Can the Dongzhaigang Mangrove in China Adapt to Sea Level Rise in the Future?

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Abstract

Considering climate change, coastal mangroves are facing serious threats from rising sea levels. However, whether the largest contiguous Dongzhaigang mangrove in China can adapt to future sea level rise, which is very critical for mangrove restoration and management, has been little known. Using the data of historical monitor since the 1950s, supplementary field research of mangrove wetland sediment rates measured, satellite remote sensing, digital elevation model, global climate models, and ArcGIS, we investigated the Dongzhaigang mangrove area changes, related causes, and the impacts of future sea level rise under greenhouse gas emission scenarios, as representative concentration pathways (RCPs) 2.6, 4.5, and 8.5. The study revealed that: (1) during 1956–1987, total mangrove area had decreased by ~ 50%, from ~ 3417 hm^2 to ~ 1710 hm^2. This was mainly because of the impacts of human activities, such as fish pond reclamation and the use of former mangrove land for economic tree planting. After the 1990s, the total mangrove area was maintained at ~ 1711 hm^2, mainly because of the establishment of the nature reserve in 1986, along with protective and restorative measures; (2) under the intermediate and high RCP 4.5 and 8.5, sea level increases are likely to cause > 25% of the mangroves to disappear by 2100, whereas for the low RCP 2.6, only 17% of the mangroves are likely to be affected; and (3) taking measures such as reestablishing ponds as mangrove forests, plant restoration, and biological shore protection could improve the adaptation of mangroves to the impacts of rising sea levels.

1. Introduction

Mangroves are woody biomes distributed in tropical and subtropical coastal areas, growing in wetlands between the mean tide level (mean sea level) and mean high water springs. The mangrove ecosystem is one of the most productive ecosystems in the coastal zone, with important functions including wind and wave resistance, coastal protection, and carbon storage. The mangrove ecosystem also plays an important role in the adaptation to and mitigation of climate change in coastal areas. However, as mangroves can only survive in intertidal mudflats where the waves are relatively weak, currents are slow, sedimentation is obvious, and tidal range is relatively low, they are vulnerable to sea level changes and extreme events such as strong typhoons and droughts. In recent decades, coastal habitats including mangrove wetlands have been severely threatened by the rapid rise in sea level and strong typhoons as global warming has intensified (Alongi 2007, 2015; Bindoff et al. 2019; Cai et al. 2016; Cai et al. 2020; Dahdouh-Guebas et al. 2005; Gilman et al. 2007; Kathiresan and Rajendran 2005; Li et al. 2020; Long et al. 2016; Accessed et al. 2019; Villamayor et al. 2016). A previous study revealed that if the rate of global sea level rise reaches 6.1 mm $year^{-1}$ in the next 30 years, mangroves will very likely struggle to adapt and survive (Saintilan et al. 2020). Studies have shown that mangrove wetlands can adapt to sea-level rise by sediment accretion. However, this is only possible if the vertical accretion rate of the mangrove wetland sediment is greater than or equal to the relative rise in local sea level to address the current threat of rising tides (Alongi 2007; Tan and Zhang 1997). Under the high greenhouse gas (GHG) emissions scenario, representative concentration pathway (RCP) 8.5, only localized sedimentation accretion effects in mangrove wetlands could keep pace with rising sea levels by 2055 and 2070 (Sasmito et al. 2016). For example, in the Caribbean mangrove margin, mangrove growth rates can be equal to the rate of sea level rise. However, if this rate exceeds 5 mm $year^{-1}$, the mangrove islands in the Caribbean are unlikely to persist (McKee et al. 2007). In the Indo-Pacific tropics, the current rate of sea level rise exceeds the vertical accretion rate of the mangrove wetland surface at 69% of all sites studied. In areas with low tidal ranges and low sediment supplies, mangroves may be inundated as early as 2070 (Lovelock et al. 2015). In other words, the ability of mangroves to adapt to rising sea levels in the context of global warming is closely related to the relative rate of local sea level rise, as well as the sedimentation accretion of mangrove wetlands and other factors.

In China, mangroves are mainly distributed in the tropical and subtropical coastal areas of Hainan, Guangxi, Guangdong, Fujian, and Taiwan provinces, with an area of approximately 21148–24801 hm^2 (Zhao and Qin 2020a) (Fig. 1a). Among them, the largest contiguous mangrove area and richest mangrove species are located in the Dongzhaigang National Nature Reserve of Haikou City, with a small amount distributed in Wenchang City, Hainan Province (hereinafter referred to as Dongzhaigang mangrove). This contiguous area is the earliest established national mangrove wetland reserve in China, with a total of 19 families and 35 species of mangrove plants, accounting for 97% of the mangrove species in China (Hainan Dongzhaigang National Nature Reserve Authority 2015). Possessing gentle terrain and a winding and curved coastline, Dongzhaigang is a drowning valley bay formed by subsidence from the 1605 Qiongzhou Earthquake (Fu 1995; Zhang et al. 1996), which is mainly located in Haikou City, with a small part located in Wenchang City, Hainan Province, respectively. Prior to 1960, the Dongzhaigang mangrove was mainly a natural mangrove forest with an area of 3416 hm^2 (Chen and Chen 1985). Nearly 700 million m^3 $year^{-1}$ of water flows into Dongzhaigang from rivers such as the Yanzhou, Luoya, Yanfeng East, and Yanfeng West. The rivers carry a large amount of sediment to be deposited, forming a wide mudflat marsh wetland, which provides a suitable environment for growth of the mangroves (Wang et al. 2006). By 1980, the area of the Dongzhaigang mangrove had been drastically reduced by more than 50% due to human logging, economic tree planting, and the reclamation of fish ponds (Chen and Chen 1985; Sun et al. 2015; Wang et al. 2006). Since the 1980s, because of the establishment of provincial and national nature reserves, the Dongzhaigang mangrove has been protected, but the area of mangrove forest has not increased, remaining stable at ~ 1600 hm^2 (Huang et al. 2015; Li et al. 2020; Wang et al. 2006).

In the context of climate change, the rate of coastal sea level rise in China in recent decades (3.4 mm $year^{-1}$, 1980–2020) is higher than the global average (Cai et al. 2020; Ministry of Natural Resources 2021). The sea level rise in the Dongzhaigang area was 4.6 mm $year^{-1}$ from 1980–2017, which was much higher than the coastal China average. Moreover, the sea level rise is expected to accelerate in the future (Kopp et al., 2014; Yan et al., 2019). As a result, the impact of rapidly rising sea levels on the mangroves in Dongzhaigang and other areas is becoming increasingly apparent. Whether the Dongzhaigang mangroves can adapt to these changes and whether countermeasures are necessary to adapt to them are currently unknown. However, few studies have been conducted in this area. The ability of mangroves to adapt to the effects of rising sea levels is closely related to the sedimentation accretion of the mangrove wetlands. Although historical data on sedimentation rates in Dongzhaigang mangrove wetlands have been investigated from observation sites such as Linshi and Daoxue villages (Wang 2011; Zhang et al. 1996), spatial representation is somewhat lacking. Accordingly, this study first analyzed the changes in the Dongzhaigang mangrove area over the past 60 years and the reasons for these changes based on historical literature, spatial remote sensing distribution data, and topographic elevation data. A supplementary survey of sediment vertical accretion rates in two mangrove wetlands at Hegang village, Yanfeng and Sanjiang Farm, Sanjiang was also utilized. Then, based on the study of historical and future relative sea level changes in Haikou City, where Dongzhaigang is located, the impacts and risks of sea level rise on mangroves in Dongzhaigang under three different climate scenarios, RCP 2.6, 4.5, and 8.5, were determined. Finally, the measures needed to adapt to rising sea levels in the Dongzhaigang mangrove were analyzed and proposed for mangrove conservation and management in China.

2. Materials And Methods

2.1 Study location

The Dongzhaigang National Nature Reserve, Haikou City, Hainan Province, China, is part of the Dongzhaigang in Meilan District, Haikou City. It was established in 1980 and approved by the State Council in 1986 as the first national nature reserve in China, with a total area of 3,337.6 hm^2. Its geographical location is 19°51'–20°01'N and 110°32'–110°37'E. The reserve was included in the List of Wetlands of International Importance in 1992 (Hainan Dongzhaigang National Nature Reserve Authority 2015). In 1996, it was added to the United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage Tentative List. In 2012, and was identified as an International Union for Conservation of Nature (IUCN) Key Biodiversity Area (http://www.keybiodiversityareas.org). The mangrove forests in and around the protected area are mainly distributed in four regions, Tashi village, Yanfeng, Daoxue village, and Sanjiang Farm, in the area of Haikou City on the west and south sides of Dongzhaigang. A small amount of the forest is distributed in the area of Wenchang on the east side of Dongzhaigang (Fig. 1b).

Dongzhaigang is located at the northern edge of the low-latitude tropics, with a tropical monsoon maritime climate. The average annual air temperature is 24.4°C, and the lowest and highest monthly average air temperatures occur in January (18.0°C) and July (28.8°C). The average annual relative humidity is 85%, and there is more than 2000 h of sunshine yearly. Thus, light levels and temperatures are sufficient for mangrove growth. Rainfall is abundant, with an average annual rainfall of ≥ 1673 mm (81% of the annual total), which is mainly concentrated in the summer flood season from May to October. In summer, the weather is hot and humid with southeast winds, and in winter (November–April), the weather is dry and less rainy with northeast winds (Hainan Meteorological Service http://hi.cma.gov.cn/).

Dongzhaigang presents an irregular strip-shaped distribution, north-south in its longest dimension. The shore of the bay has relatively gentle, mainly silty shallows or marsh areas and contains many tidal ditches, covering an area of approximately 25 km^2. Dongzhaigang encompasses a total area of 5240 hm^2 (Zhang et al. 1997) and has a total coastline length of approximately 80–84 km (Jia 2014; Lin 2019). Its tides are mixed semidiurnal with an average tidal range of approximately 1 m (Ni et al. 1996). At high tide, seawater flows from the mouth of the bay to the north into Dongzhaigang, and at low tide, seawater flows from the bay to the north through the tidal channels on both sides of Beigang Island to the sea. In addition, there are rivers in the surrounding area, such as the Yanzhou, Luoya, Yanfeng East, and Yanfeng West.

2.2 Materials

2.2.1 Mangrove data

Three types of mangrove data were utilized for this study as follows. 1) Historical sediment accretion rate data were collected from 1992 to 1994 at Linshi and Daoxue villages in the Dongzhaigang mangrove wetlands with respective station codes of LS and DX (Wang 2011; Zhang et al. 1996) (Fig. 1). 2) In this study, supplementary investigations of sediment cores were carried out on the mangrove wetlands in Hegang village, Yanfeng and Sanjiang Farm, Sanjiang. Peat drilling was used to obtain four parallel, column-like sediment cores in December 2020 at an elevation of approximately 0.5–1 m above mean sea level. The station codes were HG and SJ (Table 1 and Fig. 1). 3) A fine-resolution mangrove map of China for 2019 was derived from 10-m-resolution satellite observations and Google Earth images (Zhao and Qin 2020b). The data have a resolution of 10 m and are mainly based on the Google Earth Engine cloud computing platform, using Sentinel SAR and optical time-series images, together with a global digital surface model dataset (Zhao and Qin 2020b).

Table 1
Core stations and depths

Station	Location	Latitude	Longitude	Depth
HG	Hegang village	19.98°N	110.55°E	67 cm
SJ	Sanjiang Farm	19.92°N	110.62°E	75 cm

2.2.2 Sea level, elevation, and coast line data

The observed data from the Sea Level Bulletin of China 2020 (Ministry of Natural Resources 2021) and the used model data of the Coupled Model Intercomparison Projection 5 (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC) are from Kopp et al. (2014).

The following were used for elevation and coastline data: 1) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) v3 with a spatial resolution of 30 m (National Aeronautics and Space Administration and National Geospatial-Intelligence Agency https://earthdata.nasa.gov/), and 2) the Landsat 8 Operational Land Imager (OLI) (United States Geological Survey https://earthexplorer.usgs.gov/).

2.3 Methods

The Dongzhaigang mangrove area was calculated as follows. Using the remote sensing dataset of the spatial distribution of mangroves in China with a spatial resolution of 10 m, the distribution area of the Dongzhaigang mangroves was extracted from the national mangrove distribution data using ArcGIS after projection transformation, and its area was calculated. The following method was used to determine the shoreline of Dongzhaigang. First, after radiometric calibration and atmospheric correction of the Landsat 8 OLI data, an inter-spectral relationship analysis (Eq. 1) was used to enhance the water pixels. Threshold segmentation was then performed to obtain the shoreline. Finally, visual interpretation was used to exclude independent water bodies, such as ponds and lakes.

$$\mathrm{I} = \mathrm{Band3} + \mathrm{Band4} - \mathrm{Band5} - \mathrm{Band6} \qquad \text{(Eq. 1)}$$

In this equation, I is the inter-spectral relationship analysis. Band3–Band6 correspond to the green, red, near-infrared (NIR), and short-wave infrared (SWIR) 1 bands in the Landsat 8 OLI data, respectively.

The sedimentation rates in the mangrove wetlands were analyzed as follows. The constant flux-constant sedimentation rate model (CF-CS, Appleby and Oldfield 1992; Liu 2016) for $^{210}Pb_{ex}$ (excess ^{210}Pb) was used to estimate the rate of vertical accretion at stations B and C. The constant sedimentation rate model is the most frequently utilized ^{210}Pb dating model and is described by Eq. (2):

$$^{210}\mathrm{Pb}_{ex} = {}^{210}\mathrm{Pb} - {}^{226}\mathrm{Ra} = ({}^{210}\mathrm{Pb}_0 - {}^{226}\mathrm{Ra}_0)e^{-dl} \qquad \text{(Eq. 2)}$$

where ^{210}Pb – ^{226}Ra is the activity of $^{210}Pb_{ex}$ (excess ^{210}Pb) in the sediment at depth l, $^{210}Pb_0$ – $^{226}Ra_0$ is the activity of excess ^{210}Pb in the initial surface sediment, and d is a constant obtained by fitting the experimental data. The deposition rate was calculated as V = λ/d, where λ is the decay constant of ^{210}Pb (0.03 year^{-1}).

To obtain the projected values and rates of sea level rise in the Dongzhaigang mangrove wetlands, the IPCC-CMIP5 multi-model data for the Haikou area in 2030, 2050, and 2100 under RCP 2.6, 4.5, and 8.5 were calculated.

For the analysis of the impact of sea level rise on Dongzhaigang mangroves, two views of the SRTM DEM v3 data, named N20E110 and N19E110, were used to mosaic and extract the study area data. Global Mapper was applied to generate contours of the mangrove distribution area using the SRTM DEM data. The outer boundary of the mangrove (seaward boundary elevation) was the mean sea level or slightly above, and the inner boundary (or maximum elevation within the forest) was the mean high water springs (Zhang et al. 1997). The longest contour closest to the outer boundary of the mangrove was selected, and its height was the current mean sea level (H_0).

Equation 3 was used to predict future changes in sea level elevation:

$$H = H_0 - \Delta H_{2000\text{-}2017} + \Delta H_{2000\text{-}N} - V_a \times T \qquad \text{(Eq. 3)}$$

where H is the mean sea level height of Dongzhaigang in a future year, $\Delta H_{2000-2017}$ is the mean sea level change of Dongzhaigang from 2000 to 2017, ΔH_{2000-N} is the sea level rise in a future year (2030, 2050, or 2100) under different climate scenarios using 2000 as the base year, V_a is the rate of vertical accretion, and T is the time span. This study used a remote sensing dataset of the spatial distribution of mangrove forests in China (2019) as the basis of the current situation and utilized ArcGIS as the main analysis tool to study and map the risk distribution of future mangrove forests affected by sea level change in Dongzhaigang.

3. Results

3.1 Historical changes and current status of the mangrove area in Dongzhaigang

Based on the collation and analysis of historical theses, the changes in the area of mangrove forests in Dongzhaigang since the 1950s are presented in Fig. 4. In the last 60 years, the area of mangrove forests in Dongzhaigang has experienced large fluctuations. It decreased from 3416 hm^2 in 1956 (Chen and Chen 1985) to 3213.8 hm^2 in 1959 (Wang et al. 2006; Wang et al. 2010) and then decreased sharply to 1733 hm^2 in 1983 and 1537.5 hm^2 in 1987 (Chen 1985; Sun et al. 2015). Since the establishment of the National Nature Reserve in 1986, the decline of the Dongzhaigang mangrove has been contained (Wang et al. 2006). In 1988, its area was restored to 1809.4 hm^2, and, since the 1990s, it no longer showed a sharp decrease, remaining at approximately 1711 hm^2 (likely range of 1575–1812 hm^2) (Huang et al. 2015; Li 2017; Liao and Zhen 2018; Luo et al. 2013; Sun et al. 2015) (Fig. 4).

Based on the aforementioned data and methods, and considering the integrity of the mangrove ecosystem in Dongzhaigang, this study analyzed the mangrove forests located in the Dongzhaigang National Nature Reserve in Haikou City and northeast of Dongzhaigang in Wenchang City, and calculated the current area of mangrove forests around Dongzhaigang to be 1902 hm^2 (Fig. 1).

3.2 Investigation of the vertical accretion rate in mangrove wetlands

The vertical accretion rate, which can reflect sand trapping and siltation, in two mangrove wetlands in Dongzhaigang (Linshi and Daoxue villages) can be obtained from the historical literature. However, to reflect the vertical accretion rates of Dongzhaigang mangrove wetlands more comprehensively in time and space, in this study, we conducted a supplementary investigation on the vertical accretion rates of

Dongzhaigang mangrove wetlands, such as the Yanfeng and Sanjiang areas (Fig. 1b). The results of the analysis using $^{210}Pb_{ex}$ specific-activity measurements showed that the $^{210}Pb_{ex}$ specific activity in the cores from the mangrove wetland stations HG and SJ decayed exponentially with increasing depth, and the R^2 values of both cores were approximately 0.8 after curve fitting. This resulted in vertical accretion rates of 0.53 cm year^{-1} and 0.40 cm year^{-1} for stations HG and SJ, respectively (Fig. 5). This is in general agreement with historical findings on vertical accretion rates in the Dongzhaigang mangrove wetlands (~ 0.41 cm year^{-1} at station LS and ~ 0.64 cm year^{-1} at station DX) (Wang 2011; Zhang et al. 1996). In the present study, the vertical accretion rate of the Dongzhaigang mangrove wetlands was considered the average value of historical and measured data, which was 0.50 cm year^{-1}.

3.3 Rate of sea level rise in the coastal Dongzhaigang water

Research shows that the global mean sea level is accelerating due to global warming-induced thermal expansion of the oceans and melting of land-based glaciers and ice caps into the sea (IPCC 2019). Between 1901 and 2010, the global mean sea level rose by 0.19 m (Openheimer et al. 2019). Coastal China waters are among the most significant regions of global sea level rise. According to the results of the Sea Level Bulletin of China in 2020, the rate of sea level rise along China's coast from 1980 to 2019 was 3.4 mm year^{-1}, higher than the global average. In the future, under the premise of increasing anthropogenic emissions of greenhouse gases such as CO_2, global sea levels will rise rapidly, and it is projected that the global mean sea level may rise by 0.84 m (0.61–1.10 m) relative to current levels by the end of the 21st century (Openheimer et al. 2019). Based on observations from tide gauge stations in the Haikou area and model data from CMIP5, the rate of sea level rise around Dongzhaigang, Haikou, Hainan Province reached 4.6 mm year^{-1} from 1980 to 2018. This is much higher than the global and Chinese means (Cai et al. 2020; Yan et al. 2019), making it one of the fastest rising coastal sea level regions in China. The rate of sea level rise around Dongzhaigang will likely accelerate further in the future. Based on the results of CMIP5 model simulations under different GHG emission scenarios (Kopp et al. 2014), the relative sea level rise in the coastal Haikou waters, including Dongzhaigang, is expected to be significant by 2030, 2050, and 2100 for RCP 2.6, 4.5, and 8.5 (Table 2 and Fig. 6). Among them, for RCP 2.6, 4.5, and 8.5 by 2100, there is likely to be a rise of 65 (likely range of 42–90), 75 (likely range of 51–102), and 96 (likely range of 70–125) cm, respectively, with average rates of sea level rise of 6.84 (likely range of 4.42–9.47), 7.89 (likely range of 5.37–10.74), and 10.1 (likely range of 7.37–13.12) mm year^{-1}, respectively.

Table 2
Estimated coastal sea level rise (cm) and rate (mm $year^{-1}$) in the Haikou area under different climate scenarios (data from Kopp et al. 2014)

Sea level rise (cm)									
Year	RCP 2.6			RCP 4.5			RCP 8.5		
	mean	17–83% (likely)	5–95% (very likely)	mean	17–83% (likely)	5–95% (very likely)	mean	17–83% (likely)	5–95% (very likely)
2030	18	12–23	8–27	18	12–23	8–27	18	12–24	8–28
2050	31	21–42	14–49	33	23–43	16–51	36	26–46	19–54
2100	65	42–90	26–111	75	51–102	34–123	96	70–125	52–151
Rate of sea level rise (mm $year^{-1}$)									
Year	RCP 2.6			RCP 4.5			RCP 8.5		
	mean	17–83% (likely)	5–95% (very likely)	mean	17–83% (likely)	5–95% (very likely)	mean	17–83% (likely)	5–95% (very likely)
2030	7.2	4.8–9.2	3.2–1.08	7.2	4.8–9.2	3.2–1.08	7.2	4.8–9.6	3.2–11.2
2050	6.89	4.67–9.33	3.11–1.09	7.33	5.11–9.56	3.56–11.33	8.0	5.78–10.22	4.22–10.2
2100	6.84	4.42–9.47	2.74–11.68	7.89	5.37–10.74	3.58–12.95	10.1	7.37–13.12	5.47–15.9
Note: Settling rate: 1.09 ± 3.22 mm/y									

3.4 Impacts and risks of sea level rise on the Dongzhaigang mangrove

A previous study has shown that mangroves may have difficulty adapting to rising sea levels if the relative global rate of sea level rise exceeds 6.1 mm $year^{-1}$ (90% probability, very likely), while the survival threshold for mangroves is extremely likely to be exceeded (95% probability, extremely likely) when the rate of rise exceeds 7.6 mm $year^{-1}$ (Saintilan et al. 2020). Although Saintilan et al. (2020) studied this issue globally, it can also reflect the threat of sea level rise to local mangroves. Thus, the present study further analyzes the possible impacts and risks of sea level rise in the Dongzhaigang mangrove in the future under different climate scenarios.

Based on the predicted future sea level rise rates under RCP 2.6, 4.5, and 8.5, as well as data such as vertical accretion rates of the Dongzhaigang mangrove wetlands, the mangroves are likely to be affected by rising sea levels by 2030, 2050, and 2100 (Fig. 7and Table 3). Among them, under the low GHG emission scenario (RCP 2.6), by 2030, 2050, and 2100, there will be little effect of sea level rise and the Dongzhaigang mangrove forest area will only experience a small reduction, amounting to approximately 15.98% (likely range of 1.31–16.46%), that is 304 hm^2 (likely range of 25–313 hm^2); 16.30% (likely range of 1.26–17.35%), that is 310 hm^2 (likely range of 24–330 hm^2);and 17.14% (likely range of 1.21–30.18%), that is 326 hm^2 (likely range of 23–574 hm^2) of mangrove forest lost, respectively (Table 3 and Fig. 7a). This is mainly because the vertical accretion rate of the Dongzhaigang mangrove wetland remains largely constant with the rate of sea level rise. In contrast, under medium and high GHG emission scenarios (RCP 4.5 and 8.5), the Dongzhaigang mangrove is expected to be more affected by sea level rise. For example, for RCP 4.5, 25.87% (likely range of 15.77–40.22%) or approximately 492 hm^2 (likely range of 300–765 hm^2) of mangrove forest would likely be lost by the end of the century (Table 3 and Fig. 7b). For RCP 8.5, it is projected that 26.92% (likely range of 17.67–50.84%) or approximately 512 hm^2 (likely range of 336–967 hm^2) of mangrove forest will be lost by 2100 (Table 3 and Fig. 7c). In summary, for RCP 4.5 and 8.5, the impact of sea level rise on mangrove wetlands by 2100 is much higher than that of RCP 2.6, and is likely to result in > 25% of mangroves being lost, while for RCP 2.6, only ~ 17% of mangroves are likely to be affected.

Table 3

Area (hm^2) and percentage of future mangrove loss in Dongzhaigang under different climate scenarios (RCP 2.6, 4.5, and 8.5) (likely range)

Year	**RCP 2.6**		**RCP 4.5**		**RCP 8.5**	
	mean	**17–83% (likely)**	**mean**	**17–83% (likely)**	**mean**	**17–83% (likely)**
2030	304 (25–313)	15.98% (1.31–16.46%)	304 (25–313)	15.98% (1.31–16.46%)	304 (25–315)	15.98% (1.31–16.56%)
2050	310 (24–330)	16.30% (1.26–17.35%)	313 (25–332)	16.46% (1.31–17.46%)	319 (300–337)	16.77% (15.77–17.72%)
2100	326 (23–574)	17.14% (1.21–30.18%)	492 (300–765)	25.87% (15.77–40.22%)	512 (336–967)	26.92% (17.67–50.84%)

In addition, for RCP 2.6, the rate of sea level rise around Dongzhaigang will reach 0.72 cm $year^{-1}$ in 2030 and then decrease in 2050 and 2080 to 0.69 and 0.68 cm $year^{-1}$, respectively (Figs. 6 and 7). However, for RCP 4.5 (8.5), by 2030, 2050, and 2100, the rate of sea level rise will reach 0.72 (0.72), 0.73 (0.80), and

0.79 (10.1) cm year^{-1}, respectively, which will have a relatively large impact on the mangroves. By 2100, some mangroves in the northern part of Tashi village in the eastern part of Yanfeng, the northern part of Daoxue village, and the northeastern part of Sanjiang Farm will likely be lost due to sea level rise, and other coastal Dongzhaigang mangrove wetlands will also be impacted. The rate of sea level rise around Dongzhaigang is higher than the global average survival threshold for mangroves (i.e., the rate of sea level rise exceeds 7.0 mm year^{-1}; Saintilan et al. 2020). The Dongzhaigang mangroves are more affected by sea level rise, with a possible loss of 26–27%; however, it seems that their survival threshold has not been exceeded (Table 2, 3 and Fig. 7). Nevertheless, it is still important to discuss and analyze how to reduce the impacts and risks of sea level rise on mangroves and improve their adaptive capacity.

4. Discussion

4.1 Reasons for the historical change of mangrove area

The analysis showed that before the 1960s, the Dongzhaigang mangrove was less disturbed by human activities and mainly evolved naturally, demonstrating seaward expansion. Between 1960 and the late 1980s, the natural mangrove forests declined by nearly half, mainly due to the impact of human activities such as the use of former mangrove land for economic tree planting and the reclamation of fish ponds. Even after the establishment of the reserve in the 1990s, the mangroves were still damaged by local human activities such as shrimp farming in Dongzhaigang ponds (Huang et al. 2015; Li 2017; Liao and Zhen 2018; Luo et al. 2013; Sun et al. 2015; Wang et al. 2017). In addition, since the 21st century, tourism development and diseases, such as outbreaks of *Sphaeromatidae*, have impacted the Dongzhaigang mangrove (Fan et al. 2014; Wang et al. 2006). It is noteworthy that, although the mangrove area was damaged and reduced to some extent during the abovementioned period, a total of 173 hm^2 of mangroves was created in the Dongzhaigang reserve between 1980 and 1990, and approximately 100 hm^2 was preserved and kept alive (Liao et al. 1996).

As indicated above, before the establishment of the Dongzhaigang Reserve, that is, between the 1960s and 1990s, the reduction in mangrove area was mainly due to human destructive activities. However, the mangrove area of Dongzhaigang remained relatively stable thereafter (Fig. 4). This indicates that China has placed increasing emphasis on protecting the mangrove ecosystem over the past three decades. Against the backdrop of a warming climate, there is growing concern that the Dongzhaigang mangrove will be affected by the ongoing rise in sea level.

4.2 Adaptation responses

In general, mangroves adapt to the impacts of sea level rise through landward migration (Fig. 8a, b). The results of a national wetland survey in 2001 showed that approximately 80% of mangrove wetlands in China have tidal dykes or aquaculture ponds on the landward side (Department of Forest Resources Management of State Forestry Administration 2002; Fig. 8c). In recent decades, as China has placed increasing emphasis on the protection of mangrove ecosystems, mangrove restoration techniques, such as planting or reforestation, have been implemented on the seaward side of the mangroves or in ponds on the landward side (Fig. 8d). By using biological berms such as wooden piles or oyster shells on the seaward side of the coast (Fig. 8e), coastal erosion due to sea level rise can also be mitigated. Implementation of these measures will be beneficial in helping mangrove wetlands cope with coastal erosion. Based on the analysis results of the impact and risk of sea level rise on the Dongzhaigang mangroves, the northern part of Tashi village, the outer part of Yanfeng, the northern part of Daoxue village, and the northeastern part of Sanjiang Farm in Dongzhaigang may be seriously affected by sea level rise in the future. Of these, the northern part of Tashi village is blocked by a tidal dyke at the rear; the southern part of Tashi village and Yanfeng are interspersed with dykes, village roads, and farming ponds at the rear; and Daoxue village and Sanjiang Farm mainly have farming ponds at the rear. Based on the ecological restoration concept of "natural restoration as the mainstay and artificial intervention/support as a supplement," the main restoration and protection measures that can be adopted for the Dongzhaigang mangroves to address the rise in sea levels are listed below.

1) For the farming ponds on the mangrove landward side, in addition to the traditional model of returning the pond to the forest for restoration (Fig. 8d), attempts can be made to build ecological aquaculture complexes (e.g., tile tank ecological farming in planted or naturally restored forest areas). This not only restores natural hydrodynamic functions and improves water quality, but also stabilizes the livelihoods of fishermen and achieves green development.

2) For the mangroves on the seaward side of Tashi village and Yanfeng in Dongzhaigang, biological berms can be adopted (Fig. 8e), while the landward side mainly contains village roads and tidal dykes. Consideration can also be given to moving the tidal dykes back and ecologically transforming them, creating a buffer zone between the dykes, the road, and the mangroves in the reserve. This would reduce the direct impact of human activities and allow for better protection of mangroves in the reserve.

3) The amount of sand transported annually to Tashi Bay in Dongzhaigang is only approximately 1300 tons. This is very small compared to the river transport of sand in the Jiulong River (2.23 million tons) in Xiamen, Fujian; the Xijiang River (53.9 million tons); and Lingdingyang (Tan and Zhang 1997), making the rate of vertical accretion of sediment relatively low. For the inlet rivers of Dongzhaigang, such as the Tashi Canal Branch, consideration can be given to improving the use of their inlet gates, such as removing the gates and rebuilding them or opening them in due course. This would increase sand transport of the inlet rivers, improve the sand trapping and siltation function of the mangrove wetland, create a natural recovery environment for the mangroves, and enhance the adaptability of the mangroves to address sea level rise.

4) A comprehensive observation and monitoring system could be established. The application of remote-sensing technology could be improved to more accurately grasp the dynamic changes in mangroves. To monitor the changes in mangrove surface elevation, a rod surface elevation table-marker horizon (SET-MH) measurement system could be established in the protected area (Cahoon et al. 2002; Chen et al.

2017b; Lovelock et al. 2015) to further investigate the adaptive mechanisms of mangroves to sea level increases.

In addition, attention should be paid to the characteristics of local habitats in the conservation and restoration of mangroves. For example, in 1981, a total of 3 hm^2 of *Kandelia obovata* and *Bruguiera gymnorhiza* (L.) Lam. was planted on the bare beach west of the Sanjiang gate, but only 0.27 hm^2 of *Kandelia obovata* survived due to prolonged flooding. Approximately 1 hm^2 of mangroves such as *Kandelia obovata* and *Bruguiera sexangula* (Lour.) Poir. was planted on the bare beach at Tiaoyidu, but all of them died because of the hard substrate and high salinity of the seawater (Liao et al. 1996). Therefore, when adopting restoration measures such as mangrove planting, the salinity of the seawater in the planted area; the nature of the soil, tides and currents; and other environmental factors should be considered. Consideration should also be given to the selection of different mangrove species in different spatial zones. Examples include selecting resistant pioneer species, such as *Avicennia marina* (Forsk.) Vierh. and *Aegiceras corniculatum* (Linn.) Blanco., for the pioneer plant zone. In addition, the relationship between vegetation growth and spatial distribution in different growth periods should be considered (Xiao et al 2020), such as the width, density, and area of the forest. At the same time, to improve the survival rate of pre-dyke afforestation, coastal engineering methods or beach herbaceous plants can be used beforehand (Wu and Peng 1994).

5. Conclusions

This study, based on data on the rate of sea level increases, spatial remote sensing of mangrove distributions, and sedimentation rates in the Dongzhaigang area, investigates the adaptation of mangroves to rising sea levels in the Dongzhaigang National Mangrove Nature Reserve and surrounding mangroves. The main conclusions are as follows:

1) Between the 1950s and end of the 1980s, the mangrove area of Dongzhaigang was drastically reduced, with approximately 50% of the mangrove loss mainly attributed to human activities such as the use of mangrove land for economic tree planting and the reclamation of fish ponds. Due to the establishment of the mangrove nature reserve and the implementation of protective measures, such as a strict ban on logging and mangrove replanting, the mangrove area has remained stable at ~ 1711 hm^2 since the end of the 1980s.

2) The investigation showed that the average vertical accretion rate of the mangrove wetlands in Dongzhaigang is approximately 4.0–6.4 mm $year^{-1}$. For RCP 2.6, 4.5, and 8.5, the rates of sea level rise in Dongzhaigang are projected to reach 6.84 (likely range of 4.42–9.47), 7.89 (likely range of 5.37–10.74), and 10.1 (likely range of 7.37–13.12) mm/ $year^{-1}$, respectively, and the loss of mangrove area due to rising sea levels in the future will be 326 (likely range of 23–574), 492 (likely range of 300–765), and 512 (likely range of 336–967) hm^2, respectively. The main areas of mangrove loss were the northern part of Tashi village, the eastern part of Yanfeng, the northern part of Daoxue village, and the northeastern part of Sanjiang Farm. For RCP 4.5 and 8.5, > 25% of the mangroves are at risk of

disappearing by 2100 because of sea level rise; on the seaward side, the mangroves would be threatened. For RCP 2.6, only approximately 17% of the mangroves are likely to be affected.

3) Based on the predicted results of the impact of future sea level rises on the Dongzhaigang mangroves, the following adaptive measures can be considered. These include reestablishing ponds as forests, constructing ecological farming consortia, moving back tidal dykes and making ecological changes, removing and reconstructing river gates entering the sea or opening gates to drain water to increase the amount of sediment entering the sea, establishing monitoring systems, and creating a living environment for mangroves and artificial planting.

Declarations

RD was a major contributor in writing the manuscript. In addition, RD analyzed the change of mangrove area in Dongzhaigang since the 1950s, and estimated the impact and risk of future rising sea level on mangrove habitat in Dongzhaigang under different climate scenarios.

RC conceived and designed the study, and was another major contributor in writing the manuscript. Moreover, RC set up the frame structure, clarified the logic, and finally organized and improved the manuscript.

XY put forward several restoration and protection measures that can be adopted for the Dongzhaigang mangroves to address the rise in sea levels.

JS collected column-like sediment cores in mangrove wetlands, measured the vertical accretion rate in mangrove wetlands, and completed the relevant content of the article.

HT analyzed the rate of sea level rise in the Haikou area in 2030, 2050 and 2100 under different climate scenarios and completed the relevant content of the article.

WM & HG measured and collected column-like sediment cores in mangrove wetland, respectively.

All authors read and approved the final manuscript.

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Consent to participate: Not applicable

Consent for publication: Not applicable

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Code availability: Not applicable

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Figures

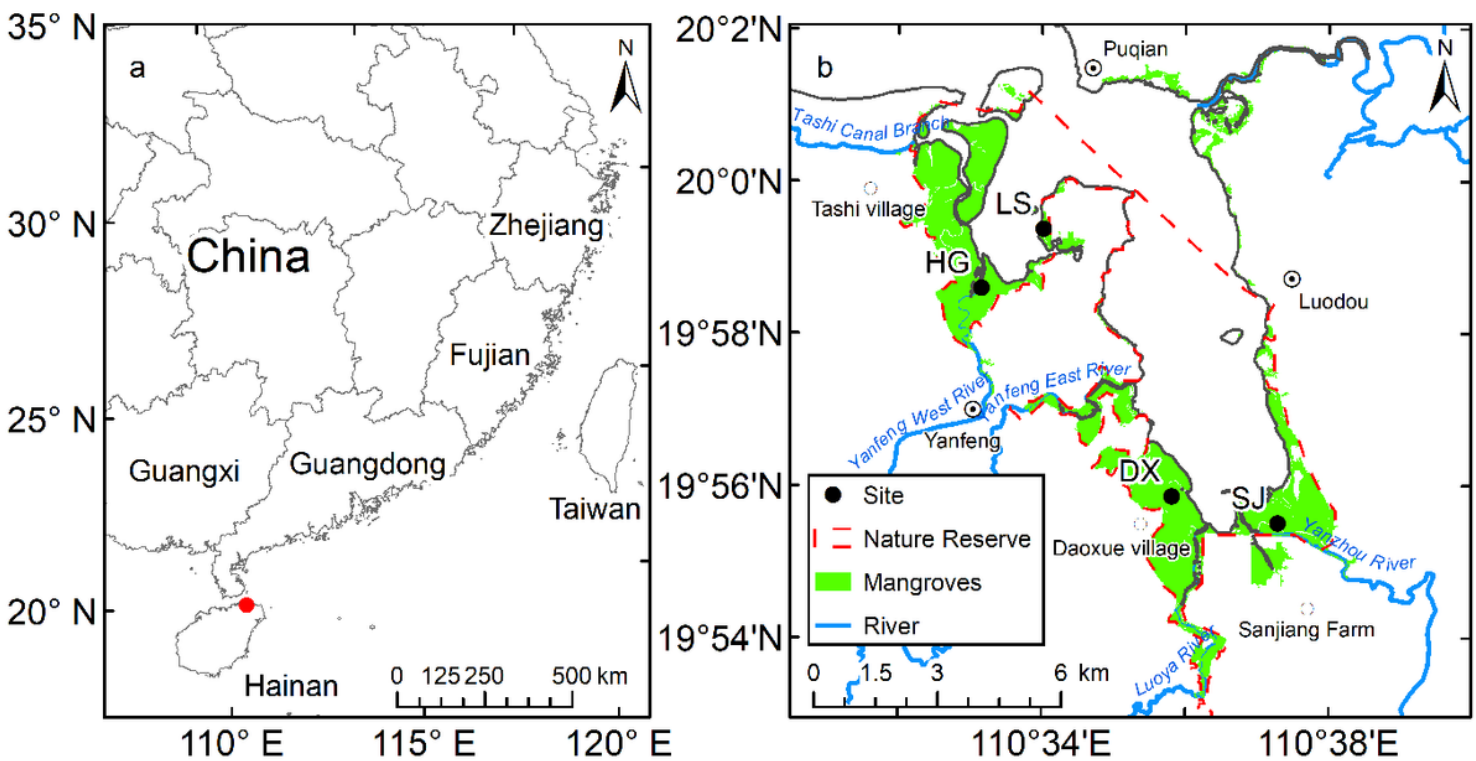

Figure 1

(a) Geographical location and (b) spatial distribution of mangroves around Dongzhaigang, Haikou City, Hainan Province, China. LS, HG, DX, and SJ refer to Linshi village, Hegang village, Daoxue village, and Sanjiang Farm, respectively. (Partial data from: Zhao and Qin 2020b)

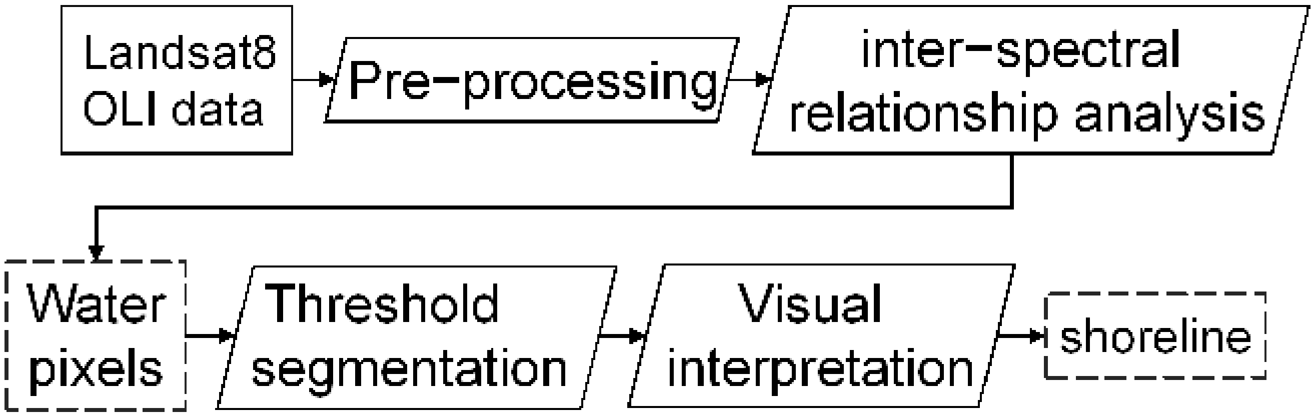

Figure 2

Flowchart of shoreline extraction

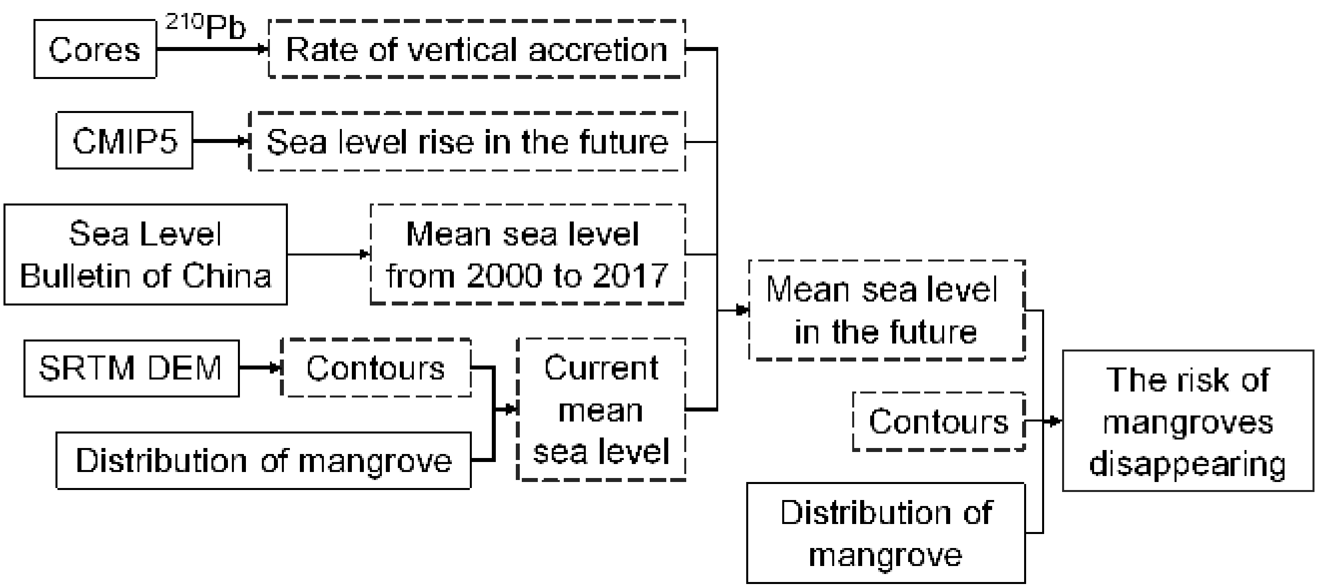

Figure 3

Schematic of impact and risk analysis of sea level rise on mangroves

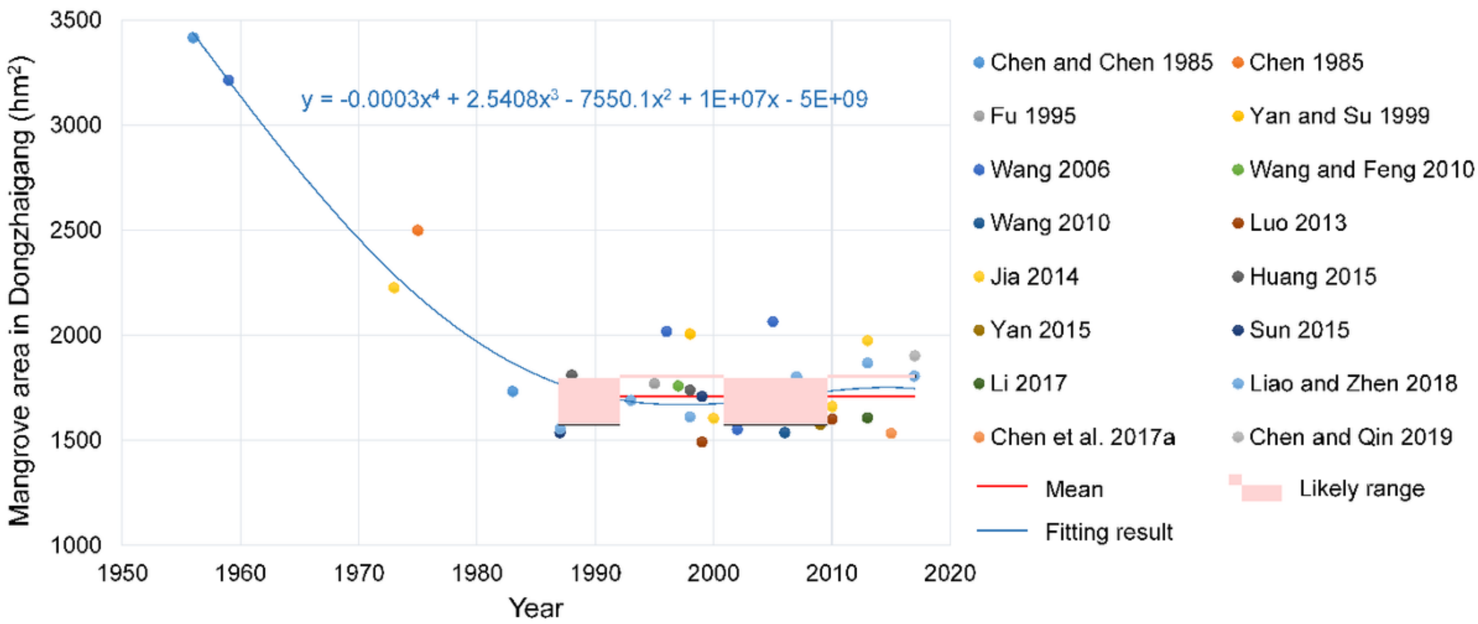

Figure 4

Changes in the mangrove area in Dongzhaigang from 1956–2017. The equation in the upper-right corner of the plot refers to a fitting equation of historical changes of area in the Dongzhaigang mangrove

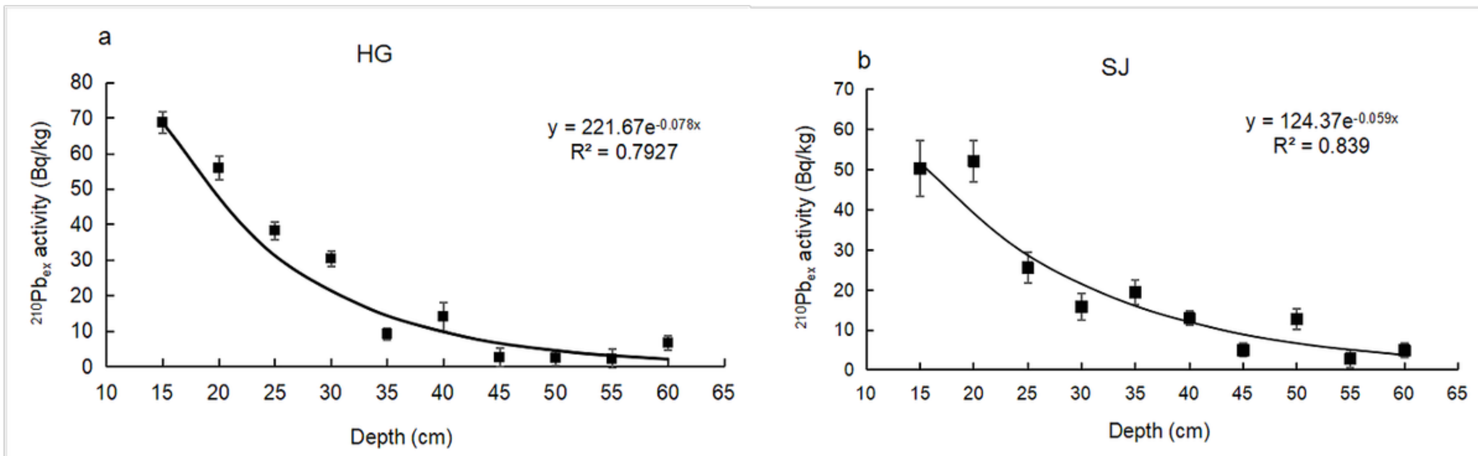

Figure 5

210Pbex activity profiles in the selected cores such as (a) station HG and (b) station SJ of this study

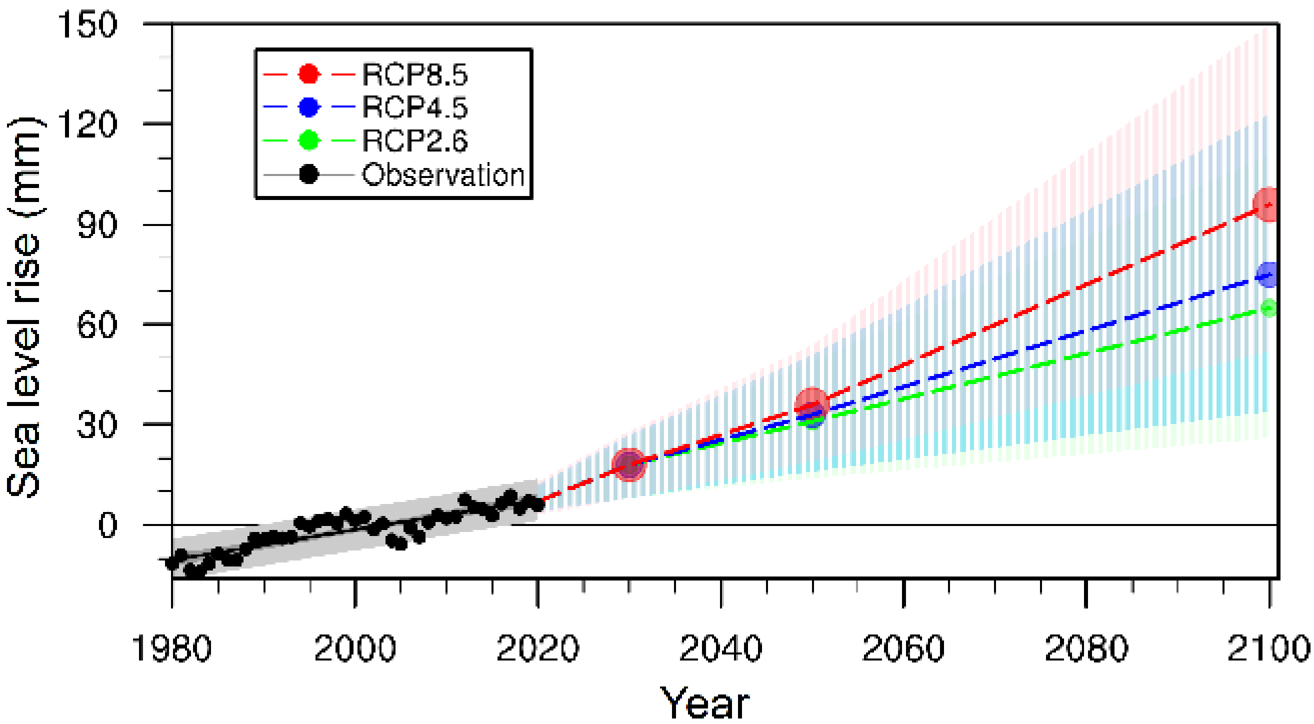

Figure 6

Sea level changes along coastal Dongzhaigang, Haikou City from 1980 to 2100. The 5–95% uncertainty ranges are shaded for RCP 2.6, 4.5, and 8.5, respectively.

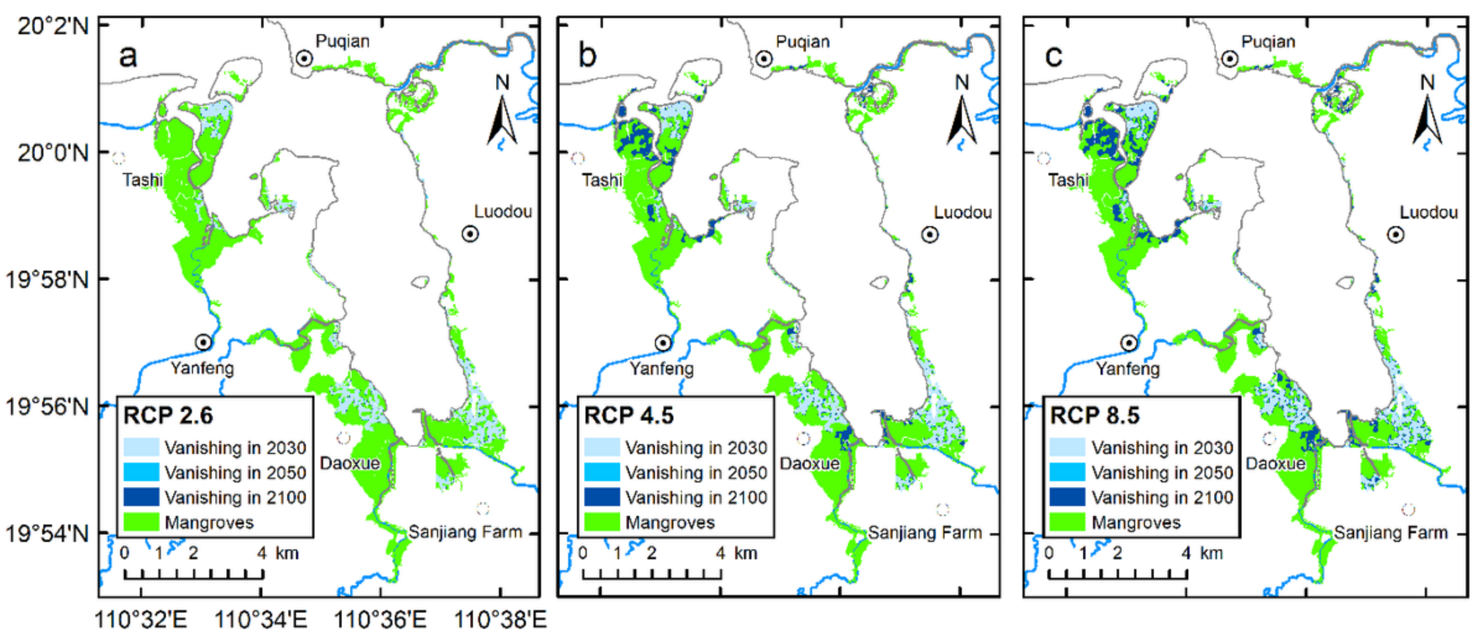

Figure 7

Potential loss of mangroves in Dongzhaigang under different climate scenarios (RCP 2.6, 4.5, and 8.5)

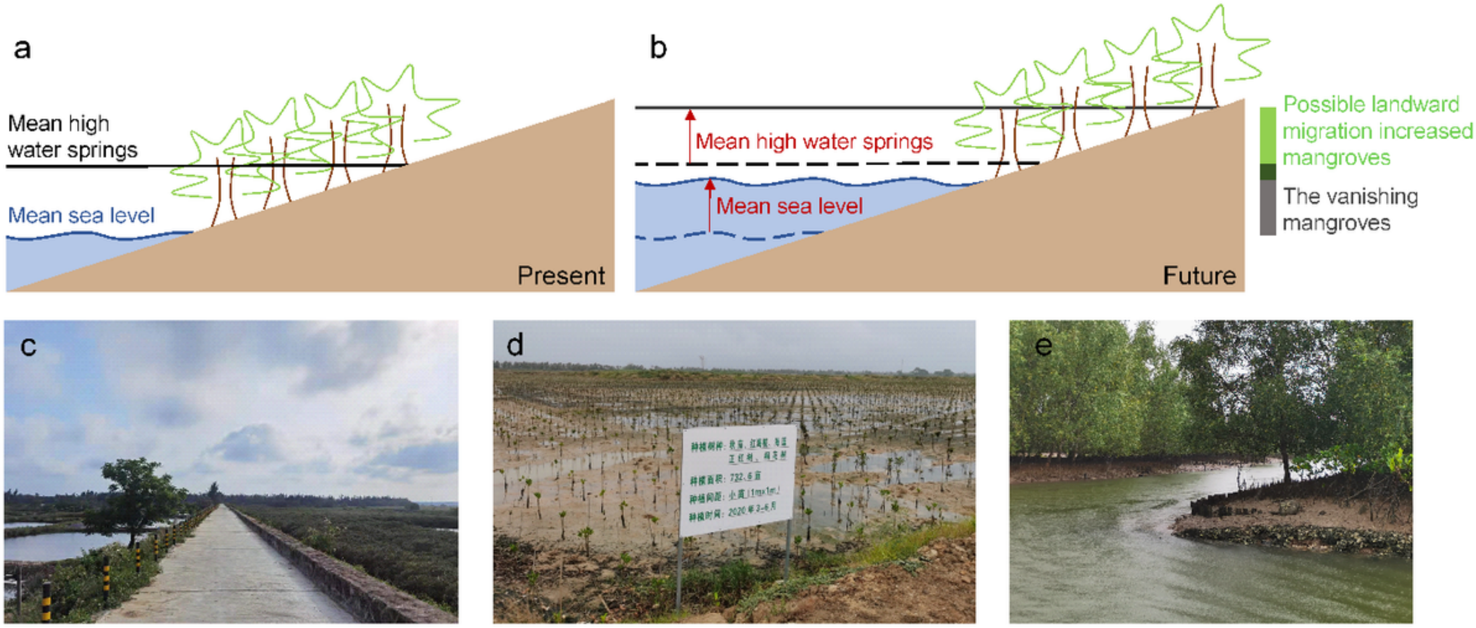

Figure 8

Mangrove adaptation to sea level rise in Dongzhaigang. (a) and (b) indicate mangroves adapt to the rising sea level by planting landward; (c) refers to tidal dykes and aquaculture ponds behind the mangroves; (d) represents the restoration by planting mangrove; (e) represents ecosystem-based adaptation