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Change and fragmentation trends of Zhanjiang mangrove forests in southern China using multi-temporal Landsat imagery (1977–2010)

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ABSTRACT

Mangrove forests, which are found in saline coastal environments around the tropical and subtropical latitudes, are among the most productive terrestrial ecosystems in the world and provide valuable ecological and societal goods and services. The objective of this work was to characterize the spatio-temporal changes in mangrove distribution and fragmentation patterns in the Zhanjiang National Mangrove Forest Nature Reserve, Guangdong province of Southern China, from 1977 through 2010. In addition, a major goal was to assess the socio-economic drivers contributing to the chronic changes taking place within and around the mangrove reserve. Land use and land cover data sets were generated for the reserve for multiple years via unsupervised classification using Landsat time series images. Mangrove fragmentation patterns were then assessed with a fragmentation model. Results revealed that the mangrove spatial extent decreased sharply during the period from 1977 to 1991 due to deforestation caused by diverse development programs, particularly shrimp farming. Afterwards, there was a continuous increase in mangrove extent from 1991 to 2010 due to afforestation and conservation efforts. The mangrove fragmentation trends depicted by the fragmentation model had a high degree of correlation with the observed areal changes. Additionally, the recorded dynamics of the local biodiversity (mainly birds) were consistent with the mangrove ecosystem fragmentation trends over time, and different fragmentation components, including interior, perforated and edge, had distinct impacts on the local mangrove-dependent biodiversity. The most effective way to protect and expand the current mangroves include the following: (1) establishment of mangrove natural reserves, (2) forceful implementation of regulations, (3) establishment of educational programs related to mangrove management, (4) deepening international exchanges and cooperation and (5) increasing the transparency of the project implementation process. Together such management measures will lead towards responsible and sustainable utilization of the mangrove ecosystems.

1. Introduction

Mangrove forests, which are found in saline coastal environments around the tropical and subtropical latitudes, are among the most productive terrestrial ecosystems in the world (Amarasinghe and Balasubramaniam, 1992; Myint et al., 2008). These forests play an important role in providing ecological and societal goods and services to local communities (Wang et al., 2004; Giri and Muhlhausen, 2008), including stabilizing shorelines and helping reduce the devastating impact of natural disasters such as tsunamis and hurricanes (Giri et al., 2007; Zhang et al., 2012), serving as breeding and nursing grounds for many marine and pelagic species (Giri and Muhlhausen, 2008), and providing food, medicine, fuel, and building materials as well as opportunities for aquaculture (Thu and Populus, 2007; Myint et al., 2008). As a consequence, mangrove ecosystems have attracted an increasing amount of attention from land and ocean managers, conservation communities and academia. However, many mangrove communities, especially those in the developing regions, are currently being subjected to disturbances from a variety of sources, including uncontrolled encroachment due to increasing populations in coastal areas, various destructive human activities (e.g., chemical spills) in surrounding catchments, tsunamis and other storms, and climate change (Manson et al., 2003; Giri and Muhlhausen, 2008). Duke

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et al. (2007) recorded that in some regions, due to illegal logging, mangroves have been declining at an alarming rate – perhaps greater than or equal to the declines in adjacent coral reefs or tropical forests. Valiela et al. (2001) and Wilkie and Fortuna (2003) observed that much of what remains from mangrove deforestation stays in degraded condition. Further, Alongi (2008) argued that mangrove stand composition and forest structure results from the complex interplay of physiological tolerances and competitive interactions, leading to a mosaic of interrupted or arrested succession sequences, all of which are strongly impacted by physical/chemical gradients and landform changes. Obviously, the mangroves around the world, especially those in the developing regions, are experiencing an intense spatio-temporal change. Regrettably, our understanding regarding the spatio-temporal dynamics and corresponding underlying drivers of change in most developing countries remains inadequate, in part because the mangrove communities are changing at a rapid rate and because the changes are very much site-specific. These changes are occurring in response to changing development and demographic pressure, which run counter to the development of targeted strategies and practices that promote the sustainable management of the existing mangroves.

China's mangroves naturally occur along the southeast Chinese coastlines and in the provinces of Hainan, Guangdong, Guangxi, Fujian and Taiwan, intermittently extending from 18°N to 27°N (Li and Lee, 1997; Fu et al., 2009). Historically, half of China's mangrove wetlands were distributed in Guangdong province (Wang and Chen, 1998). It is notable that 80% of the mangroves of Guangdong province were located in Zhanjiang city. However, rapid urban sprawl and an increasingly intensified shrimp farming industry triggered by huge demographic and development pressure catalyzed a drastic decline of mangroves, diminishing mangrove spatial extent from 62 000 ha in the 1950's to 15 000 ha in the late 1990's (Wang and Chen, 1998). Mangrove decline continued into the late 20st century. According to the latest inventory of mangrove resources, mainland China had a total of 23 081.5 ha mangroves in 2008, 39.4% (9084 ha) of which existed in Guangdong province, occupying the greatest area share (Fu et al., 2009). Fortunately, with the establishment of mangrove national reserves since 1997 in Guangdong province, continued mangrove afforestation and conservation efforts have expanded mangrove distribution to some extent in certain protected areas. Due to the spatial extent and the biodiversity conservation priority of Guangdong's mangroves, numerous mangrove-oriented studies have been conducted there. These investigations primarily focused on the following aspects: (1) mangrove wetlands protection and management (Chen et al., 2004; Zhang et al., 2010), (2) mangrove community distribution (Li et al., 2002; Tang and Yu, 2007), (3) mangrove wetlands valuing (Han et al., 2000), (4) birds in mangroves (Zou et al., 2008; Wu, 2009) and (5) vegetation rehabilitation of mangroves (Zheng et al., 1997, 2003). Furthermore, the analyses focused on mangrove protection and management. Development and planning were mainly based on qualitative and descriptive methods, and there was a lack of spatially explicit information on mangrove distribution and change. Few investigations conducted in Guangdong province were focused on the spatio-temporal changes in mangrove distributions, and no studies assessed mangrove fragmentation patterns. Thus, the rates, causes, and consequences of mangrove changes have not been adequately documented. Such information would support the strategic development of sustainable mangrove management at diverse scales, and would be invaluable for assessing the effectiveness of the existing mangrove management approaches. Hence, mapping and monitoring mangrove dynamics in an accurate, reliable and efficient fashion and providing spatially explicit information on mangrove fragmentation are important to different levels of governments and conservation communities for effective formulations of strategies and plans on mangrove management.

The major objectives of this work were: (1) to derive land use time series data sets from multi-temporal Landsat observations for Gaoqiao and Yingzai mangrove areas, which are the two prototypes of Zhanjiang National Mangrove Forest Nature Reserve, (2) to characterize changes in mangrove distribution and fragmentation patterns, and to (3) link the observed fragmentation trends to the local biodiversity dynamics to provide insights, implications and countermeasures of mangrove sustainable management.

2. Data and study area

Zhanjiang National Mangrove Forests Nature Reserve, due to the dominance of mangroves in the area and its extremely high biodiversity significance, was chosen as our study site in the current work. This reserve is the largest national-level natural reserve for mangrove protection in mainland China. The reserve was originally established in 1991, and it was approved for elevation in rank to a national reserve by the State Council of China in 1997, in part because of its importance for biodiversity conservation. The reserve has a notably rich flora and fauna, and includes 28 mangrove species, 139 fish species, 130 conch species, 133 insect species and 192 bird species. Of these, 25 species have been listed in national-level conservation directories, 34 species are listed in the key conservation lists of Guangdong province, and 82 species are listed in diverse international agreements directories (Integrated Mangrove Management and Coastal Protection Program Office, 2006). Particularly, the Zhanjiang mangrove national natural reserve was declared as a Ramsar site in January 2002, qualifying it as one of thirty "Wetlands of International Importance" in China. In recent years, mangrove coastlines have also become an attractive hotspot for eco-tourism and environmental education programs.

Zhanjiang city covers a land area of 12 471 km^2, supporting a total population of around 7.0 million. The city is located at the southernmost tip of Mainland China on Leizhou Peninsula in the northern tropical zone spanning from 109°40′E, 20°15′N to 110°55′E, 21°55′N. The annual average temperature is about 23°and the coldest monthly average temperature of 17.2°occurs in January. The area receives abundant precipitation, with an average annual precipitation of about 1500 mm. The average tidal range is about 2.53 m, and the annual average temperature of the surface sea water is about 23.7°, with a salinity ranging from 29.7‰ to 32.0‰. The two prototype mangrove sites, Gaoqiao and Yingzai in Lianjiang city (Fig. 1), were identified as our research targets in the current analysis mainly because both areas are dominated by mangrove forests and have high levels of biodiversity.

Satellite imagery used in the work included five cloud-free Landsat scenes: (1) MultiSpectral Scanner (MSS) scene, acquired on February 2, 1977, with a spatial resolution of 80 m; (2) Thematic Mapper (TM) scene, dated on October 30, 1991, with a resolution of 28.5 m; (3) Enhanced Thematic Mapper Plus (ETM+) scene, dated on October 30, 2000, 28.5 m resolution; (4) TM scene dated on November 21, 2005, 30 m resolution and (5) TM scene, acquired on August 30, 2010, 30 m resolution. These scenes were downloaded from the Global Land Cover Facility (http://glcf.umiacs.umd.edu/index.shtml) at the University of Maryland or the USGS EROS Data Center (http://glovis.usgs.gov/). Additionally, a field visit was conducted from December 1 through 4, 2010 to (1) identify land use types and mangrove disturbances in the two prototype areas, and (2) to collect the administrative histories of the reserve and biodiversity change information through interviewing and recording aged people living near the reserve and local experts of the reserve. The 2001 mangrove thematic inventory data of Guangdong province, and the mangrove afforestation statistics

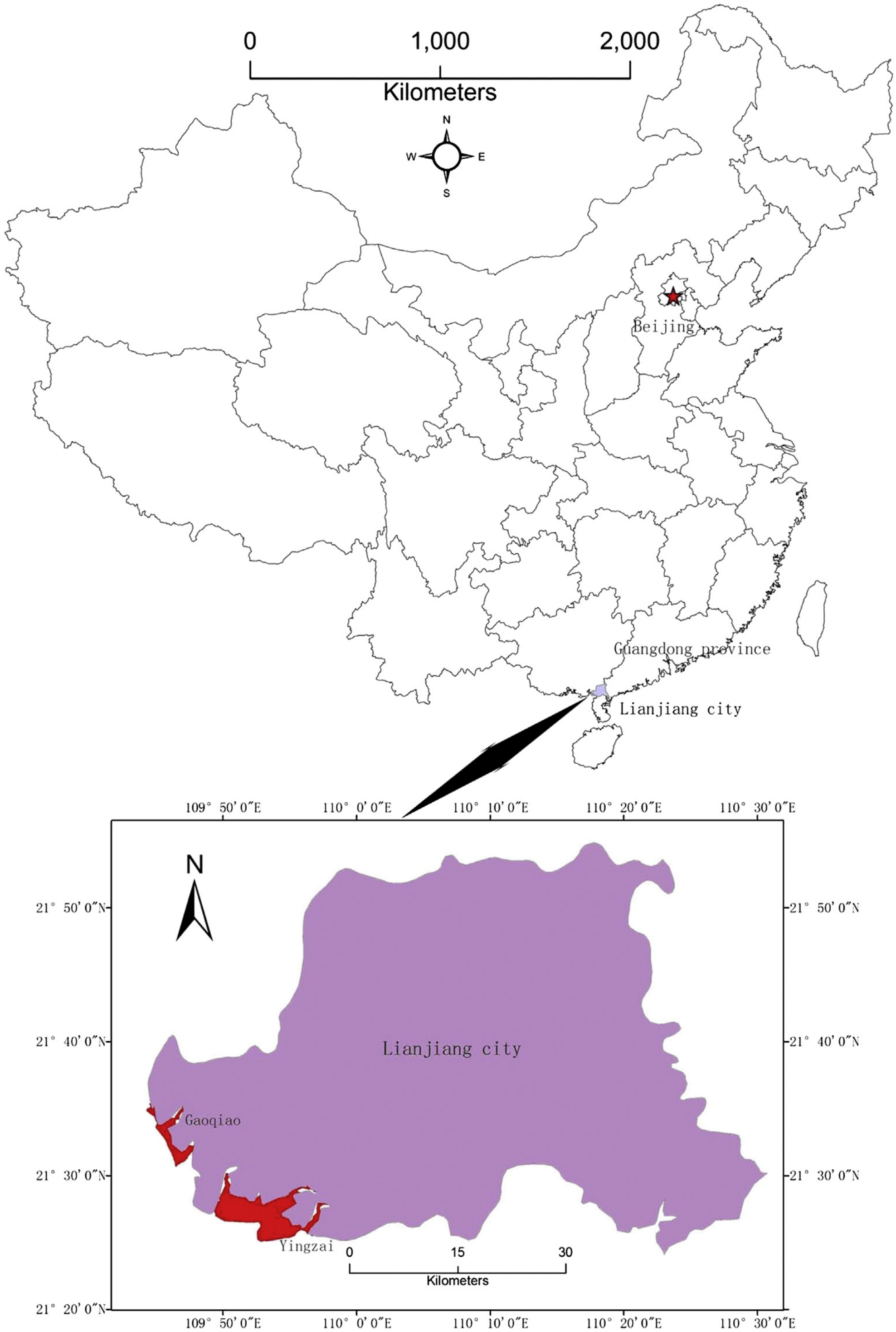

Fig. 1. Locations of the study sites. The red areas show our prototype study sites, Gaoqiao and Yingzai. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were collected from the Guangdong Provincial Center for Forest Resources Monitoring. Socio-economic data and publications related to mangrove management were also obtained from the Zhanjiang Mangrove Management and Protection Bureau. Vectorized land use data sets for 1980's, 1995, 2000 and 2005 covering the study areas, developed by the Chinese Academy of Sciences (CAS) were also collected to support the analysis. True color air photographs taken on July 13, 2000 and August 7, 2009, originally acquired for local land use surveys, were also obtained from the local surveying and mapping agency to validate the classifications of this analysis.

3. Methods

3.1. Image preprocessing

Before classification, exoatmospheric reflectance images (top of atmosphere reflectance) for the five scenes were generated. This was done by radiometrically calibrating the images using the latest published post-launch gain and offset constants to eliminate the errors caused by changes in sensor performance and characteristics over time (Chander et al., 2009). Due to the deficiency in real-time and complete profiles of atmosphere at the five time points, atmospheric corrections of the exoatmospheric reflectance images were not implemented here. After that, the five scenes were geometrically corrected and resampled to a pixel size of 28.5 m using a 2-order polynomial equation built upon a total of 13 ground control points identified from the local topographic map, with a scale of 1 versus 10 000, with RMS less than 0.5 pixels. The local 3° zonation Gauss-Kruger projection was specified during the geometrical correction process.

3.2. Image classification

After extensive consultation with the local natural resource management experts and the established land use data, five land use and land cover types for the study sites were determined: (1) mangrove, (2) intertidal zone or sandy area, (3) water, (4) aquafarm for shrimp and crab growing and (5) non-such (cropland, buildings and roads). To derive actual land use maps, the unsupervised Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA) was implemented to create 30 spectral clusters. This was followed by the conversion from the spectral classes to the actual land cover and land use classes by on-screen checking and labeling in accordance with the objects' locations, textures, tones or colors, as well as the existing reference data (e.g., the thematic surveys of mangrove and the land use data) and the inputs of the local experts. Post-classifications or further improvements to the classifications were also made by eliminating apparent gross errors through hand editing.

3.3. Assessing the accuracies of classification

Once image classifications were done, with the aid of the local experts for natural resources management, visual interpretation of the air photos taken in 2000 and 2009 was implemented to produce the reference data, which were used to validate the classification accuracies of the Landsat images. The four-point historical land use data collected from the CAS were not used to assess the accuracies because of their relative coarse resolutions (1–0.1 million), and the 2001 thematic mangrove surveys were also excluded from the validation processes due to their over-estimation of the mangrove coverage. The overall accuracies for the five identified land use classes and the spatial agreement for the mangrove class were calculated respectively to assess the classifications.

3.4. Modeling mangrove landscape fragmentation

Prior to modeling mangrove landscape fragmentation, the original land cover and land use types were aggregated to focus on the patterns of forest (mangrove) versus non-forest (aquafarm and non-such) and missing values (intertidal zone plus water), to facilitate subsequent fragmentation modeling analysis. The missing value class was not allowed to fragment the mangroves in the current analysis. Based on the sliding window analysis technique, the forest fragmentation model outlined in Wade et al. (2003) was used to develop spatially explicit maps depicting six forest fragmentation components (interior, perforated, edge, patch, transitional and undetermined) at the analytical scale of 3 by 3 pixels. This model has been proven to be an effective alternative in characterizing forest fragmentation at diverse scales (Riitters et al., 2000, 2002; Wade et al., 2003). To run the model, two indices, P_f and P_{ff}, were derived beforehand, where P_f is the proportion of nonmissing pixels within the moving window with a specified size that are forest, and P_{ff} is the ratio of the number of pixel pairs in cardinal directions that are both forest divided by the number of pixel pairs in cardinal directions where either one or both are forested. Roughly, P_{ff} measures the conditional probability that a pixel adjacent to a forest pixel is also forest. Once the P_f and P_{ff} were available, each subject forest pixel centered within the moving window was classified into one of the six forest fragmentation categories described previously by applying the discriminant rules outlined by Riitters et al. (2000).

3.5. Bird surveys

Mangrove fragmentation conditions were linked with changes in biodiversity of the reserve using routinely collected bird population survey data (Integrated Mangrove Management and Coastal Protection Program Office, 2006; Wu, 2009). During the period 2002 to 2003, sampling was implemented during three periods spanning three seasons: winter (December 23, 2002 to January 13, 2003), spring (March 3, 2003 to March 22, 2003) and summer (June 23, 2003 to July 10, 2003) to test the hypothesis that bird species richness and abundance were equal over seasons. After 2005, bird surveys were carried out mainly in spring. The number of sampling sessions was proportional to the area of mangrove, intertidal zone and aquafarm at each site. A combination of point counts and transect counts were made for the intertidal zone, and 17 transects were set up in the mangroves (Zou et al., 2008; Wu, 2009). Point count samplers documented all birds seen and heard within a 150-m radius of designated center points during 10-min sampling periods. Transect counts were 50-m wide and 1000-m long. Average sample time for each transect was about 120 min. Bird species and numbers seen or heard were recorded for all transects using methods described by Zou et al. (2001). The time of day for sampling was selected based on tidal levels. Birds on intertidal zones were sampled during low tides when the zones were exposed and birds could access them. Birds in mangrove were sampled during high tides when birds could not access intertidal zones. Binoculars (10×) and spotting scopes (30× and 60×) were used for detecting and identifying birds (Zou et al., 2008).

4. Results

4.1. Accuracy assessment

After interpreting the 2000 and 2009 air photos, the classifications derived from the Landsat scenes were evaluated. The overall accuracies of the 2000 and 2010 classification results were estimated at 92.3% and 89.7% respectively. The spatial agreement of mangroves was identified at 91.1% for 2000 and 90.3% for 2010. It needs to be noted that the air photos used were acquired for local land use surveys and not exclusively for mangrove mapping. These were acquired at 11:23 AM, July 13, 2000 and at 11:47 AM, August 7, 2009. Similar to the Landsat observations, the air photos were collected when the local tides were relatively high. This helps explain why there was a relatively high spatial agreement of mangroves derived from between the air photos and the Landsat scenes. Due to the unavailability of the reference data, we were unable to quantitatively evaluate the classifications for 1977, 1991 and 2005.

4.2. Changes in mangroves and aquafarm areas

Fig. 2 shows the land use time series maps for Gaoqiao (left) and Yingzai (right). Associated area statistics derived from Fig. 2 are summarized in Fig. 3. Mangroves in both Gaoqiao and Yingzai

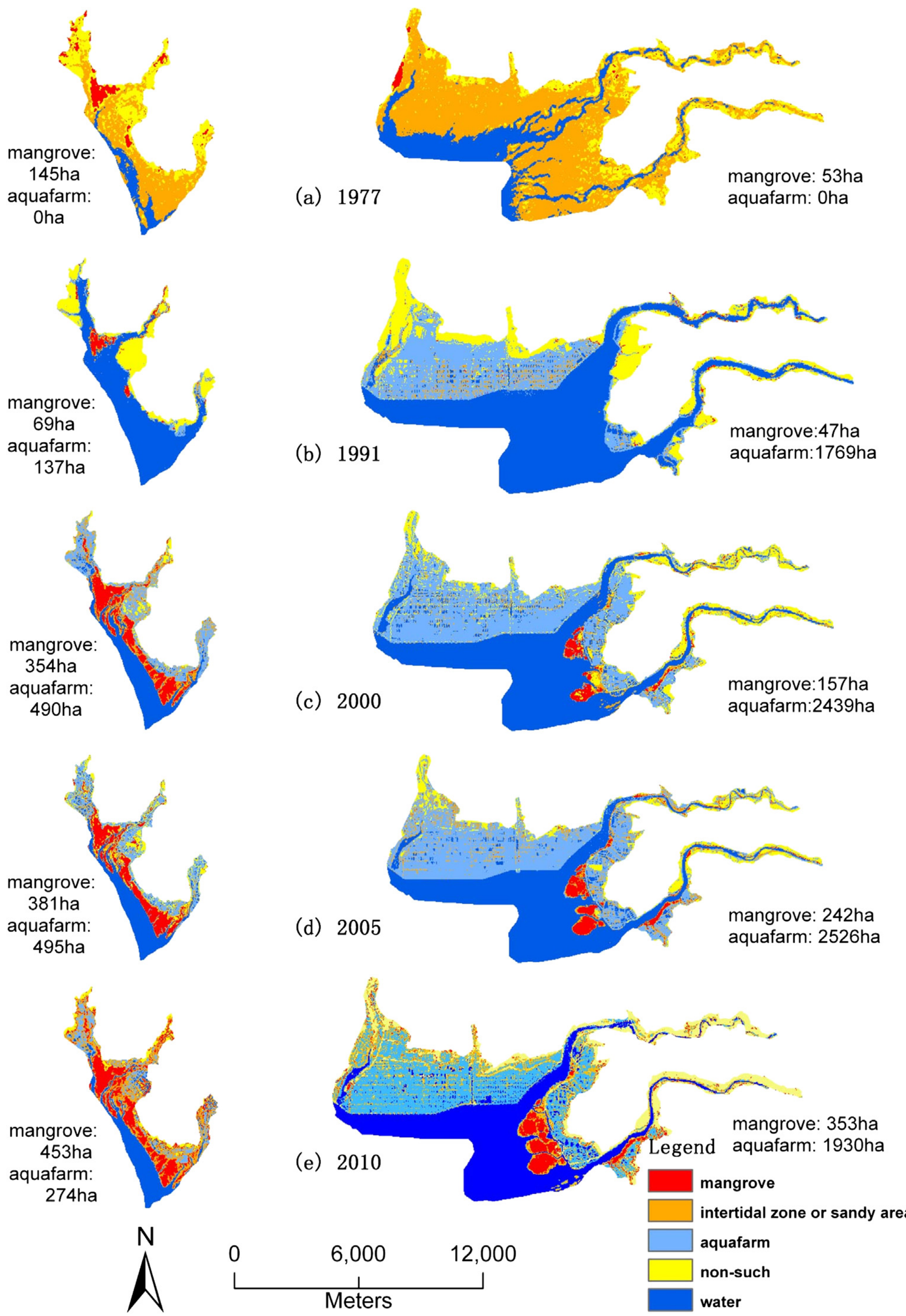

Fig. 2. Changes in land uses during the period 1977 to 2010 over Gaoqiao (Left) and Yingzai (Right) sites, derived from classifying multi-temporal Landsat scenes.

showed a similar trend characterized by a sharp decrease during the period 1977–1991 giving way to an increase during the period 1991 to 2010 (Fig. 3). Specifically, mangrove estimates for Gaoqiao and Yingzai were 145 ha and 53 ha in 1977, 69 ha and 42 ha in 1991, 354 ha and 157 ha in 2000, 381 ha and 242 ha in 2005, and 453 ha and 353 ha in 2010, respectively. Aquaculture areas in the two sites increased during the period 1977 to 2005, then decreased (Fig. 3). In detail, aquaculture areas were extremely scarce at both sites in 1977 (Figs. 2 and 3). However, in 1991, 137 ha and 1769 ha of aquafarms were mapped in Gaoquio and Yingzai, respectively. In 2000, aquaculture increased to 490 ha in Gaoqiao and 2439 ha in Yingzai, then continuously increased to 495 ha and 2526 ha, respectively, in 2005. During the period 2005 to 2010, Gaoqiao's aquaculture dropped to 274 ha and Yingzai's aquaculture decreased to 1930 ha (Fig. 3). Additionally, examination of Fig. 2 reveals that a large-scale sandy area over Gaoqiao in 1977 was changed into water in 1991. Similarly, in Yinzai, sandy area was converted to water and aquafarms during the period 1977–1991. After 1991, there was a clear trend of mangroves expanding into water at both Gaoqiao and Yingzai sites.

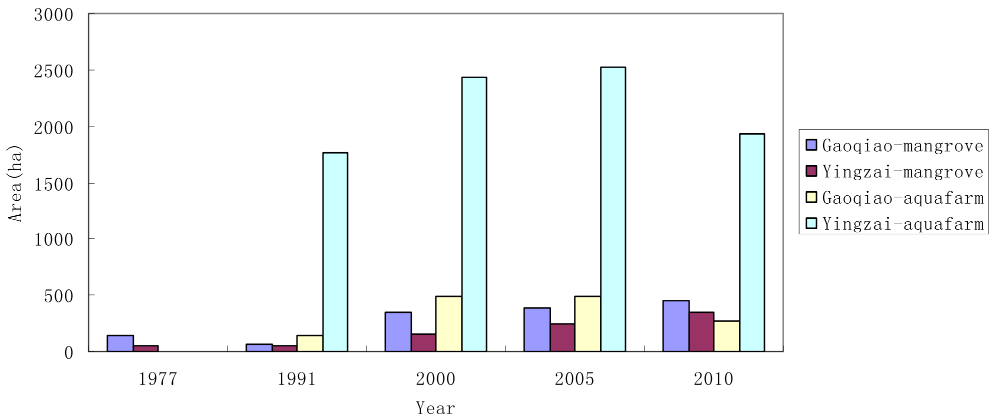

Fig. 3. Areal changes in mangroves and aquaculture areas over Gaoqiao and Yingzai sites.

4.3. Mangrove fragmentation patterns characterized by the fragmentation model

After running the fragmentation model at the analytical window size of 3 by 3 pixels, mangrove fragmentation maps were generated (Fig. 4) and associated statistics were summarized (Fig. 5) to highlight the trends of mangrove fragmentation. At this analytical scale, interior and perforated components were absolutely predominant over the other four fragmentation conditions at the five time points. Apparently, acceleration in fragmentation of mangroves occurred during the period 1977–1991, followed by a gradual deceleration in fragmentation during the period 1991–2010 (Fig. 5). This pattern was evidenced by a fact that interior mangrove forests of the two sites dropped sharply during the period 1977–1991, giving way to a gradual increase during the period 1991–2010. A continued but slight increase of the perforated component in Gaoqiao was observed during the whole period 1977–2010. However, in Yingzai, the perforated component fluctuated over time (Fig. 5). Compared to the widely used geospatial metrics, such as, the patch size and the fractal dimensions, the fragmentation maps provide more insights and implications to mangrove management and biodiversity conservation practice due to their spatially explicit information on fragmentation.

5. Discussion

5.1. Satellite-based mangrove mapping affected by the local tidal rhythms

Mangrove forests are highly productive ecosystems that typically dominate the intertidal zone of tropical and subtropical coastlines (Kathiresan and Bingham, 2001). Thus, mangrove distribution is undoubtedly dependent upon the local tidal rhythms and varies with the changes of tidal inundation. The tidal rhythms or periods over a particular place are fully determined by the lunar calendar (lunar gravity), which means that different dates in the lunar calendar will have different times for high versus low tides. Meanwhile, the Landsat satellites pass over particular locations and acquire data during extremely short time intervals, and depending on the day may acquire coastal data at high tide, low tide, or somewhere in between. Thus, mangrove distributions mapped by satellite remote sensing will be highly affected by the local tidal levels. The 2001 mangrove resource thematic inventory conducted in Guangdong province revealed that a total of 700.9 ha mangroves existed in Gaoqiao and 388.1 ha in Yingzai. However, our estimates derived from ETM+ imagery dated on October 30, 2000 were at 381 ha in Gaoqiao and 157 ha in Yingzai, respectively. Obviously, there is a big discrepancy between the two sets of statistics. The most probable reasons responsible for the gaps are three-fold. First, differences in tidal levels of the two surveys likely impacted results. The thematic survey of mangrove resources was conducted by onsite human delineation when the tide was low. Our remotely sensed observations were acquired at about 9:50 AM, October 30, 2000. According to the records from the local oceanic observatory station, on October 30, 2000, high tide occurred at 7:00 AM, with a tidal height of 5.15 m and the low tide of 0.4 m occurred at 5:00 PM. The actual tidal height for the time when the satellite acquired data was about 3.73 m. Thus, a number of mangroves, especially the stands consisting of young mangrove seedlings, were undoubtedly flooded. This would have led to the mangrove area mapped by satellite imagery being far less than that collected from the field surveys. Actually, Alongi (2008), Giri et al. (2007) and Liu et al. (2008) have all noted the effects of tidal inundation on the satellite-based mangrove area estimates. Based on the available tidal information, Liu et al. (2008) ignored the minor differences of triple-temporal tides and argued that the triple-temporal mangrove classifications based on Landsat observations were roughly comparable. Due to the unavailability of the local tidal information, Giri et al. (2007, 2008) were unable to further explore the effects of tidal inundation on satellite-based mangrove mapping. These existing studies and our current work collectively face a challenge that is how to minimize the impacts of different tidal levels upon the visibility of mangroves, or how to make the mapping results comparable when using multi-temporal remotely sensed observations, and the challenge also necessitates seeking substitutes, for example, the aerial photography. A second reason for the discrepancies between our results and survey statistics likely relates to the differences in the years when measurements were made. The ground data from the thematic survey did not correspond with the date of satellite data classified, and there was a time lag of about one year between when the maps were made. It is likely that some mangrove afforestation occurred over the time period between when our satellite data were acquired and when the survey was conducted. A third reason for discrepancies likely involved differences in measurement scales. The thematic survey was implemented from extensive field visits. Field manual delineations of mangrove patches usually overestimates mangrove area due to errors of human vision obstacles (e.g. obstructed sight) and deficiency in reference objects throughout the flat intertidal zones. For example, human delineation of the mangroves often includes mangroves and their adjacent water bodies and sandy areas, which leads to an overestimation. This was likely the case, and Giri et al. (2007) also made the same observation when monitoring mangrove dynamics of the Sundarbans in Bangladesh

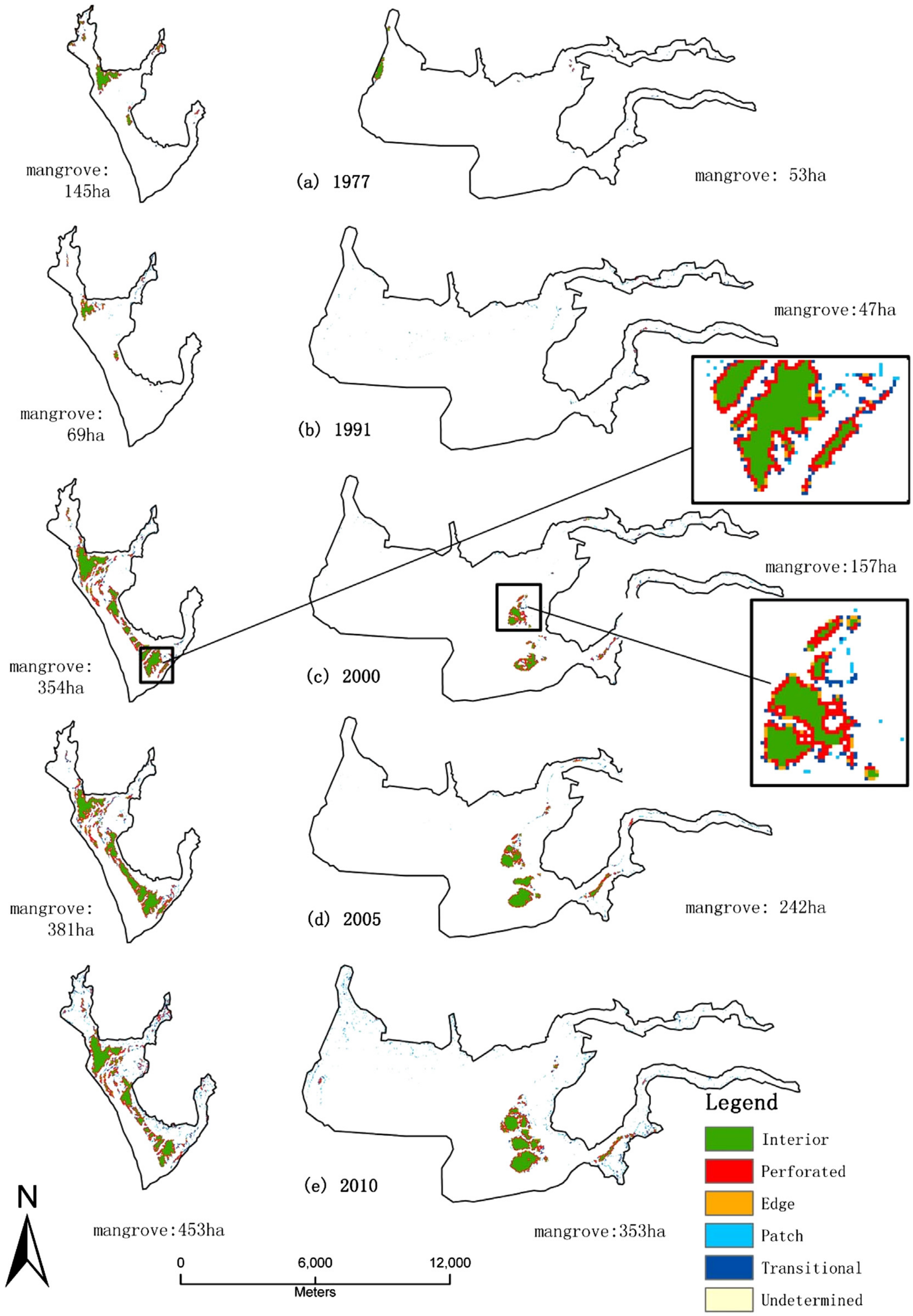

Fig. 4. Spatio-temporal dynamics of mangrove fragmentation, derived from implementing the fragmentation model at the analytical scale of 3 by 3 pixels.

and India. It should also be noted that our satellite-based derivations resulted from interpreting 30-m resolution spectral images. Undoubtedly, existence of mixed pixels led to some areal errors, especially in areas that had diverse land use types. For example, the thematic field survey certainly included newly-established mangrove seedling patches in their maps. However, the Landsat TM sensor was spectrally unable to discriminate these areas adequately due to their relative low crown closure in the dominant context of water.

Mapping mangroves is still a challenging task due to a variety of reasons, such as low accessibility of the intertidal zones, and changing tidal levels. It is relatively rare that we have access to

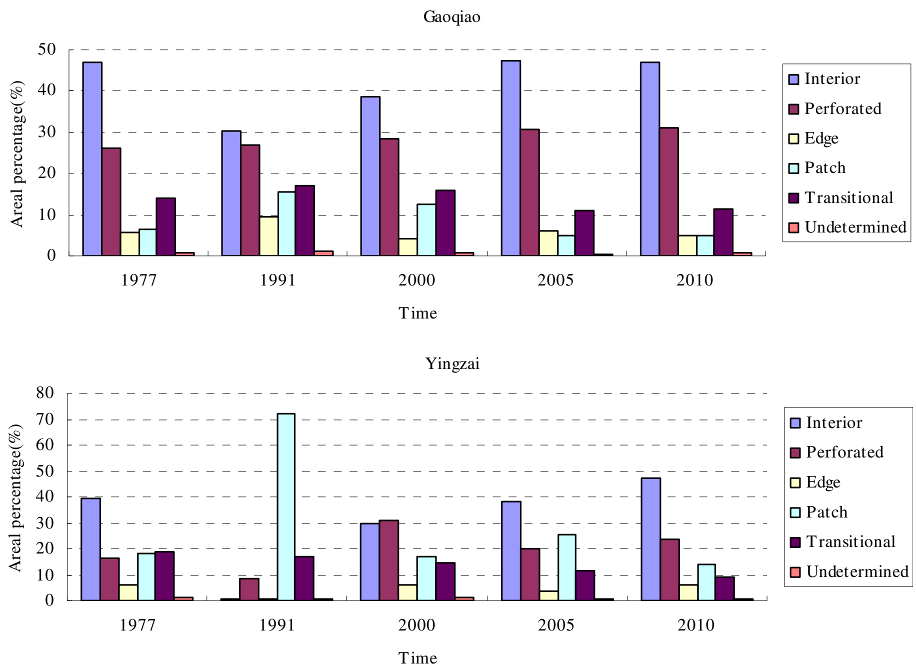

Fig. 5. Comparative patterns of the six mangrove fragmentation components, during the period 1977 to 2010.

satellite remotely sensed data acquired at the absolute lowest tides when mangrove mapping is optimal. Meanwhile, clouds and atmospheric properties can diminish the potential number of optimal scenes to analyze. Thus, satellite-based approaches tend to underestimate mangrove distribution. Aerial photography can effectively adapt to the local tidal cycles by selectively targeting acquisitions of data at times of low tide. In addition, it is generally easier to work around clouds and atmospheric problems with aerial photograph acquisitions. Meanwhile, the problems typically encountered with field surveys (e.g. human site obstructions) can be minimized through air photo analysis. Hence, to accurately map or monitor mangrove dynamics in a particular place, aerial photography can be an efficient and flexible alternative.

5.2. Biodiversity and environmental implications of mangrove fragmentation

The amount of mangroves present generally determines the mangroves located in either interior or edge. The relative ratio of interior over edge provides a measure of mangrove ecosystem health. Different mangrove conditions have significant impacts on the distributions of mangrove-dependent organisms, such as birds. For example, Wu (2009) argued that the intact interior mangrove areas were quite suitable for birds because they should afford better protection against capture than small forest patches. Although fragmentation components or categories can serve as spatial indicators for assessing whether critical components or functions of mangroves are being maintained, mangrove edges and perforations have less value where the amount of forest is low (Soledad and Santiago, 2005). This is especially true because isolation can easily occur when the mangrove landscape is highly fragmented, affecting biological exchanges throughout the mangroves. Particularly, some ground-nesting birds will be significantly affected by the distance between mangrove patches (Uezu et al., 2005). The increasing isolation of mangrove patches may also have substantial impacts on some threatened species by reducing the genetic flow between subpopulations. Sometimes, investigators have suggested that we place more attention on the perforated condition rather than "patch", because the places most likely to exhibit qualitative future changes will not be in the region of existing patches, but in the surrounding halo of perforated forest (Riitters et al., 2000). The existing fragmented areas, for instance, the "edge" and perforated mangroves mapped by the model, will be more easily further degraded and fragmented due to erosion, siltation, sedimentation and anthropogenic disturbances due to their high accessibility. Thus, it is emphasized that conservation and oceanic management strategies should always consider the quality of the whole mangrove landscape and especially the number of different mangrove habitats and their spatial arrangement (Steiner and Köhler, 2003).

The fragmentation model used in this study enabled generation of a suite of spatially explicit fragmentation maps that are effective for assessing mangrove restoration potential. These maps can help to spatially convey decision-makers' recommendations on conservation strategies. For instance, this information can be used to plan the expansion of the interior condition and to fill in the perforated regions, or to reduce vulnerability by better managing the places near the critical thresholds set by the percolation theory. Human-controlled activities, including identifying the proper sites and approaches of mangrove logging, regeneration, afforestation, as well as chemical spill controlling activities, are the typical measures that can be assessed from adequately utilizing the spatial fragmentation pattern information provided by the model. Through providing the spatial fragmentation information from the model, the findings in the current analysis will be helpful for mangrove landscape management by guiding the scientific development of utilization and conservation strategies.

Located in one of the East Siberian-Australasian flyways, attracting a variety of migrating birds and resident birds to rest, forage and breed, Zhanjiang National Mangrove Forest Natural Reserve is referred to as "the heaven of birds" and plays an extremely important role in biodiversity conservation, particularly bird biodiversity (Liu and Li, 2001; Liu, 2007; Zou et al., 2008; Wu, 2009). Currently, monitoring the dynamics of bird populations, especially the waterfowl, has been routine at the reserve. Changes in bird species and population numbers may be an effective measure of mangrove quantity, quality and fragmentation conditions and are of local economic interest. For example, the price of the teal (*Anas crecca*), a mangrove-dependent local waterfoul species, went up to 200 Yuan RMB (1 US Dollar equals to 6.3 Yuan RMB currently) driven by the Cantonese desire to eat the teal. Thus, the illegal capture and selling of the teal frequently occurred, leading to a sharp decline of the teal population of the mangrove reserve. Interestingly, staff at the reserve witnessed that the teal started to gather in the core portions of the mangrove reserve to avoid from capture in recent years. Thus, increase in mangrove coverage or reduction in mangrove fragmentation will provide the teal better protection. Another fully opposite case involves the fiddler crabs (*Uca arcuata*). Due to its low edibility and the over-feeding when growing in association with the shrimp and crabs being aqua-farmed it population showed a marked increase during the past ten years. The fiddler crabs prefer the edge and perforated components of the mangroves to obtain more sunshine, wind and movement opportunities (Integrated Mangrove Management and Coastal Protection Program Office, 2006).

Due to diverse beach development programs, especially the construction of shrimp and crab farms, mangrove forests have shrunk gradually, leading to a sharp decline in livable mangrove habitats during the period 1977 to 1991 (Figs. 2 and 3). Thampanya et al. (2006) also observed the same phenomenon in Thailand and concluded that mangrove loss was higher in the presence of shrimp farms and in areas where mangrove forests used to be extensive in the past. Additionally, owing to a long-term unlawful discharge of the industrial wastewater and domestic sewage, and an over-use of fish bait, eutrophication of the coastal water has intensified. This has posed a serious threat to mangrove habitats and has contributed to a disappearance of swans (*Cygnus* spp.) over the past fifteen years and an acute reduction of raptors such as the kestrel (*Falco tinnunculus*), and black-winged kite (*Elanus caeruleus*). Since 2005, waterfowl species and numbers within the reserve have increased gradually in response to gradual improvement of the mangrove fragmentation and degradation conditions observed. Specifically, Chinese pond-heron (*Ardeola bacchus*), great egret (*Ardea alba*) and black-collared starling (*Sternus nigricollis*) populations have increased by 10–20%, and spot-necked dove (*Streptopelia chinensis*) has increased by about 30%. The observed increase is principally attributed to the expansion of mangroves and the observed reduction of mangrove fragmentation, and the reinforcement of the environmental protection awareness of local dwellers, catalyzed by diverse programs for mangrove reforestation and conservation and educational programs executed. A bird survey for Gaoqiao (one of the mangrove study sites) summarized in Table 1 suggests that mangrove conservation practice at this site has significantly improved the quality of mangrove habitats and attracted greater numbers birds to reproduce (Zou et al., 2008; Wu, 2009). It is clear that since 2005, the number of bird species and the total numbers of birds have gradually increased and the individual populations have expanded over time. Particularly, the first appearance of the world's endangered species, black-faced spoonbill (*Platalea minor)*, in April 2006 at the Gaoqiao site, is highly notable. This bird species was found again in January 2008. Emergence of this particular endangered bird species twice significantly improved the international status of the reserve and further promoted the protection efforts of birds. Wu (2009) conducted a systematic survey on waterfowl throughout the mangrove forests of Zhanjiang and also found a similar trend in bird numbers as we have presented here. Specifically, the number of waterfowl for 2005, 2006, 2008 and 2009 observed were 1272, 2173, 2377 and 3338 respectively, and the number of waterfowl species was recorded at 24, 28, 20 and 31 accordingly. Clearly, these findings are fully consistent with our observations in Gaoqiao. The above-mentioned observations on biodiversity (mainly birds) help demonstrate the significance of expanding the interior component of mangroves. Healthy mangrove forests provide adequate breeding and nursing grounds, food and shelter for birds. Therefore, expanding the distribution of mangroves, mitigating the fragmentation of mangroves via afforestation, conservation and education programs are important for biodiversity conservation in Zhanjiang mangrove reserve.

5.3. Uncertainties

Classifications of satellite imagery into land cover and land use types always have a certain degree of error and uncertainty associated with them. Analyses of mangroves change and fragmentation patterns of the present study are undoubtedly affected by errors in the classifications. Obviously, commission errors and omission errors, commonly found in the image classifications, will cause some level of inaccuracy of the mangrove area statistics and distributions. Particularly, the 1977 land use maps were derived from the MSS images with a spatial resolution of 80 m and four spectral bands. Classifying the MSS images likely resulted in a "lower quality" classification product as compared with those derived from the TM/ETM+ scenes, which have seven spectral bands with a 30-m resolution. We need to recognize the difficulties in obtaining consistent satellite data for a long-term time series investigations. In the current work, we had a time span of about 33 years (1977–2010) and the TM/ETM+ images did not cover the entire time interval. Thus, we had to use the lower-quality MSS images to help fill in the time span in order to better detect the trends of mangrove coverage change. Nonetheless, it should be noted that there were not many mangroves in the 1970's in this area to classify, and we believe that our MSS classification adequately captured the distribution patterns of the mangrove forests that existed in the area for the purposes of the investigation.

The fragmentation model used in the analysis is based on the P_{ff} value (connectivity) and the P_f (forest area density). The outcomes (fragmentation maps) derived from the model will be highly related to the connectivity of pixels, which is closely dependent upon the accuracy of the classifications. Furthermore, the fragmentation model is scale-dependent and threshold-dependent (Riitters et al., 2000), which implies that a proper analytical scale and threshold should be cautiously specified after an intensive assessment of the properties of the specific study case coupled with the percolation theory. In addition, the current analysis was unable to separate the younger mangrove stands from the mature stands, and the dense

Table 1
Changes in bird species and population sizes at Gaoqiao site, which were adapted from Wu (2009) coupled with the daily records of the reserve.

Year	Number of bird species	Number of birds	Population 1	Population 2	Population 3
2005	7	169			
2008	9	231			
2009	17	475	Little Egret (*Egretta rzetta*) 208	Ringed Plover (*Charadrius.dubius*) 59	
2010	19	675	Little Egret (Egretta garzetta) 273	Black-headed Gull (*Larus ridibundus*) 102	Green-winged Teal (*Anas crecca*) 59

mangrove stands from the sparse stands. Thus there is some uncertainty regarding the ecological implications for species dependent up high-quality habitats situated in the interior regions of mangrove patches. In the near future, we should address all above-mentioned concerns by pursuing more accurate support datasets.

6. Conclusions

This work has successfully characterized the spatio-temporal changes in mangrove distribution and fragmentation patterns through interpreting multi-temporal Landsat observations and implementing a fragmentation model in the Zhanjiang National Mangrove Forests Natural Reserve. The socio-economic drivers responsible for the observed changes were also examined. Particularly, the linkages between mangrove fragmentation and biodiversity conservation (mainly birds) were highlighted to emphasize the significance of expanding the distribution of mangroves, mitigating the fragmentation of mangroves via afforestation, and conservation and education programs. We believe that the derived fragmentation patterns and trends will help develop strategic plans on sustainable management important to mangrove and biodiversity conservation.

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