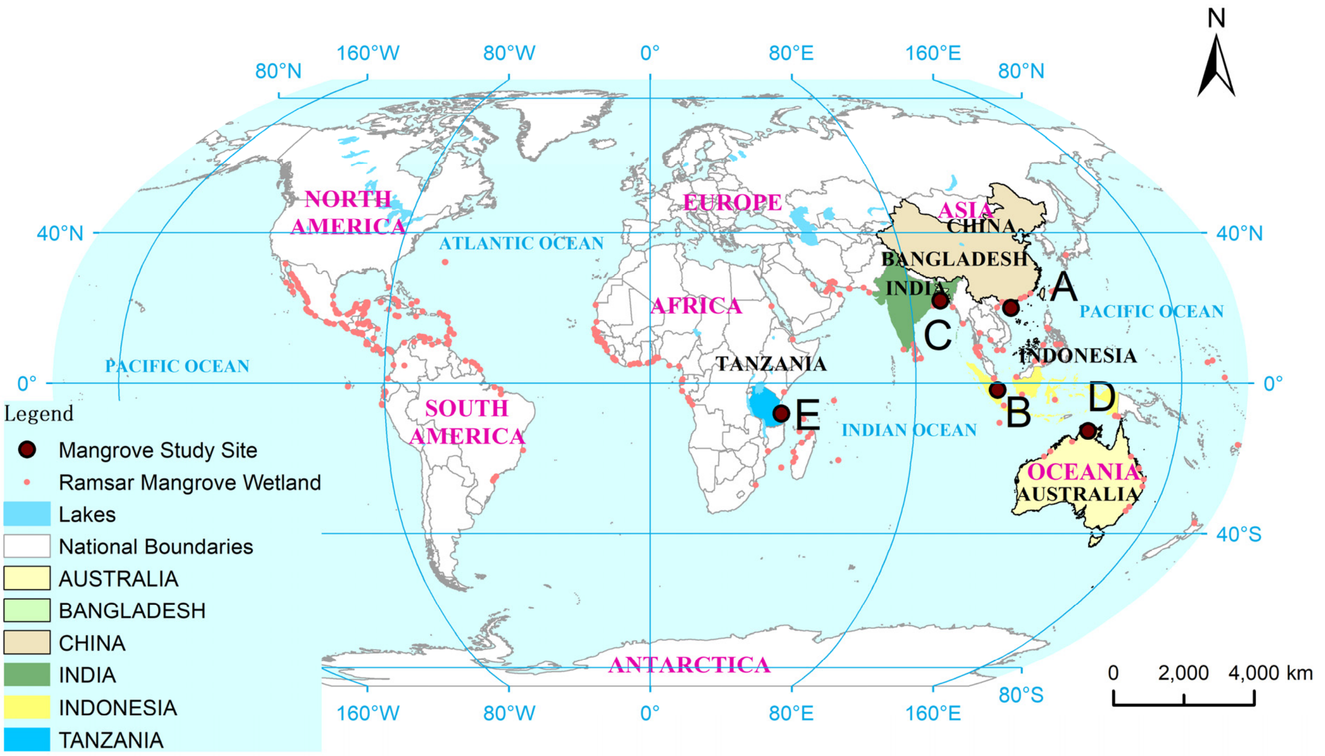

Figure 1. The map of the finally selected sites for the study. (A): Dongzhaigang; (B): Sembilang NP; (C): Sundarban; (D): Kakadu NP; (E): RUMAKI.

Table 1. The check list of five study sites to be finally selected.

Serial	Site Name	Geo-Location	Area (hm^2)	UNESCO Heritage	Ramsar List	Biosphere List	Country and Region	Major Threats
A	Dongzhaigang	19°58′ N 110°34′ E	5400	N	Y	N	China, Eastern Asia	Aquaculture; Urban expansion
B	Sembilang National Park	01°57′ S 104°36′ E	202,896	N	Y	Y	Indonesia, Southeast Asia	Aquaculture
C	Sundarban Wetland/ Sundarbans Reserved Forest	21°46′ N 88°42′ E	1,024,700	Y	Y	N	Bangladesh/India, South Asia	Cropland encroachment
D	Kakadu National Park	12°40′ S 132°45′ E	1,979,766	Y	Y	N	Australia, Oceania	Natural disasters
E	Rufiji-Mafia-Kilwa Marine Ramsar Site	08°07′ S 39°37′ E	596,908	Y	Y	N	Tanzania, Eastern Africa	Deforestation

2.2. Study Sites Introduction

As China's earliest and largest mangrove nature reserve, with an area of 5400 ha, Dongzhaigang Mangrove Nature Reserve is densely populated, surrounded by many villages and vast paddy fields. A mangrove restoration project has been underway since 2010 after this site's apparent loss of mangrove habitats. Dongzhaigang Mangrove Nature Reserve has been listed in the UNESCO World Heritage Sites Tentative List since 1996.

Sembilang Nation Park (Sembilang NP) has the largest mangrove habitats (88,046 ha) in the Indo-Malayan region [26]. Over 43% of mangrove species in Indonesia are found here. Sembilang NP has been acknowledged as a part of the UNESCO World Network of Biosphere Reserves since 2018.

The Sundarban mangrove wetland is the world's largest contiguous forest wetland system (579,446 ha). It locates in the deltas of the Ganga–Brahmaputra–Meghna rivers. It is the most diverse mangrove forest in the world and about 78 species of mangroves have been found at this site [27]. More than 12 million people live in and around the Sundarbans, of which 2.5 million depend almost entirely upon the mangroves for their livelihoods [28].

Kakadu National Park(Kakadu NP) is renowned for its exceptional beauty and unique biodiversity, with various landforms, habitats and wildlife. The mangrove habitat is a major ecosystem within Kakadu NP [29]. Kakadu NP was inscribed on the World Heritage List as a dual cultural and natural heritage in 1981.

Rufiji-mafia-kilwa marine ramsar site (RUMAKI) is located in the three districts of Rufiji, Mafia, and Kilwa, covering the most extensive mangrove habitat (48,991 ha) on the East African coast. According to the List of Wetlands of International Importance, RUMAKI is a good representative wetland for East Africa, for containing multiple and ecologically interconnected wetlands [30].

Five wetlands face different threats. Since the 1990s, the governments of China and Indonesia have encouraged the conversion of mangroves into aquaculture ponds to increase food security. Thus, aquaculture is a major driving factor in the degradation of Dongzhaigang and Sembilang NP. Because Dongzhaigang is close to the urban area and the tourism industry is relatively developed, urban expansion is another primary driver [31,32]. Development started late in Sundarban mangroves, and local governments and residents need to be aware of the conservation of mangrove wetland ecosystems. In addition, the presence of petroleum resources in the reserve and oil pollution from their exploitation are significant factors in mangrove degradation [14,33]. Australia is a developed country, and mangrove wetlands in protected areas are less affected. However, natural disasters (e.g., droughts, tsunamis) occur from time to time along the Australian coast, and this is a major factor in mangrove loss [29,34] Tanzania is developing. The inhabitants of the reserve use mangroves as economic forests to sustain their livelihoods, and indiscriminate deforestation is a major factor in the loss of mangroves in this reserve [35,36].

2.3. Data Preparing and Pre-Processing

2.3.1. Images Collection and Band Synthesis

Google earth engine (GEE) enables users to call a large number of remote sensing images online and perform calculations [37]. In this study, we used GEE to select Landsat and Sentinel images that meet cloud cover requirements (<15%) and eliminate images acquired at high tide level through visual interpretation. Too much cloud cover is not conducive to subsequent interpretation, and the high tide level will cover many mangroves. If there is no image meeting the requirements, we use all remote sensing images in the year to synthesize the maximum value of the NDVI index and the median value of the bands in this case (Figure 2). The detailed information of the used remote sensing images can be checked from Table 2.

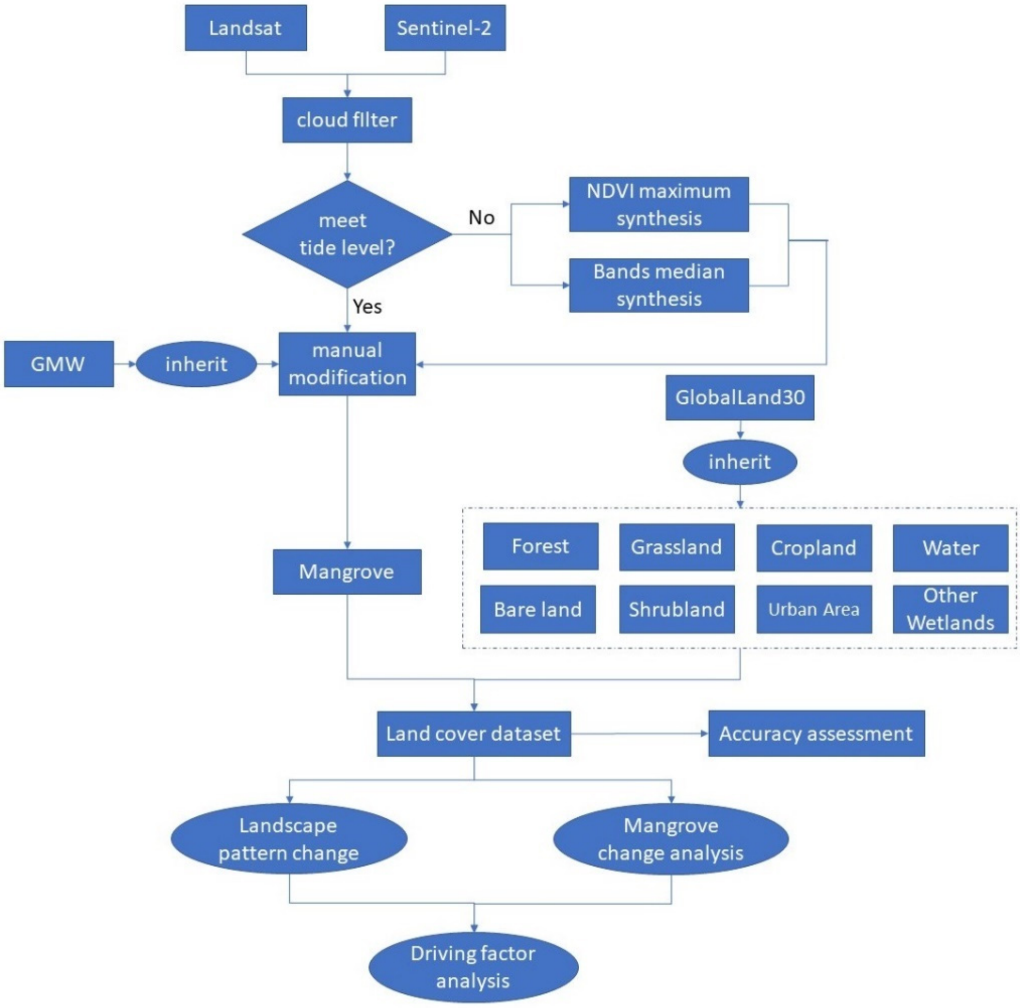

Figure 2. Flow chart of data collection and analysis procedures.

Table 2. The data source information of the remote sensing images used in five sites.

Serial	Year	Sensor	Number
A	1990	Landsat 5	6
	2000	Landsat 5/7	6
	2010	Landsat 5/7	6
	2020	Sentinel-2	40
B	2000	Landsat 7	42
	2010	Landsat 7	16
	2020	Sentinel2	146
C	2000	Landsat 7	2
	2010	Landsat 5	2
	2020	Landsat 8	2
D	2000	Landsat 7	2
	2010	Landsat 5	2
	2020	Landsat 8	2
E	2000	Landsat 7	4
	2010	Landsat 5	4
	2020	Landsat 8	74

2.3.2. Mangrove Dataset Collections

Some published mangrove data sets were evaluated carefully for selecting study sites and referring to our monitoring of the dynamics of mangrove habitats in the past 20 years. Among them, the most valuable data sets include the Global Mangrove Forests Distribution, v1 (2000, GMFD), the Global Mangrove Watch (GMW), and the 10 m GLOBAL MANGROVE CLASSIFICATION PRODUCTS OF 2018–2020 BASED ON BIG DATA (GMCP). The technical indicators are listed in Table 3.

Table 3. The basic information of free download data sources.

Data Set	Pixels	The Dates of Production	Data Format	Precision	Citation
GMFD	30 m	2000	Grid	90.75%	Giri et al. [22]
GMW	24 m	1996, 2007, 2008, 2009, 2010, 2015, 2016	Shape	95.25%	Bunting et al. [10]
GMCP	10 m, 100 m	2018–2020	Shape, Grid	91.62%	Xiao et al. [38]

2.4. Manual Modification for Mangrove Boundary and Landcover Dataset Synthesis

The mangrove extent provided by GMW is slightly inaccurate at five specific sites and does not provide the mangrove extent for 2000 and 2020. Then, we manually modified the mangrove boundary by referring to the selected or synthesized remote sensing images and the collected mangrove dataset with a high reference value in this study (Figure 2). Then, we mosaicked the Globalland30 and our manually modified mangrove datasets to obtain a landcover dataset, which contains nine land use types (Mangrove, Forest, Grassland, Cropland, Water, Bareland, Shrubland, Urban Area, and Other Wetlands) to subsequently analyze the conversion between mangroves and other land-use types. The Globalland30 dataset is available at http://www.globallandcover.com/home.html?type=data (accessed on 1 January 2014) [39]

2.5. Accuracy Assessment

In order to verify the developed mangrove dataset, we merged the nine land cover types into three types: mangrove, water, and others. Balanced number of validation samples were generated for each type. For instance, the area proportion of the water body and mangrove is very low in Kakadu NP, and we appropriately increased the validation samples in the area where the water body and mangrove forest are located in the typical area, rather than simply generating random test points according to the uniform distribution. Otherwise, most test points were distributed in other land types, such as forests and grassland. Fewer samples of test points in water and mangrove will result in accuracy errors. We determined the actual land use types represented by the sample points with the help of Google Earth, other mangrove datasets, and Sentinel data [22,38].

2.6. Landscape Pattern Change Analysis and Mangrove Change Analysis

We used ArcGIS software to statistically analyze the land cover dataset during different periods, including conversion between mangrove habitats and other land-use types, mangrove degradation direction, and changes in mangrove landscape patterns for different periods (Figure 2). We counted four landscape indexes using ArcMap10.2: Number of Patches (NP), Area of Maxsum Patch (MAXP); Mean Area of Patches (MPS); Total Area of Patches (CA). MPS reflects an average condition and demonstrates the degree of landscape fragmentation and heterogeneity in the landscape analysis. NP reflects the total number of patches in the landscape pattern, and generally, a larger NP indicates a higher degree of fragmentation. The four parameters can comprehensively reflect the degree of fragmentation of the landscape and other ecological information of the landscape. To show the degradation of mangroves more visually, we mapped the direction of mangrove degradation by mangrove to other land-use types.

3. Results

3.1. Accuracy Assessment

The accuracy assessment results are shown in Table 4. Both the mangrove accuracy and overall accuracy are above 95%, which meets the standards for analyzing landscape changes.

Table 4. Accuracy assessment table.

Serial	2000		2010		2020	
	Mangrove	Overall	Mangrove	Overall	Mangrove	Overall
A	98.3	96.6	96.7	95.4	97.5	96.7
B	97.2	95.1	97.5	95.4	97.1	95.2
C	98.0	97.0	98.1	97.2	98.4	97.4
D	97.1	96.1	97.2	95.9	97.5	96.3
E	97.4	95.2	97.5	95.4	97.8	95.8

3.2. Landscape Pattern Change of the Mangrove Habitats from 2000 to 2020

The landscape matrix of the changed mangrove habitats in the five sites was generated using the landcover dataset. The detailed dynamic information of the mangrove habitats from 2000 to 2020 can be checked in Table 5. From 1990 to 2000, the NP of the mangrove habitats in Dongzhaigang tripled from 27 to 87 ha; but the MPS decreased from 71 to 20 ha, nearly 70%. This indicates that the process of mangrove habitat fragmentation was very severe. Fortunately, the fragmentation of mangrove wetlands in the other four protected areas, except for Sundarbans, decreased or remained the same from 2000. The fragmentation process of Sundarbans mangrove only gradually stopped in 2010.

Table 5. Landscape matrix of the changed mangrove wetlands in five sites (ha).

Seria	Index	1990	2000	2010	2020
A	NP	27	87	41	64
	MAXP	742	247	683	505
	MPS	71	20	42	33
	CA	1930	1683	1733	2097
B	NP	-	1279	881	913
	MAXP	-	32,746	20,435	20,255
	MPS	-	70	100	96
	CA	-	89,698	87,965	88,046
C	NP	-	4859	6666	6788
	MAXP	-	26,154	23,251	23,102
	MPS	-	123	86	85
	CA	-	595,537	575,700	579,446
D	NP	-	1003	918	979
	MAXP	-	1140	1140	1137
	MPS	-	9	10	9
	CA	-	8965	8942	8882
E	NP	-	1668	1312	1185
	MAXP	-	6909	6801	6793
	MPS	-	31	38	41
	CA	-	51,003	49,748	48,991

"-": no data; The Dongzhaigang data are partially cited from the Ph.D. thesis of Jia (2014) with corrections and slightly adjusted classification.

3.3. Mangrove Habitats Change Analysis from 2000–2020 at Five Sites

3.3.1. Analyzing the Dynamics of Mangrove Habitats in Dongzhaigang

The mangrove habitats area decreased by 12.8% from 1990 to 2000 before increasing from 2000 to 2020. The mangrove area increased by 24.6% from 2000 to 2020 according to the statistical data (Figure 3). The degradation of mangroves has been presented from 1990 to 2020. However, the degradation area had been decreasing (Figures 4 and 5). The highest percentage of mangroves was converted to other wetlands (mainly aquaculture) from 1990 to 2000, but the highest percentage of mangroves was converted to forest from 2000 to 2010. In addition, there were larger areas of mangrove wetlands that had been encroached on by cropland (Figure 6). The degraded area of mangroves was already much lower than the new area of mangroves from 2010–2020, which should be attributed to mangrove planting and conservation policy of the local government. Mangrove degradation mainly occurred in the landward direction from 1990 to 2010, and mangrove degradation mainly occurred in the seaward direction from 2010–2020 (Figure 6). Comparing the landscape matrices between 1990 and 2000, it was obvious that the lost mangrove habitat was replaced by the pond, which might be used for fishery purposes. The area of mangrove habitat increased obviously after 2000, attributed to mangrove planting supported by the local government.

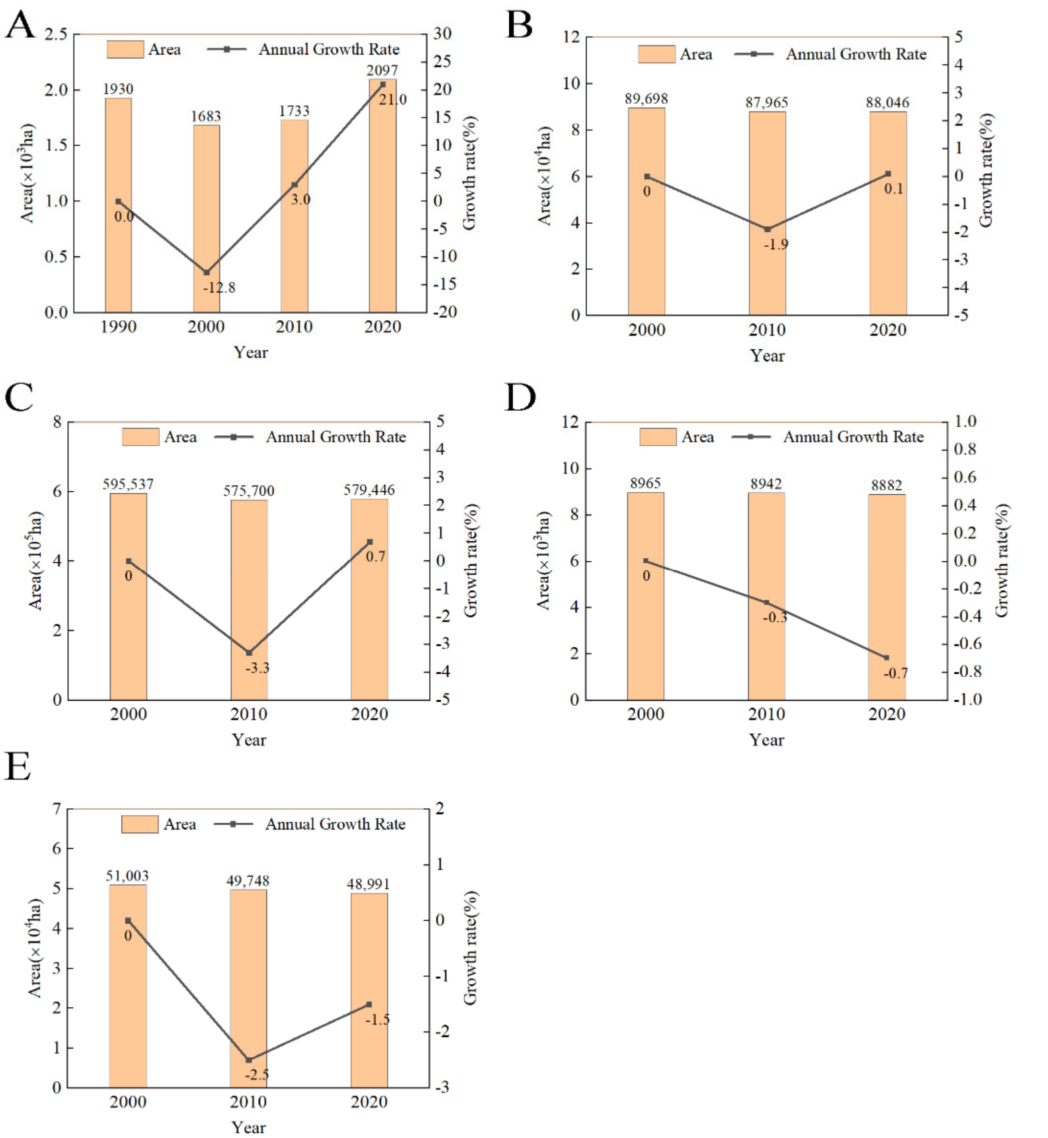

Figure 3. The dynamics of the mangrove habitats in five sites. (**A**): Dongzhaigang(1990−2020); (**B**): Sembilang NP; (**C**): Sundarban; (**D**): Kakadu NP; (**E**): RUMAKI (2000−2020).

3.3.2. Analyzing the Dynamics of Mangrove Habitats in Sembilang NP

Mangrove habitats are mainly dispersed in the central part of Sembilang NP (Figure 7). Mangrove area decreased by a total of 1733 ha from 2000 to 2010 with a 10-year decrease ratio of 1.9%, though it increased a total of 81 ha from 2010 to 2020. It indicated that the protection of mangroves in the latter 10 years was significantly more effective than that in the former, which not only curbed the previous trend of decreasing mangrove wetland area but also contributed to a slight increase of the mangrove habitats (Figure 3). Degradation occurred primarily at the landward edge of the northern mangroves, mainly degraded to forest and other wetlands, however, the increase in mangrove area also came mainly from forest and other wetlands (Figures 8 and 9). In the southeast coastal region of the reserve, there are other farming ponds that have not yet been retired.

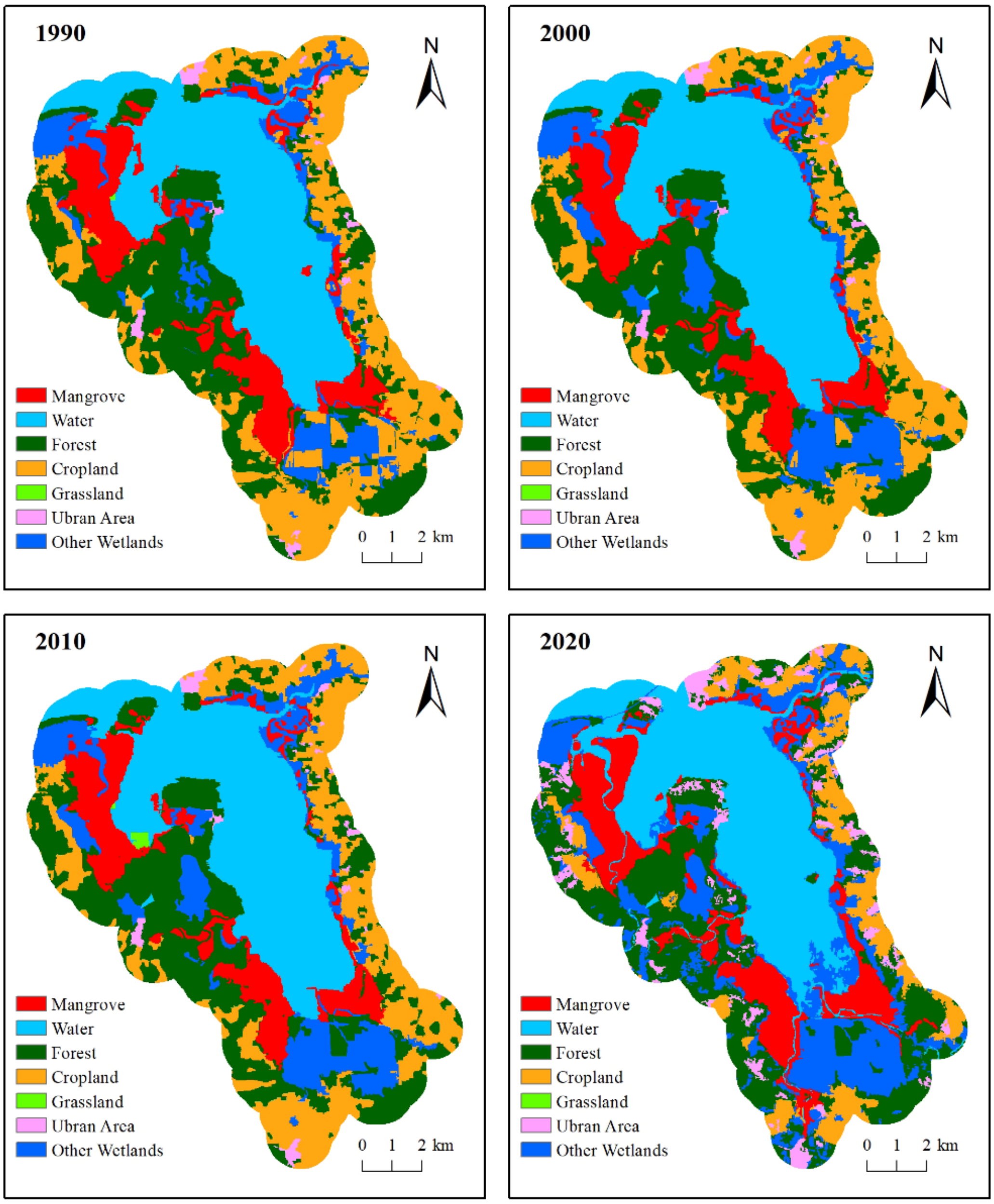

Figure 4. Landscape thematic maps in Dongzhaigang from 1990 to 2020.

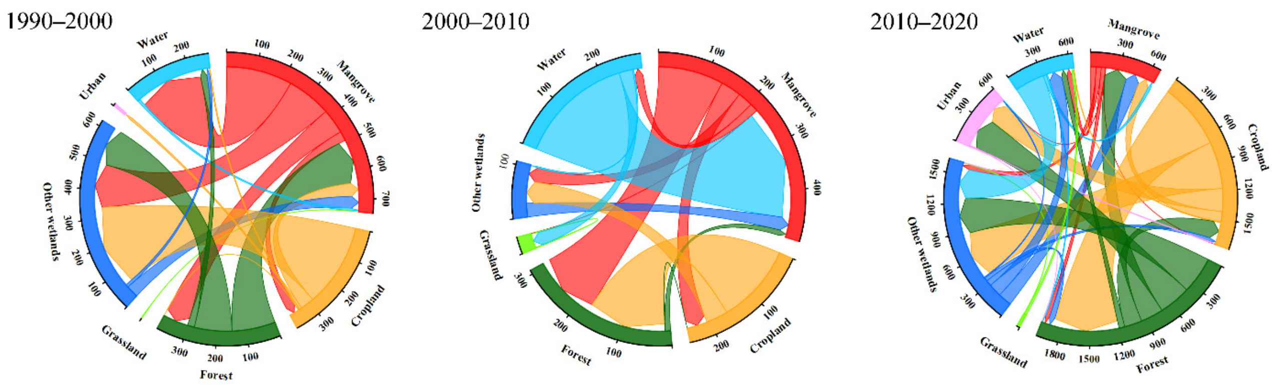

Figure 5. Transfer direction between the different land-use types in Dongzhaigang ((**left**): 1990−2000, (**middle**): 2000−2010, (**right**): 2010−2020).

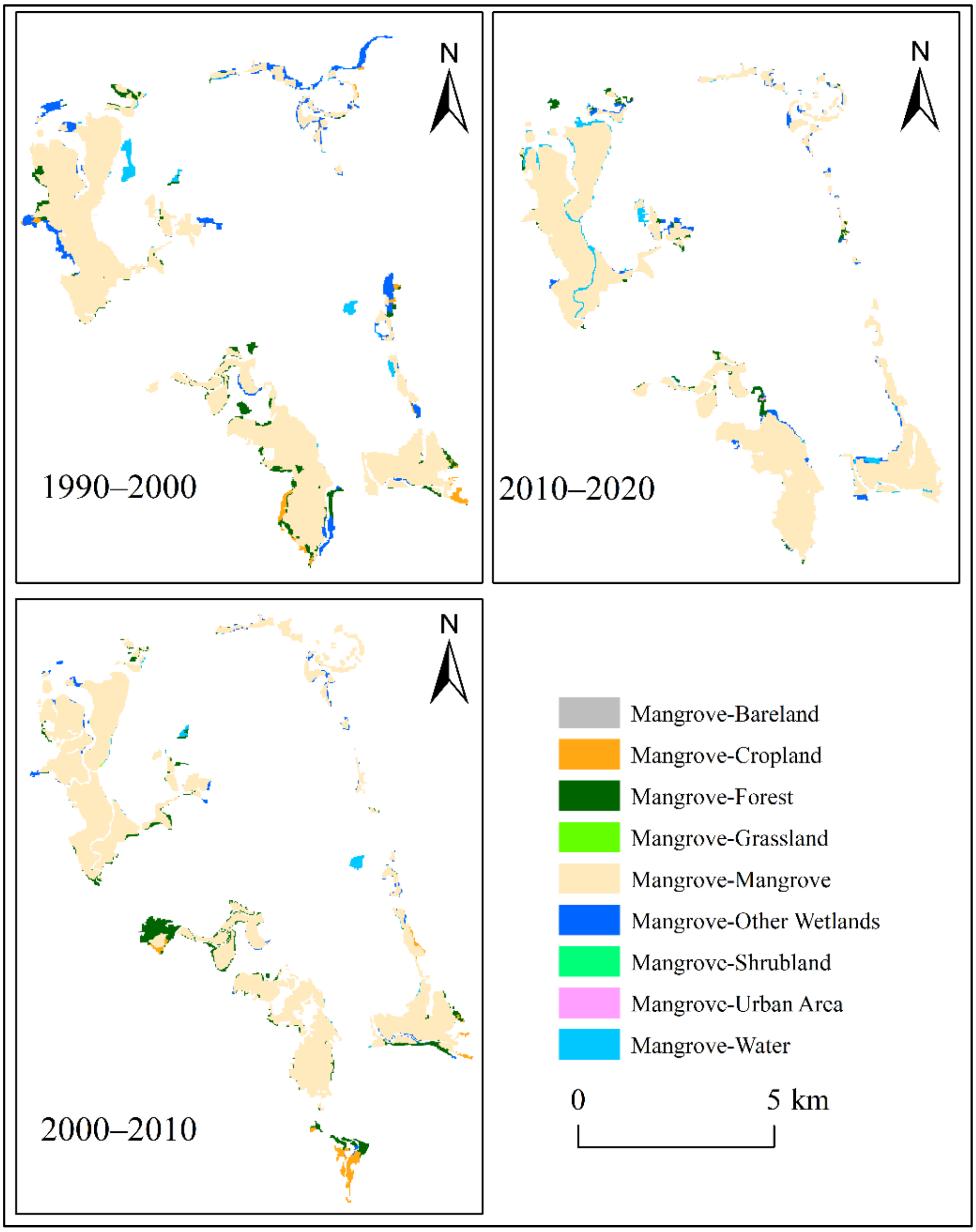

Figure 6. Maps of spatial–temporal distribution of mangrove degradation in Dongzhaigang from 1990 to 2020.

3.3.3. Analyzing the Dynamics of Mangrove Habitats in the Sundarban

The degradation of mangroves in Sundarban was concentrated in the northern (near the boundary) and the eastern part of the reserve. Mangroves were mainly degraded to cropland and other wetlands in the first ten years, and to wetlands during the second ten years. The degraded area was drastically reduced and more dispersed (Figures 10 and 11). Mangrove habitat area decreased by a total of 19,837 ha from 2000 to 2010, with a 10-year decreased rate of 3.3%. The decrease rate is higher than the other four sites in the same period. The degraded area in 2000–2010 was significantly larger than that in 2010–2020 (Figures 3 and 11). A total of 3746 ha increased with an increased rate of 0.7% from 2010 to 2020, indicating that the downward trend at the beginning of the 21st century was significantly contained, and the protection and restoration of mangrove habitats in the past ten years have achieved remarkable achievements (Figure 3).

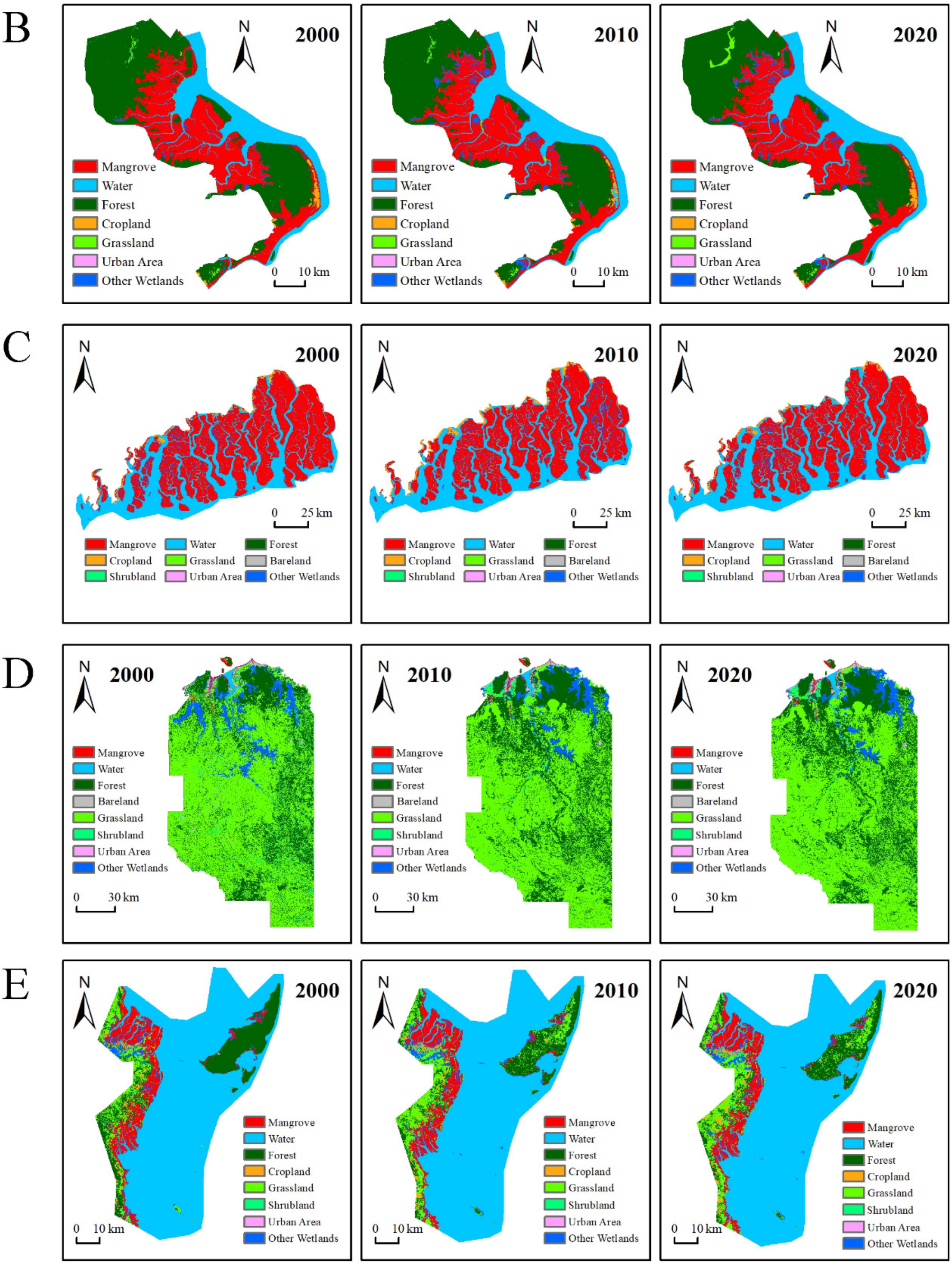

Figure 7. Landscape thematic maps in four sites from 2000 to 2020 (**B**): Sembilang NP, (**C**): Sundarban, (**D**): Kakadu NP, (**E**): RUMAKI.

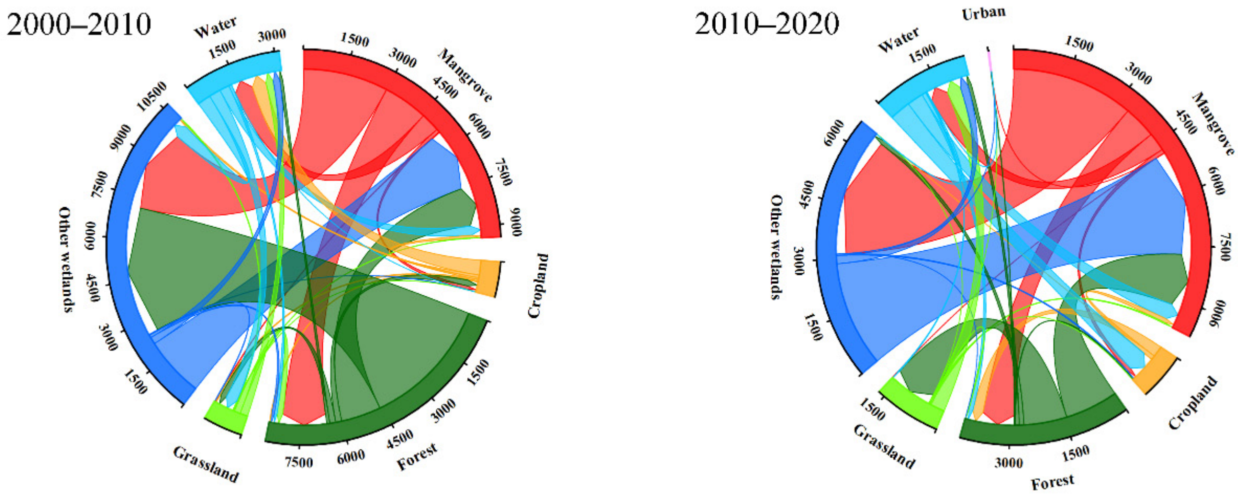

Figure 8. Transfer direction between the different land-use types in Sembilang NP ((**left**): 2000–2010, (**right**): 2010–2020).

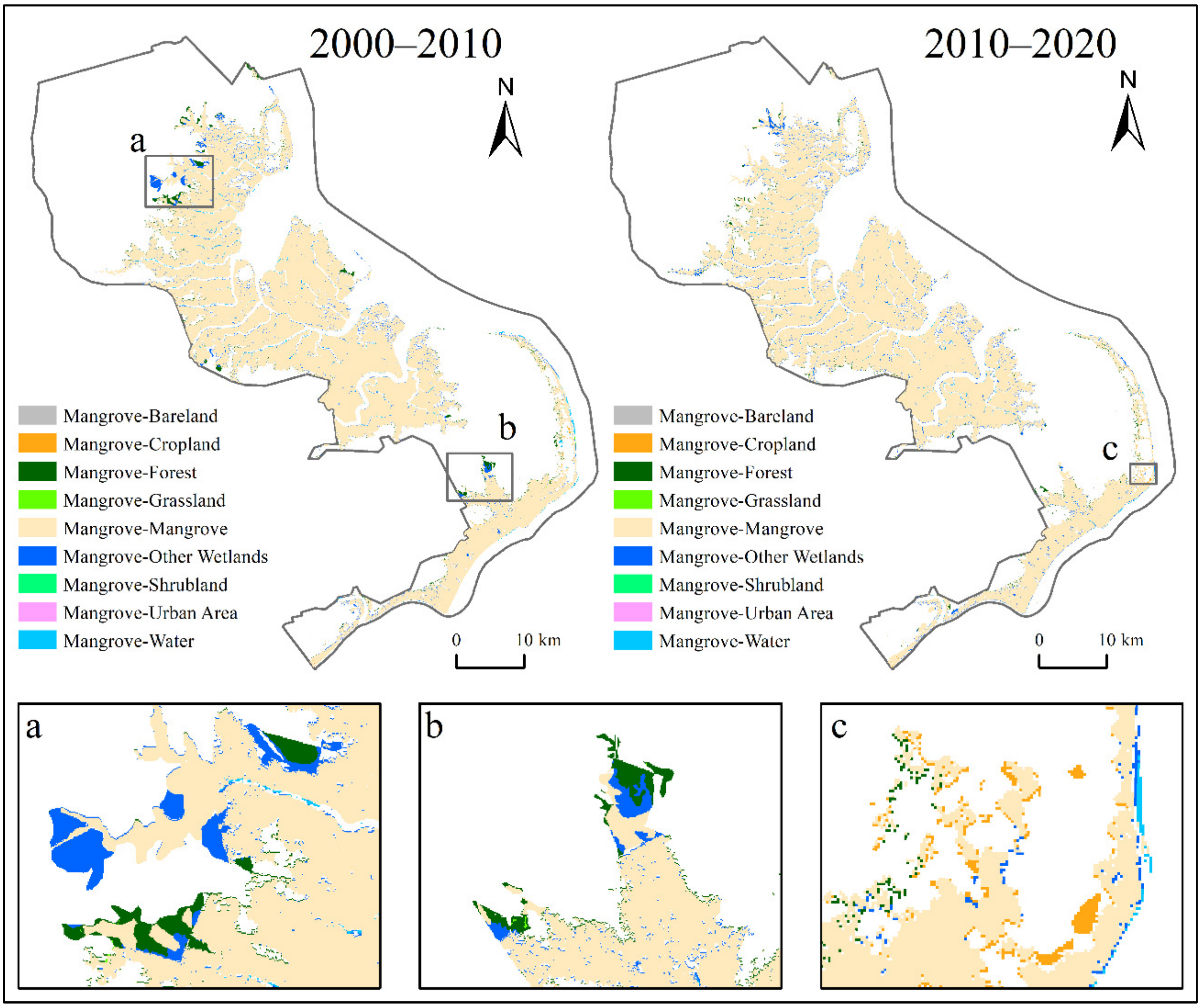

Figure 9. Maps of spatial–temporal distribution of mangrove degradation in Sembilang from 2000 to 2020. (**a**) first degradation detail picture; (**b**) second degradation detail picture; (**c**) third degradation detail picture.

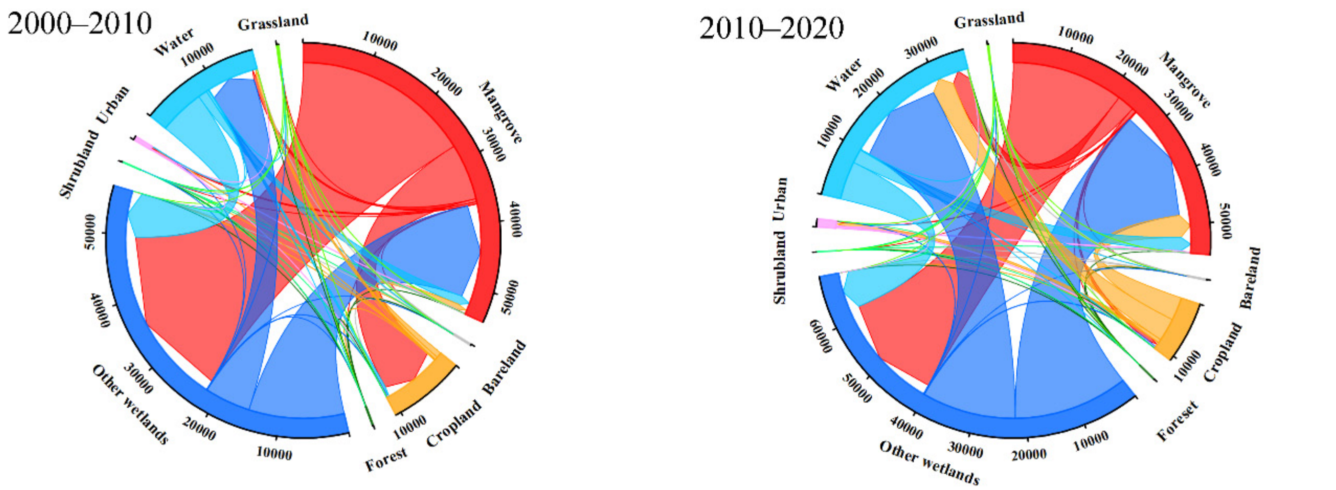

Figure 10. Transfer direction between the different land-use types in the Sundarban ((**left**): 2000–2010, (**right**): 2010–2020).

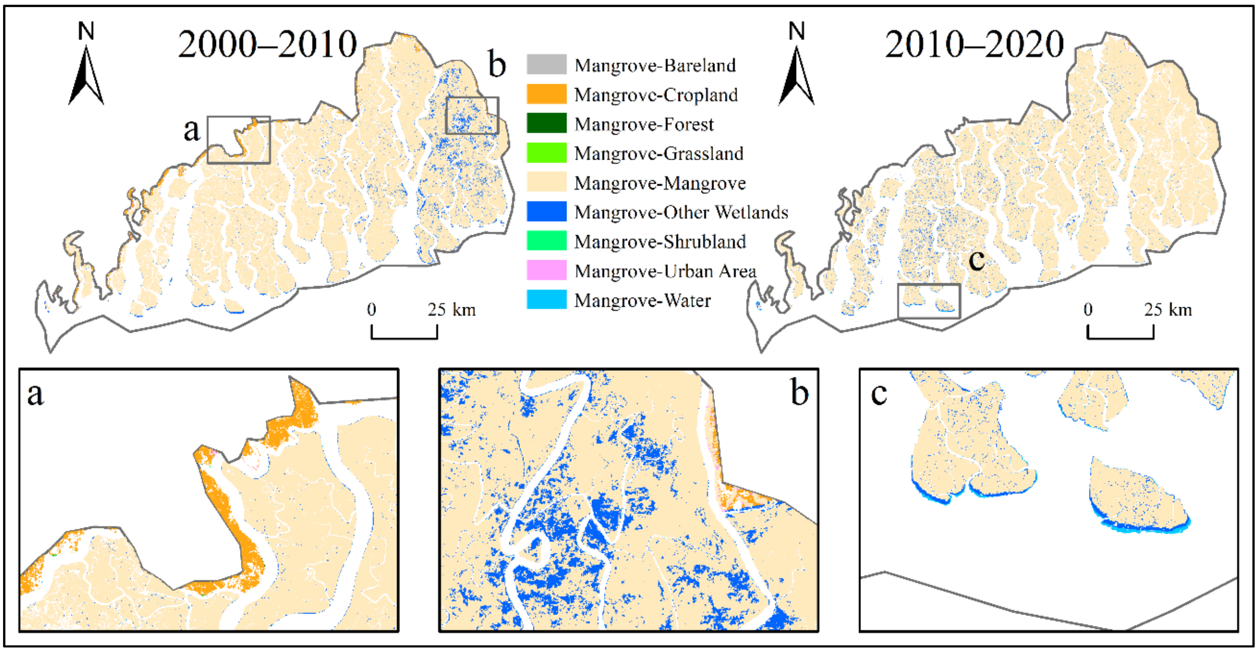

Figure 11. Maps of spatial–temporal distribution of mangrove degradation in the Sundarban from 2000 to 2020. (**a**) first degradation detail picture; (**b**) second degradation detail picture; (**c**) third degradation detail picture.

3.3.4. Analyzing the Dynamics of Mangrove Habitats in Kakadu NP

Mangrove habitats are mainly located in the northern part of Kakadu NP, along the Van Diemen's coastline. Forest and grassland are the most prominent landscape types in Kakadu NP, while mangrove habitats account for a relatively small area (Figure 7). Mangrove habitat area decreased by only 23 ha from 2000 to 2010, with a 10-year decrease rate of only 0.3% and decreased by 60 ha from 2010 to 2020, with a 10-year decrease rate of 0.7%, doubling the rate of reduction over the former 10-year period (Figure 3). As a whole, Kakadu NP was second only to Dongzhaigang in terms of the conservation effect from 2000 to 2010, and the total decrease of mangrove habitats area (83 ha) and decrease rate (0.9%) were lower than those of the other three sites. Unfortunately, mangrove habitats at other sites have shown an increasing trend over the last decade (except for sites in Tanzania), while mangroves within Kakadu NP have continuously decreased. Mangrove wetlands are mainly degraded to other wetlands, followed by forest and water (Figures 12 and 13).

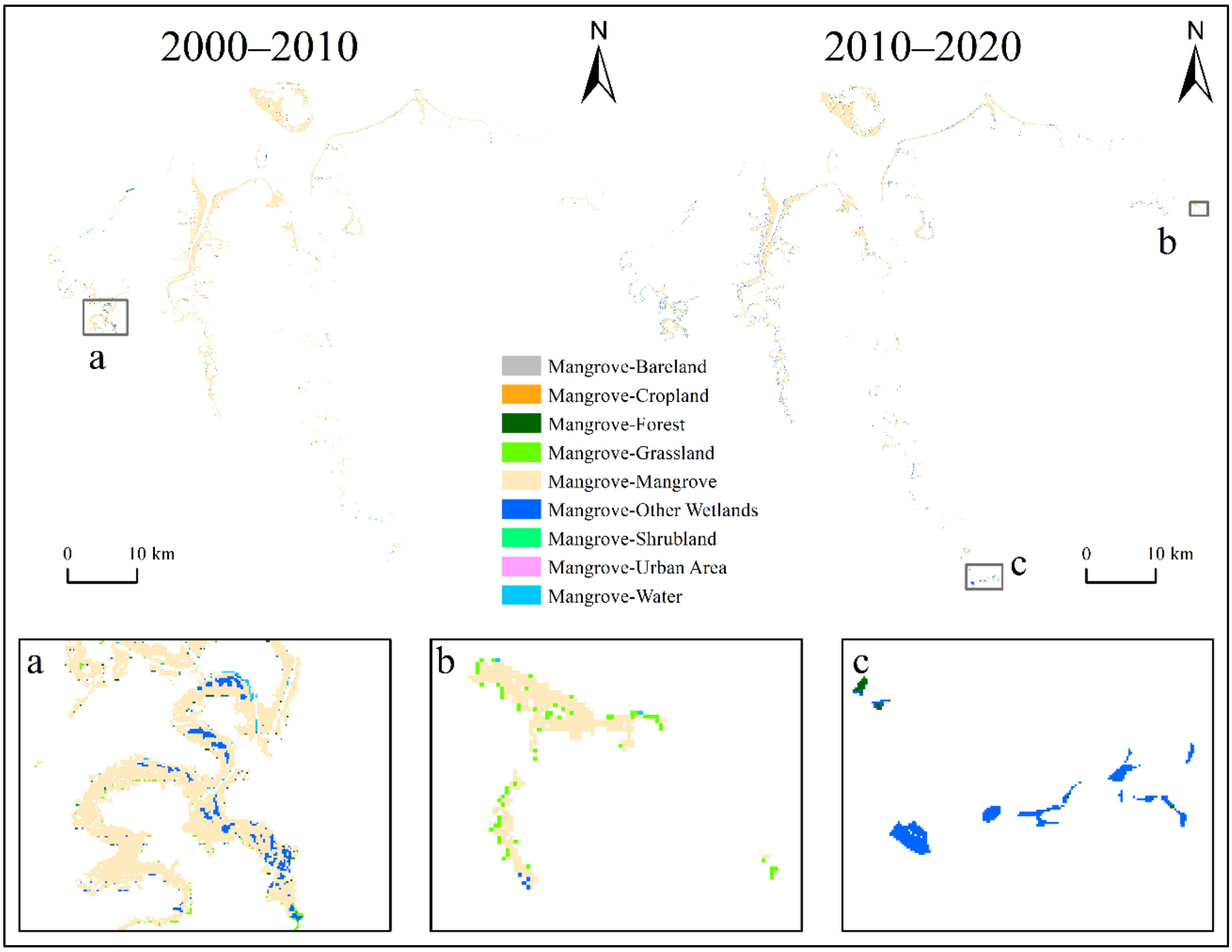

Figure 12. Maps of spatial–temporal distribution of mangrove degradation in Kakadu NP from 2000 to 2020. (**a**) first degradation detail picture; (**b**) second degradation detail picture; (**c**) third degradation detail picture.

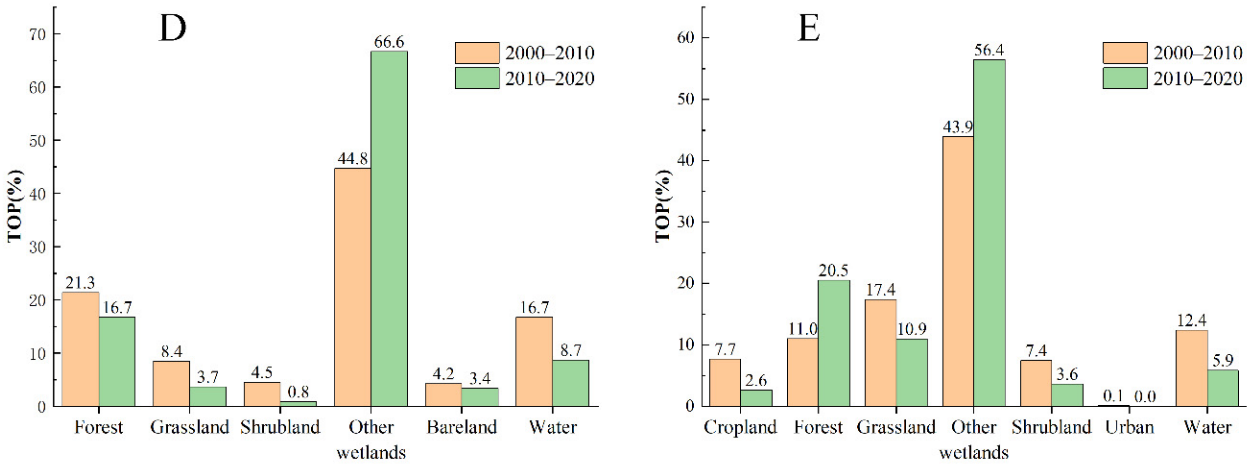

Figure 13. Maps of other land contributing to mangrove transfer out percent (TOP) in Kakadu NP (**D**) and RUMAKI (**E**) from 2000 to 2020 (e.g., a total of 100 ha of mangroves are transferred out, of which 50 ha are other wetlands, the corresponding TOP = 50%).

3.3.5. Analyzing the Dynamics of Mangrove Habitats in RUMAKI

Mangrove habitats within RUMAKI were dispersed north to south along the mafia channel, degraded mainly to cropland, other wetlands, and grassland (Figures 7 and 13). The extent of degradation was concentrated more in 2010–2020 compared to that in 2000–2010 (Figure 14). Mangrove habitat area decreased by 1255 ha with a 10-year decrease of 2.5% from 2000 to 2010, and by 757 ha with a 10-year decrease of 1.5% from 2010 to 2020 (Figure 3). It was still relatively higher compared to other regions except Kakadu NP, although the decrease proportion of mangrove habitats has slowed down in the past ten years.

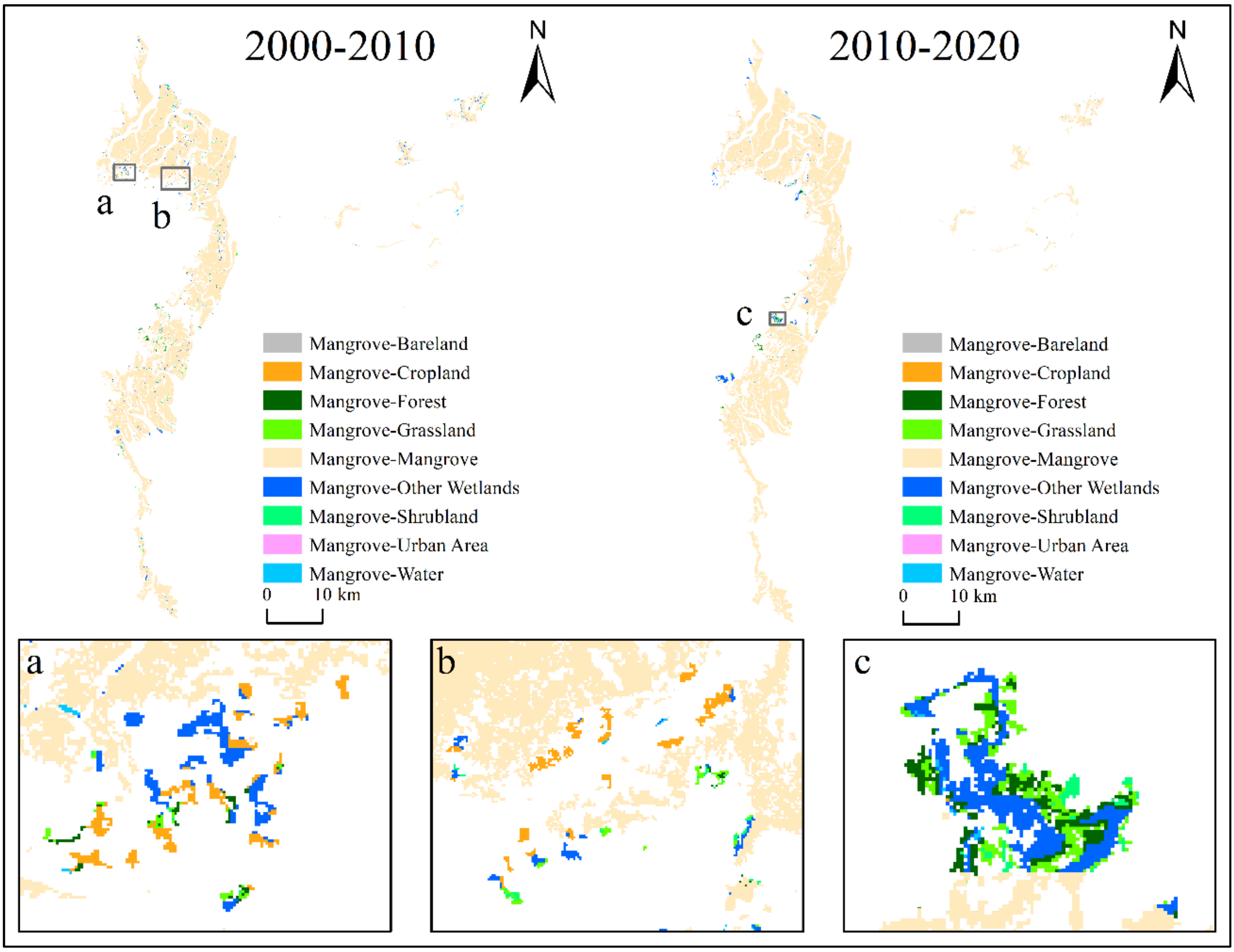

Figure 14. Maps of spatial–temporal distribution of mangrove degradation in RUMAKI from 2000 to 2020. (**a**) first degradation detail picture; (**b**) second degradation detail picture; (**c**) third degradation detail picture.

3.3.6. Comparison of Mangrove Habitats Changes from 2000 to 2020 in Five Sites

Dongzhaigang (China) is the only reserve where the mangrove area expanded between 2000 and 2020 at a rate of 24.6%. Several other reserves experienced different degrees of mangrove habitat loss. RUMAKI (Tanzania) has the most significant loss among the five reserves, but the loss proportion is at most 4.0%. The mangrove habitats in Sundarban (India) have experienced a shift from rapid degradation to positive growth. The degradation rate of mangrove wetlands in Kakadu NP (Australia) has remained the lowest (Figure 15).

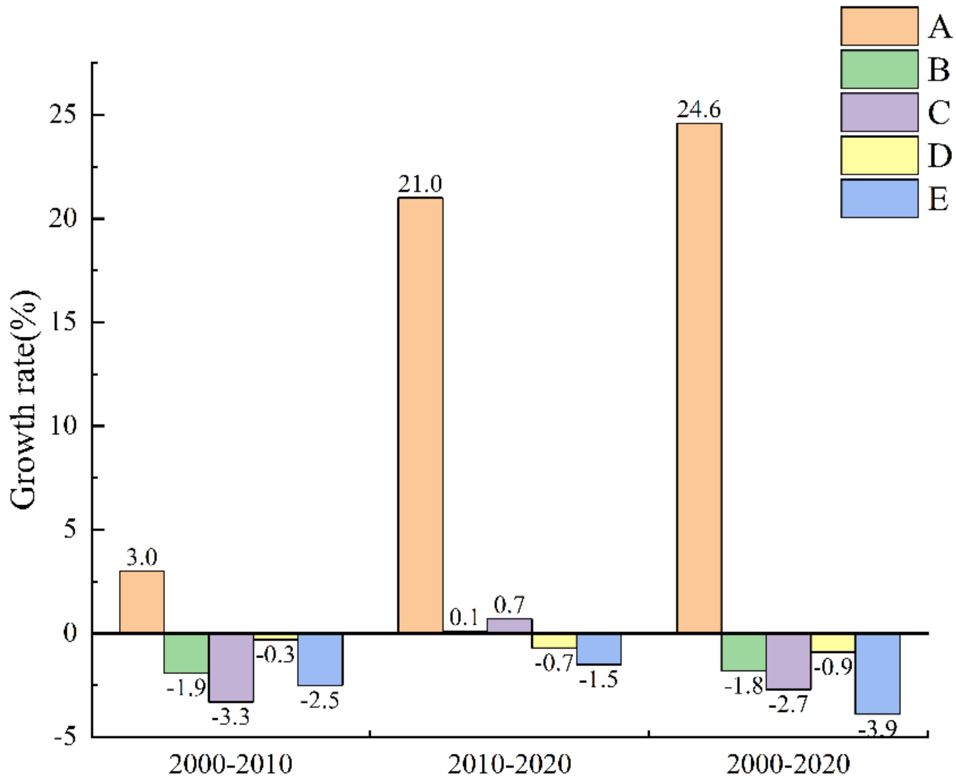

Figure 15. Comparison of the dynamics of mangrove habitats in five sites from 2000 to 2020. (A): Dongzhaigang; (B): Sembilang NP; (C): Sundarban; (D): Kakadu NP; (E): RUMAKI.

4. Discussion

4.1. Driving Forces of Mangrove Degradation in the Five Protection Areas

The driving forces of mangrove degradation are mainly divided into climatic factors (precipitation, temperature, sea level rise, natural disasters, etc.) and human activities (agricultural encroachment, urban expansion, aquaculture, etc.) [13–15]. Dongzhaigang is close to the urban area, and urban expansion and aquaculture were the main factors of mangrove wetland degradation. The Chinese government increased the protection of mangrove habitats and implemented mangrove restoration projects after 2000; thus, the mangrove wetlands were effectively restored [2]. The Indonesian government formulated and implemented a policy to vigorously develop the aquaculture industry in order to achieve economic development after the 1980s, which led to aquaculture being the most critical factor in the degradation of mangrove forests in Semmelang NP [40,41]. The Sundarban mangroves is the largest contiguous mangrove forest in the world, and the northern part of the reserve is adjacent to farmers' settlements. Farmers entering the reserve might develop the mangrove wetland into farmland for their livelihood, which becomes the most significant human activity factor for mangrove degradation [42,43]. Kakadu NP is the only mangrove reserve in a developed country with more stringent legislation and regulations for mangrove protection. However, the mangrove wetlands in reserve are mainly exposed to natural disasters because the northern part of Australia is highly influenced by climatic factors [11,43]. The laws on mangrove habitats protection made in Tanzania cannot be effectively implemented, and mangroves are used as a source of timber and woodland destroyed by local residents. On the one hand, the local population is considered by the government to be the destroyer of mangroves; on the other hand, the impoverished population has to rely on mangrove raiding for their livelihood. Poverty-induced agricultural encroachment is a major factor in mangrove degradation in this study area [44].

4.2. Comparison with Other Studies

The State of the World's Mangroves 2022 [45] notes a global mangrove loss of 5245 km^2 from 1996 to 2020, with an average annual decline rate of 0.34%; a global mangrove loss of 327 km^2 from 1996 to 2010, with an average annual decline rate of 0.21%; and a global mangrove loss of 66 km^2 from 2010 to 2020, with an average annual decline rate of 0.02%. The results are consistent with our findings, indicating that the rate of mangrove degradation has slowed down significantly after 2010. Dongzhaigang lost 62% of its mangrove area from 1973 to 2000, but achieved rapid growth after 2000, and the mangrove area recovered to the 1980 level by 2020 [2]. Correspondingly, our results indicate that the mangrove habitats of Dongzhai lost more than 10% from 1990 to 2000 and achieved a 24% increase from 2000 to 2020, a rate that is much higher than that of the entire East Asia region (Table 6). The State of the World's Mangroves 2022 [45] indicates that aquaculture has made Southeast Asia the fastest-degrading region for mangrove wetlands (1996–2020: 4.8% degradation proportion). However, our results show that RUMAKI in East Africa has the highest rate of mangrove loss among the five typical reserves, which is a side indication that mangroves in the Sembilang NP is better protected. The State of the World's Mangroves 2022 shows an overall degradation rate of 3.0% (1996–2020) in South Asia, and our results show a degradation rate of 2.7% (2000–2020) for mangrove habitats in the Sundarbans mangroves in South Asia, which is consistent with each other and the changes in degradation rates are uniform: the area of mangrove habitats started to increase after 2010. Unfortunately, the results are contrary to those of Giri et al. [42]. This may be an error in the mangrove extent interpretation process, and the authors consider mangrove degradation in protected areas to be insignificant and a case of dense population–nature symbiosis. The results of Bunting et al. [10] show that the average annual rate of loss of mangrove habitats in Australia is 0.23% (1996–2010) and 0.1% (2010–2020), while our results showed that the rate of mangrove loss within Kakadu NPark was 0.03% (2000–2010) with an increasing trend after 2010, suggesting that mangrove habitats within Kakadu NP is better protected.

Table 6. Changes in mangrove area by region (Leal & Spalding, [45]).

Region	Mangrove Area (ha)			Proportion of Change (%)		
	1996	2010	2020	1996–2010	2010–2020	1996–2020
Eastern Asia	257.2	223.6	227.7	−13.1	1.8	−11.5
Southern Asia	9960.7	9710.4	9661.1	−2.5	−0.5	−3.0
Southeastern Asia	50,678.8	48,440.9	48,222.3	−4.4	−0.5	−4.8
Australia & New Zealand	10,945.0	10,562.5	10,466.9	−3.5	−0.9	−4.4
Eastern Africa	7883.3	7688.6	7610.0	−2.5	−1.0	−3.5

4.3. Limitations

The tide levels could have an impact on the interpreted mangrove extent. Although we obtained synthetic NDVI and band information using the annual maximum and annual median methods, we were still unable to eliminate the inaccuracy caused by the high tide level conaealing the seaward mangroves. In addition, a comparison of conservation effectiveness cannot be made based solely on an analysis of the changing characteristics of mangrove ecosystems within protected areas. The conservation effect can be reflected better if comparing the change of mangrove wetlands inside and outside the protected area. Hence, it will be our next research direction.

5. Conclusions

(1) The dynamics of the mangrove habitats. From 2000 to 2020, the mangrove area in Dongzhaigang increased by 414 ha, with an increased percent of 24.6%. The mangrove area in Sembilang NP, Sundarban, Kakadu NP, and RUMAKI decreased by 1652 ha, 16,091 ha, 83 ha, and 2012 ha, with a decrease of 1.8%, 2.7%, 0.9%, and 3.9%, respectively.

(2) Direct driving factors of mangrove habitats. Other types of wetlands play a key role in degradating the mangrove wetlands in all five protected areas. The increase of mangroves in Dongzhaigang is a result of the local government-supported conservation scheme for returning ponds to forests and plantations. Agricultural encroachment is the other factor in reducing of mangrove areas in Sundarbans. Natural disaster is another factor to degrade the mangrove wetland in RUMAKI.

(3) The rate of mangrove degradation has slowed dramatically over the past two decades, based on five sites, which are generally consistent with those of other researchers. Among the five typical reserves, the mangrove area in Dongzhaigang is the only one to have expanded. The mangrove area in the other four locations has fallen to a lesser level, with the greatest decrease not surpassing 4%.

Recommendations

Our research did not cover mangroves in the Americas, and we hope to scale up to the global scale and encrypt more representative mangrove sites in the future.

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