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Hurricanes Induced Irreversible Large-Scale Loss of Mangrove Forests

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Key Points:

- The area of mangrove in South Florida experienced four sharp declines, with a slow recovery after each decline
- Mangroves loss showed an exponential decrease landward during tropical cyclones, while vegetation fringe extended seaward in fair weather
- Sea-level rise contributed insignificantly to mangrove deterioration in South Florida

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Mangrove forests act as effective natural barriers against tropical storms. However, little information is available on the resilience of mangrove forests against hurricane impacts. Here we quantify the response of Florida mangroves to hurricane forcing. We found that the mangrove area in South Florida experienced four sharp declines over the past thirty years, with a slow recovery trend observed after each decline. The loss of mangroves displayed an exponential decrease from the ocean to the upland during tropical cyclones, while the vegetation fringe underwent seaward extensions in fair-weather periods. Hurricanes of category three or higher were responsible for the sharp declines in mangroves, while sea-level rise was not related to vegetation loss. We project that mangroves loss in Florida mangrove can total 533 km^2 by 2050 and 1,956 km^2 by 2100, driven by an increase in frequency and intensity of tropical cyclones.

Plain Language Summary

Mangroves provide flood defense valued at approximately 65 billion USD annually. The effectiveness of mangroves in Asia, Africa, and North America in mitigating typhoons and large waves is widely recognized globally. However, global mangrove forests have been declining due to the multiple threats of human activities, sea-level rise, and increasing storm surges. Here, we found that between 1986 and 2022, the Everglades mangroves in Florida experienced a net loss of 547.3 km^2, with a total loss of 645.1 km^2 and a gain of 97.8 km^2. Over the period from 1986 to 2022, the vegetation fringe remained largely unchanged in non-hurricane years, with hurricane incursions being the primary cause of the landward retreat. Moreover, hurricanes cause an exponential decrease in mangroves loss from south to north, with category three or higher storms being the main drivers of mangroves loss. Sea-level rise did not significantly contribute to mangrove deterioration. Projections suggest that, with the forecasted increase in hurricane frequency, mangroves could loss 533 km^2 by 2050 and 1956 km^2 by 2100.

1. Introduction

Mangrove forests grow in the intertidal zone and are among the most biomass-rich coastal ecosystems (Atwood et al., 2017; Hamilton & Casey, 2016; Kauffman et al., 2011; Swales et al., 2015). Mangroves play a vital role in carbon sequestration, coastal stabilization, and sediment trapping (Hochard et al., 2019; Jerath et al., 2016). The dense canopy of mangroves effectively withstands the impact of winds and waves during tropical cyclones (Alongi, 2008). As a result, mangroves provide flood defense valued at approximately 65 billion USD annually (Menendez et al., 2020). Mangroves in Florida, USA, protect communities from hurricanes, with economic benefits. The effectiveness of mangroves in Asia, Africa, and North America in mitigating typhoons and large waves is widely recognized globally (Menendez et al., 2020).

A 100 m stretch of mangrove forest can reduce waves by at least 50% (Smith et al., 2016), highlighting the natural ability of mangrove canopies to defend against storm surges (Garzon et al., 2019; Zhou et al., 2022). However, under the multiple threats of human activities, sea-level rise, and increasing storm surges (Alongi, 2008; Chavez et al., 2023; Friess et al., 2019), global mangrove forests have been declining at a rate of 1% to 2% per year since the latter half of the 20th century (Alongi, 2015). This has directly resulted in the narrowing or disappearance of mangrove forest fringes, significantly reducing their capacity to withstand increasingly intense storm surges. When the mangrove fringe is too narrow or the hurricane's waves too large, mangroves can be damaged, leading to reduced resilience against tropical cyclones and causing flooding in the nearby cities. This is common in Southeast Asia, where tropical cyclones frequently make landfall and mangroves are prevalent (Ahamed &

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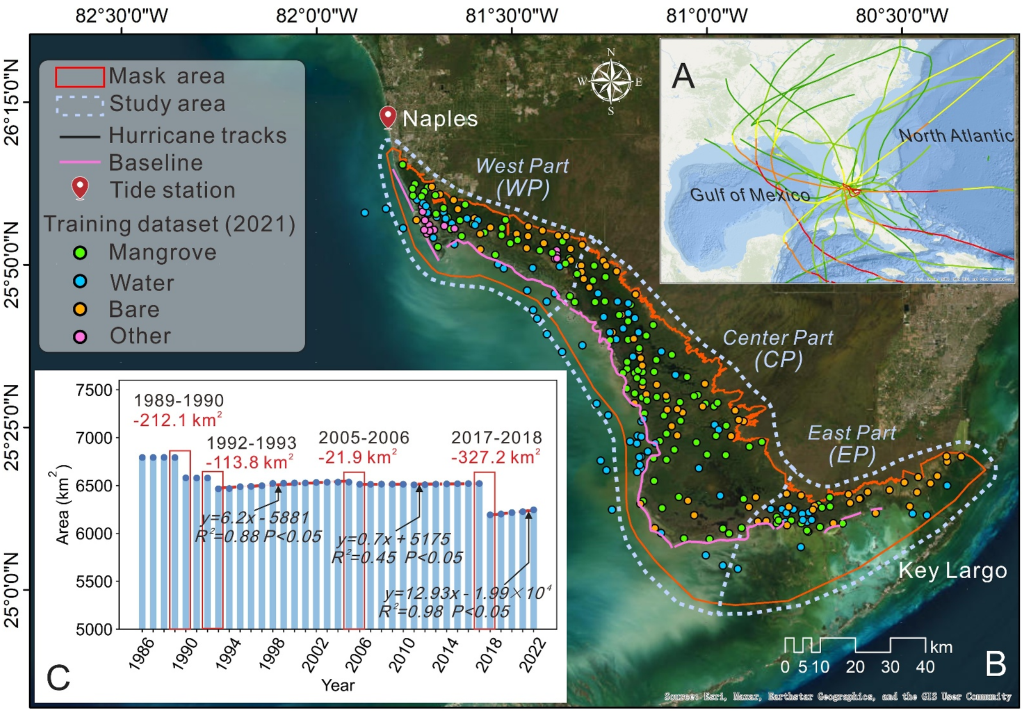

Figure 1. Location of the study area (a. Hurricane tracks in Florida; b: Study area, distribution of training data set in 2022, and baseline setting for DSAS; c: Variation of mangroves area in time).

Bolten, 2017; Giri et al., 2015). However, data on the total mangrove areas damaged by tropical cyclones remains limited.

Sea-level rise and more frequent storms threaten mangroves and might cause large-scale diebacks, placing many coastal cities around the world at risk. Recent research has focused on the flooding and economic losses of cities hit by tropical cyclones (Brown et al., 2021; Gao et al., 2020; Liu et al., 2023; Wu et al., 2024), but there is no holistic examination on mangroves damage, and their natural recovery after the dieback. Given the limited research on the negative impacts of tropical cyclones on mangroves, there is a risk of overestimating the long-term protection these ecosystems provide to shorelines. Therefore, it is essential to quantify the loss of mangroves caused by tropical cyclones and their subsequent recovery.

Hurricanes are extreme climate events prevalent in the United States, causing severe coastal disasters that impact the economy and result in significant loss of life (Czajkowski et al., 2011; Menendez et al., 2020). The fringe mangroves in the Everglades, Florida, are located in the western part of the Atlantic Basin tropical cyclone zone, and play a significant role in mitigating wind and storm surges (Zhu et al., 2021). Previous studies have shown that hurricanes in this area trigger mangroves dieback (Lagomasino et al., 2021), and the structural damage to mangroves in 2017 was due to Hurricane Irma's impact (Han et al., 2018; Lagomasino et al., 2021; Radabaugh et al., 2019). Although former have improved understanding of the effects of hurricanes on mangroves, there is limited reporting on how mangroves recover after storms and how mangrove fringe advance or retreat.

In this study, we used all available Landsat images to extract the distribution of mangroves in the Florida Everglades from 1986 to 2022. Using machine learning algorithms, we investigated the quantitative relationship between mangrove loss and recovery after a hurricane impact. Our main goal is to detect how hurricanes and sea-level rise affect mangroves in this protected area, in order to reveal their recovery and resilience, and provide critical data sets for global restoration.

The Everglades National Park (hereinafter referred to as the Everglades) is located at the tip of the Florida Peninsula on the eastern coast of the Gulf of Mexico (Figure 1a) and hosts the largest mangroves forest in North America (Castañeda-Moya et al., 2013). The forest is dominated by *Rhizophora mangle, Avicennia germinans (L.)*, and *Laguncularia racemosa* (Stevens et al., 2006), and experiences a small tidal range of about 1–1.7 m

(Stumpf & Haines, 1998). The waves are predominantly wind-generated, with an average height ranging from 0.2 to 0.5 m, however, under the influence of hurricanes, wave heights can reach up to 5 m (Smith et al., 2009). The study area is frequently affected by hurricanes that land in the Florida region due to atmospheric circulation and ocean thermal conditions, triggering frequent hurricanes (Figure 1a). According to geomorphological characteristics and the common landfall paths of hurricanes, we divide the study area into three parts: West Part (WP), Center Part (CP), and EP (East Part) (Figure 1b). The WP coast is primarily composed of sand, with numerous residential areas located inland from the mangroves. The CP coast is muddy and features extensive mangrove forests. The southernmost tip of Florida is located in CP and often serves as the frontline for direct hurricane impacts. In contrast, the EP coast has sparse mangroves, primarily the short *L. racemosa,* distributed along the bay side of elongated islands such as Key Largo and Tavernier (Clarke & Dalrymple, 2003). The division of study area is conducive to a targeted discussion on variation characteristics of mangroves in different regions and the corresponding dominant mechanisms.

2. Materials and Methods

2.1. Materials

USGS Landsat images from 1986 to 2022 were analyzed with GEE (Google Earth Engine) in this study. Hurricane data for Florida were derived from the National Centers for Environmental Information (https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/shapefile/), encompassing global tropical cyclones records from 1980 to the present, along with wind field data from the European Center for Medium-Range Weather Forecasts (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). The upper boundary of the research area was delineated based on the Estuarine and Marine Wetland land cover from the National Wetland Inventory surface waters and wetlands (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/), with a mask area extended seaward (Figure 1b). All hurricane data passing through the research area from 1986 to 2022 were collected and analyzed, encompassing tracks, wind speeds, air pressure, and timing, to assess the hurricanes' impact on the regional mangroves. Rainfall data within the masked research area were derived from the CHIRPS data set, a quasi-global rainfall data set spanning over 30 years, which integrates 0.05° resolution satellite imagery with in situ station data to generate gridded rainfall time series for trend analysis and seasonal drought monitoring. Sea-level data were derived from the annual average sea-level data of the Permanent Service for Mean Sea Level (PSMSL) data set at the Naples NOAA tide gauge station 8,725,110 (https://psmsl.org/data/obtaining/map.html), to evaluate the trend of regional sea-level rise.

2.2. Mangrove Area Extraction

In this paper, the CCDC algorithm and machine learning were used on the GEE platform to load and operate all available Landsat images from 1986 to 2022, extracting the spatial distribution of mangroves within the research area. CCDC is an algorithm developed to monitor changes in land cover or land use using dense time series of satellite imagery. Its core lies in analyzing the change patterns of each pixel over time to identify and classify different types of land cover variations (Z. Zhu and Woodcock, 2014). This study set up four types of land cover: mangroves, water, bare soil, and other, and derived a set of sample data sets every 5 years (1986, 1991, 1996, 2001, 2006, 2011, 2016, 2021), with approximately 300 sample points evenly distributed within the research area (Figure 1b). All sample points were then aggregated into one sample point data set, loaded into the CCDC algorithm for training. More details are presented in Figure S1 in Supporting Information S1.

The resolution of Landsat images is 30 m, which may fail to capture the detailed changes of fine-scale mangroves. Therefore, regions with different crown widths and tree ages and exhibit relatively significant changes are selected as verification sample to verify the accuracy of CCDC algorithm. Specifically, the spatial distribution and area of mangroves in the sample area from 2016 to 2022 were extracted by random forest method on the basis of Sentinel-2 image data that has higher 10 m resolution, which were then compared with the information extracted by CCDC. The results showed that Sentinel-2 image indeed show more detailed information on mangroves than Landsat and the area of mangroves is generally higher, but the deviation is less than 2% (Table S1 in Supporting Information S1). Therefore, in spite of a certain error in mangrove forest extraction using Landsat images, it is still within an acceptable error range since the study area covers almost 7,000 km^2, thus can generally reflect the variation tendency of mangrove area.

2.3. Mangrove Fringe Analysis

Through the CCDC algorithm, the land cover data for each year were extracted and exported to ArcGIS, where the calculation of mangrove area and the extraction of mangrove fringe were completed. With the help of the DSAS method proposed by NASA (Thieler et al., 2009), the trend of change in the mangrove fringe was analyzed. The baseline of DSAS was set along the seaward edge of the mangroves (Figure 1b), and the interval between transects was 100 m. By calculating Net Shoreline Movement, End Point Rate and other parameters, the variations in time of the mangroves boundary were analyzed. The extension area of the mangroves were quantified using the follow formula:

$$S = \int_{1}^{X} l(x)\, d(x) \tag{1}$$

where S is area, X is the number of the transect, $l(x)$ is the relative distance between the end points, and $d(x)$ is the interval between each transect (100 m in this study).

3. Results

3.1. Temporal Variation of Mangrove Area

From 1986 to 2022, the area of Everglades mangroves exhibited a decline occurring in stages, with the total area reducing from 6,793.5 km^2 in 1986 to 6,246.2 km^2 in 2022, with a cumulative loss of 547.3 km^2 (Figure 1c). From 1986 to 1989, the mangroves remained relatively stable at 6,793 km^2. Afterward, periods of increase and decrease were observed in 1990, 1993, 2006, and 2018. Specifically, the area of mangroves experienced a sharp decline of 212.1 km^2 from 1989 to 1990, followed by a period of stability from 1990 to 1992, and then a decrease of 113.8 km^2 from 1992 to 1993. From 1993 to 2005, there was a gradual increase at a rate of 6.2 km/year, amounting to a total increase of only 70.1 km^2. A minor decrease of 21.9 km^2 occurred from 2005 to 2006, followed by a slow recovery from 2006 to 2017, returning to the levels seen between 1993 and 2005. In 2017–2018, there was a significant sharp decline, with the area of mangroves reducing by as much as 327.2 km^2. From 2018 to 2022, a recovery trend was observed, with an annual growth rate of approximately 12.9 km^2, and a total increase of 52.3 km^2. Overall, the mangroves area in the Florida Everglades displayed a general contraction over a 40-year period, with occasional increases that were significantly smaller in magnitude compared to losses. Aside from a minor loss between 2005 and 2006, three notable sharp declines were observed throughout the study period.

3.2. Spatial Variations of Mangrove Area

From 1986 to 2022, the area of Everglades mangroves decreased by 547.3 km^2, with a loss of 645.1 km^2 and an increase of 97.8 km^2. Loss and recovery were spatially organized (Figure 2a). In latitude, the mangrove loss increased exponentially from North to South, starting from 2.11 km^2 per 1 km, to a maximum loss of 124.8 km^2 at the southernmost end (Figure 2b). Local large-scale loss of about 130 km^2 was also present in the open CP coast. Locations were mangroves expanded were mainly distributed inland, far from the coastline (Figure 2a). The amount of mangrove expansion did not vary significantly in latitude, but was related to the general loss, with degraded areas displaying a larger expansion (Figure 2b). Furthermore, in the years of sharp decline, 1989–1990, the areas experiencing loss were relatively scattered, appearing as sporadic dieback zones, and occurred mainly in areas at higher elevations far from the coastline (Figure 2c, Figure S3a in Supporting Information S1). In 1992–1993, the areas experiencing loss were concentrated in the open central part of CP (Figure 2d, Figure S3b in Supporting Information S1), and in 2005–2006, they mainly occurred in the southern part of CP (Figure 2e, Figure S3c in Supporting Information S1). During 2017–2018, locations experiencing loss were even more extensive, almost covering the entire research area, with the largest dieback patches in the southern and central parts of CP (Figure 2f, Figure S3d in Supporting Information S1). Taken together, the spatial changes in the research area's mangroves were significantly different, with the central and southern parts experiencing greater losses. During the periods of sharp decline, the loss areas in 1989–1990 were scattered and far from the shore, while in 1992–1993, 2005–2006, and 2017–2018, the loss patches were larger and more distributed near the coastline.

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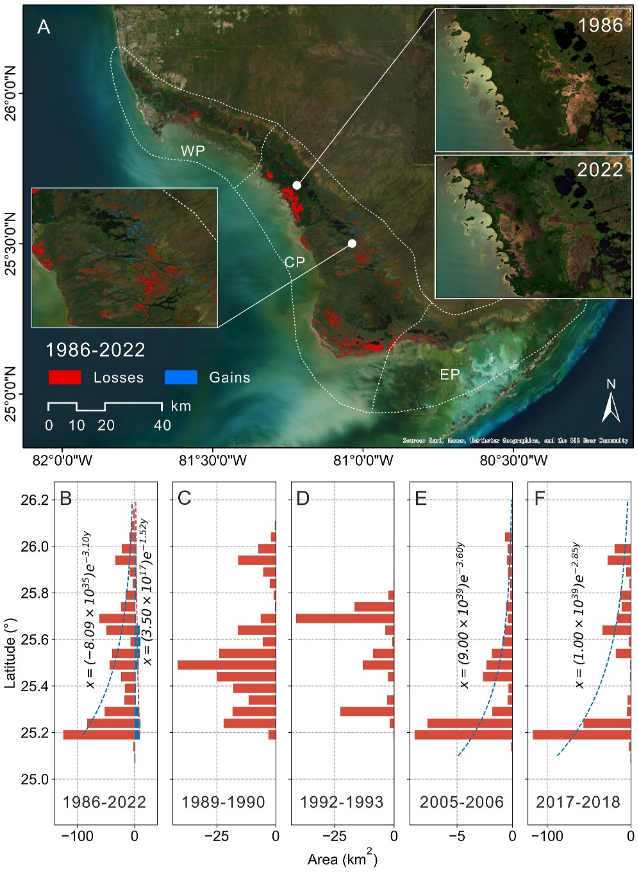

Figure 2. Spatial distribution of mangrove gains and losses from 1986 to 2022.

3.3. Change of Mangrove Forest Shorelines

By analyzing 1,645 sections (Figure 3a), it was found that the overall mangroves shoreline retreated landward by 4.98 km^2 from 1986 to 2022, with an average erosion rate of about −0.90 m/yr, and a maximum erosion rate of −13.4 m/yr (Figure 3b). Limited seaward expansion only occurred in the southern protruding part of CP from Transect 1,100 to Transect 1,645, with an average expansion rate of 0.16 m/yr and the maximum expansion rate of 12.3 m/yr, yielding a total expansion of about 0.65 km^2. From 1989 to 1990, the mangrove fringe hardly changed (Figure 3c); from 1992 to 1993, significant erosion occurred near Naples (Transect 80–200) and in the CP area (Transect 550–1,000), with a maximum erosion of 352 m (Figure 3d), and a total eroded area of about 0.7 km^2. From 1993 to 2005, a larger area near Naples continued to erode, while in the central area (Transect 550–1,000), we detected seaward expansion, with a rate of 15 m/yr (Figure 3e). From 2005 to 2006, a larger area experienced erosion -from Transect 100 to Transect 1,400- with the maximum retreat distance reaching 403 m (Figure 3f). From 2006 to 2017, the mangroves in the research area still showed a certain degree of landward erosion between Transect 100 and Transect 1,300, but there was also expansion between Transect 900 and Transect 1,645 (Figure 3g). During 2017–2018, the mangroves in the research area experienced intense erosion, with the most intense degradation between Transect 100 and Transect 400 and between Transect 1,100 and Transect 1,550, with the maximum erosion distance reaching 966 m (Figure 3h), and an eroded area of about 3.4 km^2. From 2018 to 2022, the erosion weakened, and continuous seaward progradation was present between Transect 1,100 and Transect 1,550, with a maximum rate of advance 109.2 m/yr (Figure 3i).

4. Discussion

4.1. Impact of Hurricanes

Hurricane landfalls can inflict substantial damage to mangroves, leading to the collapse and die-off of large forest areas (Chavez et al., 2023; Lagomasino et al., 2021). We identified all hurricanes that made landfall in the study area from 1986 to 2022, analyzing their tracks and intensities. Our analysis revealed that 14 hurricanes affected the study area during this period (Table S2 in Supporting Information S1), including Hurricane Andrew in 1992, which was a category 5 storm at landfall (Figure S4a in Supporting Information S1). In 2005, Hurricanes Katrina and Wilma impacted the area, with Wilma's landfall wind speeds reaching category 3 levels (Figure S4b in Supporting Information S1). The most severe storm was Hurricane Irma in 2017, the strongest in the past 80 years, with category 5 intensity at landfall, causing extensive damage to Florida (Figure S4c in Supporting Information S1). Additionally, several weaker hurricanes, including Floyd (1987), Fay (2008), Bonnie (2018), and Sally (2020), made landfall in the study area (Figure S4d, Table S2 in Supporting Information S1). Concurrently, we observed a significant decrease of 212.1 km^2 in mangroves cover during the hurricane-free period of 1989–1990, with scattered dieback patches, predominantly in higher elevation regions (Figure S3a in Supporting Information S1), possibly due to extreme drought conditions. This is attributed to the lowest annual precipitation recorded in the study area in 1989, at only 17.6×10^4 mm, compared to the multi-year average of 21.9×10^4 mm (Figure S5 in Supporting Information S1). Generally, increased annual rainfall fosters the expansion of mangroves (Alongi, 2015), while excessive drought can result in mangrove mortality (Osland et al., 2018).

Years with sharp mangroves decline correspond to years when hurricanes landed in the research area, indicating that tropical cyclones are the main cause of loss. Hurricane Andrew in 1992 affected a large area in the lower part of the Florida Peninsula and caused trees to shed leaves, ultimately leading to widespread dieback (Thomas W. Doyle et al., 1995), with a loss of about 113.8 km^2 of mangroves. During the period of 2005–2006, the mangroves area decreased by about 21.9 km^2. The two hurricanes Katrina (2005–08) and Wilma (2005–10), which passed through the research area, caused damage despite being relatively weak. Irma was one of the top five strongest

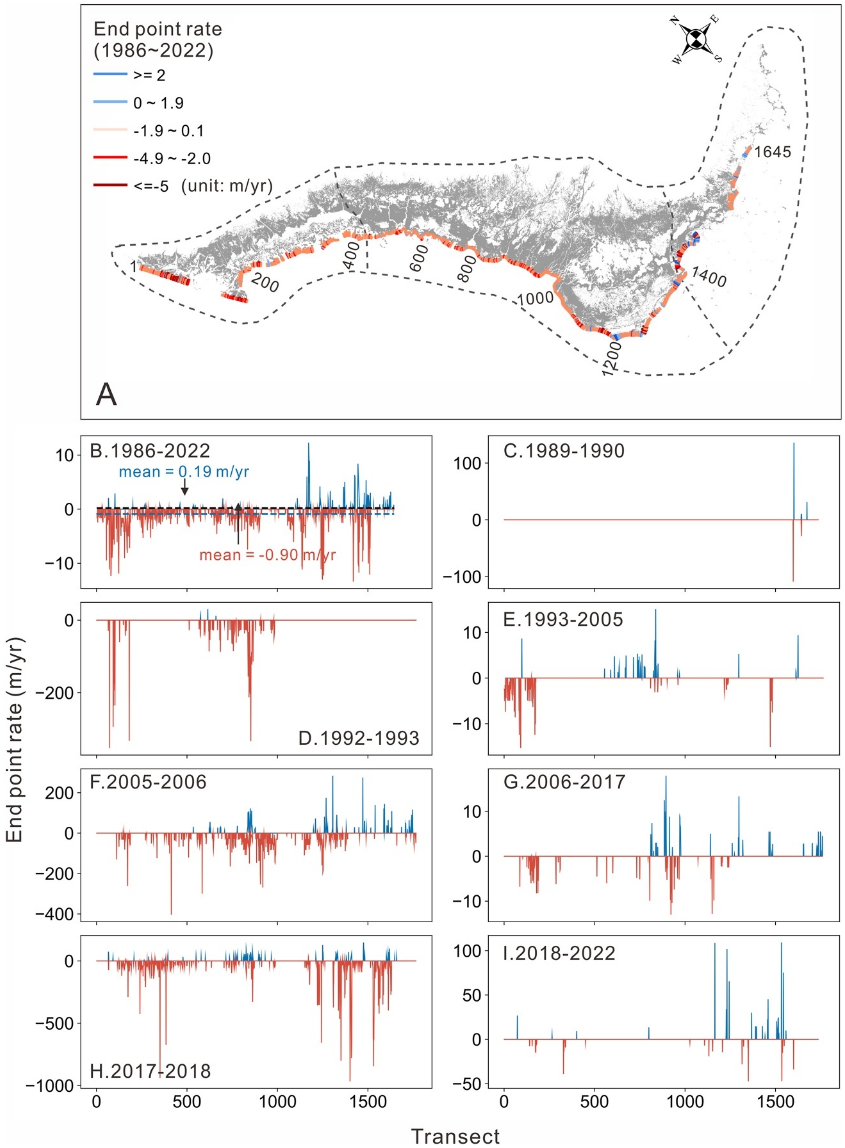

Figure 3. Mangrove fringe change during the period 1986–2022.

hurricanes in the Atlantic in the past 80 years. Its wind field severely damaged the mangroves in the research area, with about 327.2 km^2 of forest being destroyed. In addition, several other hurricanes landed in the research area, but did not trigger mangroves loss, indicating that not all tropical storms cause damage. Mangroves showed a slow recovery after hurricane, with its area increasing by 52.3 km^2 from 2018 to 2022, which can be attributed to the landward moving of sediment induced by hurricane. Mangrove captures the suspended sediment through its root system, thus enhance the tidal flat elevation and providing implantation space for mangrove propagules.

During a hurricane landfall, the wind speed shows a significant exponential decay with distance from the shore (Kaplan & DeMaria, 1995; Powell & Houston, 1996), and mangrove loss also displays a similar decay (Figure 3b). Taking Irma as an example, we computed the cumulative amount of wind speed (sumi) at the latitude of the research area during the hurricane passage (2017.9.9–2017.9.12) (Figure S6 in Supporting Information S1). A significant exponential relationship between cumulative wind speed and mangrove loss was found (Figure 4a). We also found a significant exponential relationship between the intensity of the hurricanes that landed in the research area and the area of mangrove damage (Figure 4b). In addition, the southern protruding part of CP bears the impact of the hurricane first, hence the loss of mangroves there is the greatest. The wind speed decays

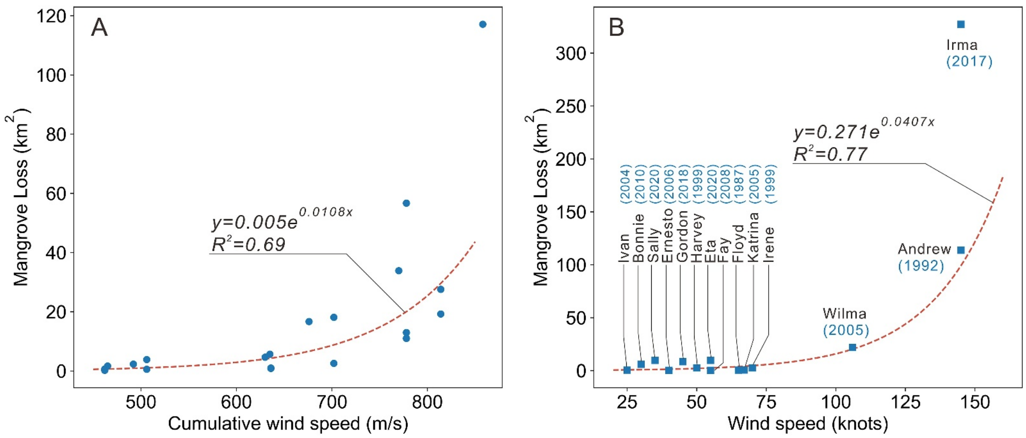

Figure 4. Correlation between wind speed and lost mangroves area. (a) Correlation between spatial loss and cumulative wind speed for different latitudes after Hurricane Irma. (b) Loss of mangrove area for different hurricane intensities.

exponentially with distance from the shore after the hurricane lands, and the area of damaged mangroves also decreases exponentially.

Although mangroves are known as "sea guards" and provide wind protection and wave blocking, their bearing capacity is limited. They can withstand weaker hurricanes well, but when the intensity of the hurricane reaches level 3 and above, they will find it difficult to survive undamaged. With an increase in the intensity of the hurricane, the area of damaged mangroves also increases exponentially (Figure 4b).

4.2. Impact of Sea-Level Rise

Global sea level is rising driven by global warming, and it has an impact on the growth and survival of mangroves (Xiong et al., 2024; Yang et al., 2023). Data from the Naples tide gauge station NOAA 8725110 show that sea level in the research area has been rising at a rate of 5.3 mm per year since 1986 (Figure S7 in Supporting Information S1). Through DSAS analysis, it was found that the mangrove fringe has retreated between 1986 and 2022 with an average rate of 0.9 m/year. However, among the 1,645 sections, 938 (57%) had a progradation rate greater than or equal to 0. Prograding sections reached 95% in the non-hurricane period of 2006–2017, with only 74 sections retreating (Figure 3g). In addition, it was found that from 1986 to 2022 the mangroves in the research area retreated landward by a total of 4.98 km^2. During periods with strong hurricane impact in 1992–1993 and 2017–2018, the mangroves in the area retreated landward by 0.7 and 3.4 km^2, respectively, accounting for 82% of the total erosion area from 1986 to 2022. Therefore, hurricanes are the primary cause of mangrove retreat, suggesting that sea-level rise has had minimal impact in this pristine area with little human activity. Inputs of fluvial sediments are absent, indicating that mangroves capture sediment from the ocean to prograde and accrete thus offsetting sea level rise. We used the Sediment Elevation Change (SET Method) data set from Northeastern Florida Bay (FCE) from 1996 to the present (https://fce-lter.fiu.edu/data/core/metadata/?packageid=knb-lter-fce.1214.6) to extract data from six observation points in southern Everglades (Figure S8a in Supporting Information S1). The analysis revealed that the surface elevation generally showed a slow accretion trend from 2000 to 2017 (Figure S8b in Supporting Information S1). This further suggests that sea level rise has not had a significant impact on this region.

4.3. Prospective

Mangrove forests mainly grow on tidal flats in the tropical zone. The rise in sea level threatens their seaward edge, forcing them to retreat landward (Meeder & Parkinson, 2018; Wdowinski et al., 2016). Coastal development, in particular aquaculture, also pose threats to mangrove growth as ~26.7% of global mangroves loss is caused by the conversion of mangroves to aquaculture (FAO, 2023; Kirwan & Megonigal, 2013; Lin & Yu, 2018). Our study area locates in the Everglades National Park, which is the first national park aiming at protect the fragile ecosystem in the United States, thus coastal development and human activities such as aquaculture are controlled strictly. Therefore, the influence of human activities on mangrove forests as well as the hurricane vulnerability in the study area is relatively limited. Our research results show that, during periods with weak tropical cyclones (1992–2005, 2006–2017, and 2018–2022) the total area of mangroves slowly increased (Figure 1c). Moreover, mangrove expanded mainly in areas previously damaged or where the shoreline had retreated. After a disturbance, mangroves expanded in the following years, indicating slow recovery (Alongi, 2008). However, the recovery rate is far less than the scale of destruction by hurricanes. If the frequency of tropical cyclones increases, mangroves survival will be jeopardized.

Previous work indicated that for every 0.56°C increase in sea surface temperature, the frequency and activity of hurricanes increases by 40% (Saunders & Lea, 2008). According to predictions based on CMIP6 (Coupled Model Intercomparison Project Phase 6), under the SSP1-2.6, SSP2-4.5, and SSP3-7.0 scenarios, the global surface temperature may rise by about 1.97°C, 2.18°C, and 2.32°C by 2,050, and by 2.04°C, 3.18°C, and 4.56°C by 2,100 (Figure S9a in Supporting Information S1) (Scafetta, 2024). Two hurricanes of level 3 or above hit the mangroves in the past 30 years, yielding an average annual loss of about 14.7 km^2. Based on Saunders' findings, we constructed a set of equations relating mangrove loss to changes in global temperature (Formula 2).

$$\text{Rate}_{\text{loss}} = \frac{\Delta T}{0.56} \times 0.4 \times 14.7 + 14.7 \tag{2}$$

where $\text{Rate}_{\text{loss}}$ is loss rate of mangrove, ΔT is the difference from the temperature of 2022.

We project a reduction in mangroves area in the Everglades of 510, 533, and 535 km^2 by 2050 and 1,560, 1,956, and 2290 km^2 by 2100 for the three scenarios, respectively (Figure S9b in Supporting Information S1). The reduced mangroves area by 2,100 for the three scenarios respectively accounts for 24.9%, 31.3%, and 36.6% of the total mangroves area in 2022 (Figure S9c in Supporting Information S1). The wort-hit areas during 1987–2022 are mainly located in the southernmost Florida and the middle-upper CP that are vulnerable to hurricanes (Figure 2a). This can be explained by the cyclones from the Atlantic Ocean, which moves west and goes through above areas firstly by hitting the front, these areas therefore are recommended to have priority when construct protection measures.

5. Conclusions

Mangrove forests provide valuable protection against tropical cyclones, which are becoming increasingly frequent because of global warming. We found that between 1986 and 2022, the Everglades mangroves experienced a net loss of 547.3 km^2, with a total loss of 645.1 km^2 and a gain of 97.8 km^2. Over the period from 1986 to 2022, the mangrove fringe retreated landward by 4.98 km^2, with an average erosion rate of approximately −0.90 m/yr and a maximum erosion rate of −13.4 m/yr. The mangrove fringe remained largely unchanged in non-hurricane years, with hurricane incursions being the primary cause of the landward retreat. Moreover, hurricanes cause an exponential decrease in mangroves loss from south to north, with category three or higher storms being the main drivers of mangroves loss. Sea-level rise did not significantly contribute to mangrove deterioration. Projections suggest that, with the forecasted increase in hurricane frequency, mangroves could loss 533 km^2 by 2050 and 1,956 km^2 by 2100.

Data Availability Statement

Hurricane data for Florida were derived from the National Centers for Environmental Information (https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/shapefile/). Rainfall data were derived from the CHIRPS data set (https://www.chc.ucsb.edu/data/chirps). Sea-level data were derived from the annual average sea-level data of the PSMSL data set at the Naples NOAA tide gauge station 8725110 (https://psmsl.org/data/obtaining/map.html).

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