Do hurricanes or freezing events regulate the sustainability of subtropical mangroves on the Gulf of Mexico coast?

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Abstract

Global warming has caused poleward mangrove expansion, but extreme climatic events have significantly impacted the mangroves along their boreal limits. This study aimed to determine which natural hazard is more important in limiting the sustainability and survival of subtropical black mangroves—hurricanes or freezing events? Satellite and drone images indicated Hurricanes Zeta and Ida (2020 – 2021) caused only minor damage to Avicennia trees (~5%, 6.32 ha) compared with the extensive mortality caused by the winter freeze of Dec/2017- Jan/2018 (~ 89%, 110 ha) at Port Fourchon, Louisiana. However, mangroves impacted by winter freezes had a faster recovery (~1 year), while the losses of mangrove areas by hurricanes are longer-lasting. This finding is novel and important because it implies that subtropical mangroves have low resistance but high resilience to winter freezes, while these forests present high resistance but low resilience to hurricanes. Overwash processes driven by hurricanes are the primary threat to mangroves at Port Fourchon due to the high rate of beach barrier retreat, which causes the burial of the back-barrier wetlands. In 2022 a new beach renourishment project is currently underway, resulting in shoreline progradation. This human intervention is essential to guarantee the stability of the beach barrier and slow down the increased losses of mangrove and salt marsh areas caused by sea level rise and extreme events. The mangrove at Port Fourchon is a microcosm of the general ecological balance of mangroves growing along their northern distribution limit. Thus, our findings apply to the coastal wetlands on the entire northern Gulf of Mexico.

Introduction

The importance of mangroves has been recognized globally as they play an important role in global carbon sequestration (Bouillon et al., 2008; Kauffman et al., 2011; Kristensen et al., 2008; Walsh and Nittrouer, 2004), organic matter export to coastal ecosystems (Lara and Dittmar 1999; Dittmar et al. 2001, 2006b), and as a natural barrier stabilizing and protecting the coastline from coastal hazards (Ewel et al. 1998; Spalding et al. 2010; Hutchison et al. 2014). These forests can mitigate the effects of hurricanes and potentially some tsunamis on the shoreline (Dahdouh-Guebas et al. 2005; Alongi 2008; Koh et al. 2018). In the face of accelerating global warming (Dunn et al. 2020), the poleward migration of mangroves has been documented worldwide (Gilman et al. 2008a; Osland et al. 2017a, 2021; Cohen et al. 2020; Rodrigues et al. 2022; Yao et al. 2022a). In North America, the historical latitudinal range limit of mangroves was located in Cedar Keys, Florida (~29°N, Little, 1978). However, with the increasingly warmer climate during the past few decades, more mangrove colonies have been spotted along the northern GOM coasts (~30°N) in the Florida Panhandle (Yao et al. 2022a; Snyder et al. 2022), Louisiana (Cohen et al., 2021; Rodrigues et al., 2021a; Ryu et al., 2022), and Texas (Montagna et al. 2011; Osland et al. 2013). While mangroves are expanding their frontiers toward the subtropical coastlines, they also face more ecological and environmental challenges, including rapid sea-level rise, habitual competition, and especially natural disturbances such as winter freezes and hurricane landfalls (Gilman et al. 2008a). Thus, the resilience and resistance of mangrove populations near their latitudinal range limits are becoming a focus of research and concern for ecologists and stakeholders around the globe (Derose and Long 2014).

Among the three true mangrove species (*Avicennia germinans*, *Laguncularia racemosa*, and *Rhizophora mangle*) found in North America, *Avicennia germinans* (black mangrove) is the most resistant and resilient species (Tomlinson 2016), due to their unique adaptation traits (e.g., resistant to sub-zero temperature, resilient to physical trauma by resprouting from epicormic shoots, and tolerant to hypersaline conditions) (Alongi 2008; Osland et al. 2018; Osland and Feher 2020). Given that their locations are among the northernmost populations in the North Hemisphere (~29°09`, Alongi, 2002), the black mangroves in the Northern Gulf of Mexico (GOM) are particularly susceptible to winter freezes and hurricane landfalls (Ellison 2008; Cavanaugh et al. 2014; Giri and Long 2014). Previous studies have documented that winter freezes (< - 4°C) can cause physiological damage or even mortality to *Avicennia germinans* (Ross et al. 2009a; Quisthoudt et al. 2012; Osland et al. 2020). On the other hand, while hurricanes can cause mangrove dieback (Lagomasino et al. 2021), they can also have beneficial effects by fertilizing mangrove forests (Castañeda-Moya et al. 2020). However, mangrove resilience vs. resistance against these extreme disturbances has rarely been quantitatively compared and discussed, particularly among populations along their latitudinal range limits. Thus, this paper aims to fill this knowledge gap.

Mangrove forests in the Mississippi River Delta (MRD) are susceptible to climate variations (Ellison 2008; Cavanaugh et al. 2014; Giri and Long 2014) because they are reaching one of their northernmost distribution limits in the Northern Hemisphere. In particular, the northern GOM coast is prone to intense hurricane landfalls. For example, 90 hurricanes have made landfall near the MRD since the 1850s, and 32 were category 3 - 5 hurricanes (Saffir-Simpson Scale) with an average return interval of ~5 years (NOAA 2021). In 2020 and 2021 respectively, Hurricane Zeta (cat 3) and Ida (cat 4) made landfalls near Port Fourchon, Louisiana, in two consecutive years for the first time since 1850s (Yao et al. 2022b). The combined effects of hurricanes and relative sea-level rise (~9.16 mm/year at the present) (Jankowski et al. 2017; NOAA 2021) have caused shoreline retreat at a rate of up to 14 m/year (Cohen et al., 2021; Dietz et al., 2018; Penland et al., 2005; Yao et al., 2018). The rapid shoreline retreat has prompted the Louisiana Coastal Protection and Restoration Authority (CPRA) to intervene by launching beach renourishment projects in 2013 to halt the land loss and coastal erosion (CPRA 2017).

Moreover, the 2017/2018 cold wave brought freezing temperatures to much of central and eastern North America and resulted in 14 days (Dec/25/17-Jan/10/18) with minimum temperature ≤ 0°C near the MRD (Cohen et al., 2021). In contrast to the mangrove populations found at lower latitudes, *Avicennia* colonies near their latitudinal range limit are characterized by having a short stature (< 2.5 m) and a disjunct distribution (Cohen et al., 2021). How these unique mangrove populations respond to the above-mentioned extreme disturbances is still unknown partly because of the lack of baseline data to quantify the duration and magnitude of ecosystem responses. Therefore, which natural hazard is more important in limiting the sustainability and survival of mangrove populations on their latitudinal range limits—hurricanes or freezing events? The effects of these two disturbance agents on mangroves have never been quantitatively compared and evaluated in the literature, but this question is vital for understanding and predicting the future extent and pace of poleward mangrove migration across the globe.

To fill these gaps in the literature, this study focuses on wetlands at Port Fourchon near the MRD, which contains the largest mangrove colonies along their boreal range limit across the GOM coast. This paper evaluates the effects of hurricanes Zeta and Ida on muddy flats occupied by saltmarshes and black mangroves along the coast of Port Fourchon by a spatial-temporal analysis mainly based on drone images obtained before (November 2019) and after Hurricane Zeta and Ida (November 2021). This study also aims to compare the mortality, damages, and recovery patterns of *Avicennia* in response to the 2017/2018 winter freezes versus Hurricane Ida and Zeta, and the effectiveness of anthropogenic interventions to protect this coastal wetland.

Geographical Background

2.1 Vegetation

The study area (29º 09’ – 29º 06’ N, 90º 11’ – 90º 08’ W; 937 ha) near the MRD contains one of the northernmost mangrove colonies in the North Hemisphere (Fig. 1). It is under the influence of a humid subtropical climate, with monthly temperatures between 6ºC and 30ºC, and an average annual accumulated precipitation at ~1600 mm/yr (National Climatic Data Center, 2018). It is part of the Lafourche subdelta lobe, between 0 and 2 m above mean sea-level, and under the influence of the Mississippi River (Coleman et al. 1998) (Fig. 1). It contains a hypersaline (45‰) lagoon-tidal flat system (Bay Champagne) with diurnal microtides (tidal range <30 cm). Historically, the study area was dominated by saltmarsh (*Spartina alterniflora)*, but it has suffered a significant beach barrier retreat since at least 1884 (U.S. Army Corps of Engineers 2004). As a result of the marine incursion and a warming climate, *Avicennia germinans* populations were established near MRD 200 years ago and have became the dominant vegetation since the early 20th century (Rodrigues et al., 2021; Yao et al., 2022a).

2.2 Meteorological information on recent hurricanes

Although Port Fourchon is protected from waves and currents by a beach barrier, the barrier was regularly breached by storm surges caused by landfalling hurricanes (Dietz et al., 2022; Henry and Twilley, 2013), such as Lili (2002), Katrina (2005), Rita (2005), Gustav (2008), and Ike (2008) (Berg 2009; Liu et al. 2011). These hurricanes contributed to the shoreline retreat

(~1550 m, between 1887 and 2012), with various rates of ~14.8 m/yr (1887-1930), ~9.8 m/yr (1956-1998), ~12 m/yr (1983–2018), and 22.7 m/yr (2004 – 2012) (Byrnes et al., 2019; Cohen et al., 2021; Dietz et al., 2018; Williams et al., 1992).

Most recently, our study area was at the center of two intense hurricanes (category 3-4 on Saffir–Simpson Scale) when they made landfall near the MRD. Hurricane Ida made landfall directly over our study site on 29 August 2021 as a Category 4 hurricane. Ida caused up to 5 m of storm surge and maximum sustained wind of ~240 km/h at land fall (NOAA 2022). It was the 5th and 2nd strongest landfalling hurricane in the continental U.S. and Louisiana on the record, respectively. Approximately ten months prior to Ida, another major hurricane, Zeta, made landfall ~50 km west of Port Fourchon, on 28 October 2020. Zeta was a Category 3 hurricane at landfall with maximum sustained winds of ~185 km/h. It caused 1 to 2 m of storm surge at Port Fourchon (Blake et al. 2021).

2.3 2017 – 2018 winter freeze

Between December 2017 and January 2018, a cold wave swept across the eastern GOM and resulted in an average minimum temperature of 4.1 ºC in January and 14 days (3 days in Dec/2017 and 11 days in Jan/2018) with minimum temperature ≤ 0 ºC. During this cold spell, the recorded minimum sea surface temperature was ~5.4 ºC. Winters similar to 2017-2018 occurred four more times since 2000 with a frequency of 1 winter freeze every ~4 years (Cohen et al., 2021), causing damage and mortality in Avicennia germinans (Osland et al., 2019a).

2.4 Relative sea-level rise and fluvial sediment supply

Eustatic sea-level rise (3 mm/yr), local subsidence (10 mm/yr) and reduced fluvial sediment supply have caused retrogradation of the MRD (Blum and Roberts, 2012a; Cohen et al., 2021; IPCC, 2014; Jankowski et al., 2017a; Maloney et al., 2018; Meade and Moody, 2010; Yao et al., 2022a). These processes caused a coastal barrier retreat (165–142 m) in front of the study area between 2004 and 2012, resulting in a loss of ~15.6 ha of backbarrier wetlands by the landward movement of dunes onto the *Avicennia germinans* (1.08 ha) and *Spartina* (14.52 ha) (Cohen et al., 2021).

2.5 Human engineering

To keep oil and gas support facilities at Port Fourchon, the Louisiana Coastal Protection and Restoration Agency (CPRA) installed stone and rubber bulkheads in front of the studied beach barrier (Fig. 1c). It has mitigated the effects of waves and currents on the studied coast (Coastal Protection and Restoration Authority 2015). A beach nourishment project (Nov/2012 - Jan/2015) dredged and transported offshore sand to establish dune and beach habitats (Cohen et al., 2021; Dietz et al., 2022; Jafari et al., 2018), causing the seaward expansion of the beach barrier (30–95 m), an elevation in the dune crest from 1.1–1.3 m to 2.5–3.0 m (2013 – 2019), and stable condition from Jan/2015 to Mar/2019, allowing the mangroves (3.2 ha) and saltmarshes (25.4 ha) establishment on the landward boundary of the beach barrier after 2013 (Cohen et al., 2021). Recent interventions (June/2020 – June/2021 and Jun/2022 - today), involving sediment dredging and constructing earthen containment dikes along the back-barrier and renourished beach, have been implemented to protect the beach barrier and wetlands against wind and wave-induced erosion, sea-level rise, hurricanes and subsidence. In addition, this project intends to generate marshes by dredging sediments from 1.5 miles offshore in the Gulf of Mexico for settlement marsh area (Consultants 2020).

Materials And Methods

The study was based on a spatial-temporal analysis of Lidar data (2002 and 2013), QuickBird satellite (Nov/2004, Oct/2007, Nov/2012, and Jan/2015) and drone images (Oct/2017, Nov/2019, Nov/2021 and Jul/2022). Planialtimetric data and vegetation classification obtained by drone survey were validated by ground control points (Table 1, supplementary material), as presented in a methodology flow chart (Fig. 2) and described in the supplementary material.

Results And Discussion

4.1. Mangrove dynamics between 2004 and 2017

At Port Fourchon, significant expansion of *Avicennia germinans* has been occurring in the study area in a 13-year interval prior to the winter freeze and direct hurricane landfalls: 2004 (23 ha), 2007 (39 ha), 2012 (102 ha), 2015 (90 ha) and 2017 (122 ha) (Fig. 5), a gain of 99 ha (530%). Mangrove expansion has occurred from the south, near the beach barrier and islands in Bay Champagne, to the north of the study area on tidal flats previously occupied by *Spartina*. According to the planialtimetric data obtained by Lidar (2002 and 2013) and drone images (2019), mangrove areas established before 2002 increased their maximum height from ~1.0 m (2002) to ~2.0 m (2013), and to ~2.5 m in 2018 (Fig. 3b). *Spartina* vegetation presented a maximum height of about 0.7 m in 2018. Thus, our result is in line with previous studies that mangroves have expanded on flats previously occupied by saltmarshes, and their population increased at or near their poleward limits over the past few decades (e.g., Field, 1995; Gilman et al., 2008; Osland et al., 2017b; Saintilan et al., 2014), as a consequence of a significant warming trend in annual T_{min} of 0.12 °C/y between 1980 and 2017 (Cavanaugh et al. 2019).

4.2 Loss of mangrove and saltmarshes between 2019 and 2021

Spatial-temporal analysis based on drone images obtained before (Nov/2019) and after (Nov/2021) Hurricanes Zeta and Ida indicates a loss of 9.2% (11.72 ha) of mangrove area (2019= ~126 ha, 2021= 115 ha, Tab. 1). It was caused by a combination of three processes: lateral erosion of mangrove substrate (6 ha), machine dredging of the muddy flats with mangroves (5.4 ha), and sand deposition on mangrove mudflats (0.32 ha) (Fig. 6b). In addition, 28% (~40 ha) of salt marshes were lost by lateral erosion (15%, 21.2 ha) and sand accumulation on muddy flats (13%, ~18.5 ha).

Table 1 – Parameters related to the mangrove, saltmarsh and beach barrier areas before and after the hurricanes Zeta and Ida.

Parameter	**Before (Nov/2019)**			**After hurricanes (Nov/2021)**						
	Area (ha)	**Sed. Volume (m3)**	**Dune crest Height (m)**	**Area (ha)**	**Dune crest Height (m)**	**Beach Barrier Retreat (m)**	**Sed. Volume (m3)**	**Losses by erosion (ha)**	**Losses by sand accumulation (ha)**	**Losses by dredging (ha)**
Mangrove	**126.7**	-	-	**115**	-	-	-	**6**	**0.32**	**5.4**
Mang. Inland	111.4	-	-	105.4	-	-	-	6	-	-
Mang. Back Barrier	15.3	-	-	9.58	-	-	-	-	0.32	5.4
Marsh	**100**	-	-	**60.3**	-	-	-	**21.2**	**18.5**	**-**
Marsh Inland	62.7	-	-	41.5	-	-	-	21.2	-	-
Marsh Back Barrier	37.3	-	-	18.8	-	-	-	-	18.5	-
Beach Barrier	**74.2**	**738,275**	**1.5 – 2.8**	**74.2**	**0.5 – 1.3**	**50**	**447,066**	**-**	**-**	
Front Barrier	34.7	522,087	-	34.7	-	-	147,938	-	-	-
Back Barrier	39.5	216,188	-	39.5	-	-	299.128	-	-	-
Transect 1	-	-	2.1	-	1	62	-	-	-	-
Transect 2	-	-	2.2	-	0.9	25	-	-	-	-
Transect 3	-	-	2.2	-	0.8	64	-	-	-	-

4.2.1 Loss of mangrove and marsh by lateral erosion

Substrate erosion with *Avicennia germinans* was recorded in ~4.7% (~6 ha) of the mangrove area. The *Avicennia* trees collapse by erosion of muddy flats was more accentuated in the north of the studied mangrove areas along the edges of the channels, where the density of the *Avicennia* population is the lowest (1000 – 5000 trees/ha) on flats at elevations between 13 and 25 cm above mean sea-level (amsl) (Figs. 3c and 3d), causing muddy flat retreats between 12 and 2 m (Fig. 6b). By contrast, the southern mangrove areas had the smallest mud flat retraction along channels by lateral erosion, from ~5 to ~1 m (Fig. 6b). These areas also showed a high density of *Avicennia* (5000 – 10000 tree/ha) on higher flats between 20 and 50 cm amsl. Most significant erosion (15%, 21.2 ha) occurred in muddy flats with an elevation between 0 and 12 cm amsl dominated by *Spartina alterniflora* in the northeastern sector of the study area (Figs. 4d and 6b). Some muddy flats with marshes in front of Bay Champagne were eroded away entirely (Fig. 7b).

4.2.2 Loss of mangrove and marsh by sand burial along the back-barrier

The study area has a history of coastal barrier retreat (Cohen et al., 2021; Dietz et al., 2018), marked by erosion along this sandy coastal barrier, resulting in loss of wetland (~15.6 ha) along 4 km of coastline. This process caused a landward sand migration onto flats with *Avicennia germinans* (~1.1 ha) and *Spartina* (~14.5 ha) until 2013, when a beach nourishment project caused an increase in sediment volume and seaward advance of the beach barrier between Nov/2012 and Jan/2015, followed by a relatively stable period between Jan/2015 and Mar/2019. These factors contributed to the increase of mangrove (3.2 ha) and saltmarshe (25.4 ha) areas along the backbarrier after 2013 (Cohen et al., 2021). However, the new spatial-temporal analysis indicated that ~0.32 ha (~0.25 %) of mangrove area was lost by sand accumulation on muddy flats occupied by mangroves near the beach barrier between Nov/2019 and Nov/2021. The mortality of *Avicennia* population predominantly occurred where sand accumulated over the muddy flats and reached the top of pneumatophores. In addition, sand accumulation on muddy flats buried ~18.5 ha (13%) of marsh areas along the back-barrier zone (Figs. 4c, 6b, and 7c). Planialtimetric data obtained between Nov/2019 and Nov/2021 indicated significant beach barrier retreat between 10 and 66 m (Fig. 4c). The sandy flat in front of the beach barrier, exposed to waves, currents, and wind, suffered significant erosion ~374,149 m^3 in sediment volume. On the contrary, the back-barrier wetlands gained ~83,000 m^3 in sediment volume via aeolian and washover transport (Fig. 4). These data indicate that more frequent and intense hurricane landfalls are likely to accelerate shoreline erosion and cause permanent habitat loss for coastal wetlands.

4.2.3. Resistance of mangroves and marshes at Port Fourchon to hurricanes

Hurricane impacts on mangroves may be caused by wind, storm surge, and sandy sediment accumulation on muddy flats (Smith et al. 2009). Strong wind can break branches, defoliate canopy and topple mangrove trees (Doyle et al. 1995; Smith et al. 2009). However, drone images obtained in Nov/2021 have not indicated significant wind impacts on the studied mangrove area. Some Avicennia tree defoliations were recorded only at the edges of mangrove zones that are more exposed to the wind effects.

Storm surge can carry suspended sandy sediments that are deposited on the mangrove substrate as the surge retreats (Risi et al. 1995). Planialtimetric data obtained before (Nov/2019) and after (Nov/2021) hurricanes Zeta and Ida indicate sand layer accumulation between 20 and 60 cm thick along the previous back-barrier wetland substrate, causing the death of mangroves (~0.32 ha, 0.3%) and saltmarshes (~18.5 ha, 13%) (Figs. 4, 6b and 7c). The back-barrier zone received ~83,000 m^3 of sediments by aeolian and washover transport between Nov/2019 and Nov/2021 (Fig. 4 and Tab. 1). Even though most Avicennia trees in the study area have pneumatophores longer than 30 cm, the sand deposits were still thick enough to bury the pneumatophores and kill the Avicennia trees in the back-barrier zone.

The impacts of sediment deposition on mangroves depend on the depth and texture of the sediment accumulated on muddy flats, which affect the mangrove root and soil gas exchange. This relationship has been reported in northern Brazil, where the mangrove community was also degraded by the sand deposition (Cohen and Lara 2003; Cohen et al. 2009). Beach barriers, which may reduce hurricane impacts on inland wetlands by decreasing the wave action (Stone and McBride 1998; Dietrich et al. 2011), can also be a source of sandy sediments for the back-barrier (Turner et al. 2006; Tweel and Turner 2014), thereby degrading the mangroves and marshes (Guntenspergen et al., 1995; Donnelly; et al., 2001). Hurricane Katrina, which impacted our study area in Port Fourchon in August 2005, accumulated 50 cm of a coarse-grained sand layer on the marsh substrates of Bay Champagne (Naquin et al. 2014). In addition, vegetation structure affects sediment deposition. For instance, Hurricane Andrew (1992) caused sand accumulation twice as thick in flats occupied by Juncus roemerianus than in substrates with Spartina alterniflora due to a greater stem density in the former community (Nyman et al. 1995).

Inland mangroves also exhibited minor damage with some loss of mangrove area by lateral erosion of its substrate (~4.7%) along the edges of the channels. This is evident predominantly in the northern part of the studied area, where the density of Avicennia is the lowest on the lower mudflats. These mangroves are relatively young (established after 2004, Fig. 3a). In contrast, relatively little erosion occurred in the south, where Avicennia density is high on the higher mudflats. Mangroves have occupied these muddy flats before 2004. It is noteworthy that a high density of Avicennia trees on elevated flats occurs along the concave edge of two mangrove islands facing the lagoon in the southern part of the study area that experienced the smallest lateral erosion (~1 m of flat retreats) (Figs. 3c, 3d and 6b). It is remarkable that the resistance of the muddy flats occupied by mangroves is different from those occupied by marshes. The contrast is most evident in the northern part of the study area, where significant lateral erosion (15%, 21.2 ha) occurred in the muddy flats occupied by Spartina alterniflora along river channels with an elevation between 0.2 and 12 cm amsl, which is lower than the mudflats occupied by mangroves (13 – 50 cm amsl) (Fig. 6b and 7b). Saltmarshes are recognized as being able to attenuate the wave effects and stabilize the coast (Shepard et al. 2011; Foster et al. 2013; Möller et al. 2014), but some studies have also revealed the vulnerability of saltmarshes to lateral erosion (Marani et al. 2011; Fagherazzi et al. 2013; Leonardi et al. 2016). The ability of saltmarshes to resist the erosion of marsh edges depends on the intraspecific variability in root density (Ford et al. 2016; Wang et al. 2017; Lo et al. 2017; De Battisti et al. 2019).

The hydrodynamics involving water flow and mangrove roots on muddy flats have mitigated erosion caused by the action of waves and currents during hurricanes. The density of the Avicennia trees and their root structures represent essential parameters regulating the sedimentation, sediment density, and resistance to erosive processes (Kathiresan Kandasamy 2003; Nardin et al. 2021; Kazemi et al. 2021). Avicennia trees have complex root systems, with pneumatophores where oxygen spreads by roots. Pneumatophores may be taller (>30 cm) and more abundant in anaerobic and oil-polluted conditions (Kathiresan and Bingham 2001). Water flows around the mangrove prop roots produce a depositional region posterior to the roots (Furukawa and Wolanski 1996; Furukawa et al. 1997). Kazemi et al. (2021) proposed a model for critical flow speed for incipient erosion that considers the mangrove root porosity and the near-bed turbulence effect. In addition, mangrove species may influence the sedimentation rates and substrate resistance to erosion (Krauss et al., 2003; Rogers et al., 2005; McKee et al., 2007; Di Nitto et al., 2013b). Rhizophora, with prop roots, contributes more effectively to the vertical accretion than Avicennia with pneumatophores (Furukawa and Wolanski 1996; Krauss et al. 2003). Studies indicated that muddy flats with a mixed community of Avicennia and Rhizophora trap more sediments than pure stands of Avicennia or Rhizophora (Kathiresan Kandasamy 2003).

Therefore, the presence of mangroves in the study area caused an increase in the resistance of the tidal flats to erosion. The establishment and expansion of Avicennia—and perhaps Rhizophora in the future—in the study area will significantly contribute to the vertical accretion of mudflats and protect these surfaces against erosive processes triggered by hurricanes. Avicennia trees also showed resistance to the sand accumulation on their substrates, acting as a buffer, attenuating the spread of washover deposits into the lagoon.

4.4 Resistance of mangroves and saltmarshes at Port Fourchon to winter freeze

The winter freeze of Dec/2017- Jan/2018 caused defoliation and dry branches on ~ 89% (110 ha) of the *Avicennia* areas at Port Fourchon. The damage primarily occurred in young (established after 2004) and short (1 - 1.5 m tall) trees developing at densities between 1,000 and 10,000 *Avicennia* trees ha^{-1} and on lower flats (13-26 cm above mean sea level), and along the limits of the mangrove stands. Conversely, the damage was less severe in the inner part of the mangrove stand and on the highest muddy flats (20 - 46 cm), where the *Avicennia* trees were taller (1.5 – 2.2 m) and their density was higher (4,000 and 8,000 trees ha^{-1}). These data suggest that vegetation height and tree density controlled the winter freeze damages on *Avicennia* trees, as these features weakened the wind effects along a microclimatic gradient (Cohen et al., 2021). The topography of muddy flats also influenced the damages on *Avicennia* as the coastal plain becomes anaerobic in permanent or frequently inundated areas. Bacteria reduce sulfate to sulfide in tidal flats (Holguin et al. 2001), and low Eh and sulfidic sediment inhibit mangrove development (Lyimo and Mushi 2007). These stress agents and low winter temperatures can intensify the mangrove freeze damage in lower surfaces (Osland et al. 2019b), resulting in enclaves of healthy mangroves amid degraded mangroves (Cohen et al., 2021). Damages to mangroves were no longer identified ten months after this winter freeze. Microclimate and topography likely modulated the pattern of mangrove recovery from the internal to the external mangrove areas (Cohen et al., 2021).

Typically, the low tolerance of mangroves to low winter temperatures makes them more susceptible to winter freeze events than salt marshes, where *Avicennia* is the most cold-tolerant genus of mangroves (Saintilan et al. 2014b). The temperature limits for leaf damage in *Avicennia germinans* are ~−4°C, while the temperature limits for mortality are at about to −7°C. *Avicennia germinans* recovery rates in the post-freeze growing season were 90%, 78%, 62% and 45% for temperatures of −4, −5, −6 and −7°C, respectively, with an expectation of complete recovery between 1 and 3 years (Osland et al. 2019a). Mangrove seedlings (2–3 years old) are also sensitive to temperature fluctuations (Pickens and Hester 2011; Adgie and Chapman 2021). McMillan and Sherrod (1986) reported 100% and 80% survival of Louisiana *Avicennia* seedlings exposed to 2–3°C for 24 h and 5 days, respectively. For this reason, the winter freeze of Dec/2017- Jan/2018, characterized by 14 days of minimum temperature ≤ 0°C and an average minimum temperature of 4.1 ºC in January/2018, degraded ~ 89% (110 ha) of the mangroves at Port Fourchon. In contrast, this extreme event did not cause any damage to the salt marshes species (Fig. 6a).

The immunity of saltmarshes to low winter temperatures has contributed to the mangrove expansion to higher latitudes because the above-ground biomass and the saltmarsh substrate benefit the survival of encroaching mangroves. The dense cover of saltmarshes probably protects mangrove seedlings compared to the lack of vegetative cover in mudflats (Adgie and Chapman 2021). In addition, winter freeze events may affect fewer mangrove seedlings (20–50 cm in height) due to the proximity of the substrate that is warmer than the air (Ross et al. 2009b; Osland et al. 2015). During the winter freeze of Dec/2017- Jan/2018, mangrove seedlings without signs of defoliation were recorded predominantly on muddy flats with saltmarshes at Port Fourchon, which can be related to the dense *Spartina* vegetation (<70 cm tall), protecting the seedlings against wind. Then, seedlings could be protected from the cold winds up to ~70 cm tall. However, above ~70 cm height, *Avicennia* shrubs would be gradually more susceptible to winter freezes up to ~1.5 m tall and a tree density of ~4,000 trees ha^{-1} (Cohen et al., 2021).

Moreover, the physical structure of saltmarsh reduces tidal currents. The friction with vegetation favors mud (fine silt and clay) accumulation on tidal flats by the processes of settling and biological trapping (Stumpf 1983), resulting in an appropriate surface for mangrove establishment (Furukawa et al. 1997). The vegetation structure in saltmarshes also retains buoyant *Avicennia germinans* propagules dispersed by tides, enabling mangrove recruitment (Peterson and Bell 2012). Therefore, saltmarshes can act as pioneer vegetation for establishing the muddy substrate, which in turn facilitates mangrove expansion by trapping seedlings (Peterson and Bell 2012) and creating a warmer layer that protects mangrove seedlings from winter freeze damage (Guo et al. 2013).

4.5 Winter freeze vs. hurricane impacts on mangroves

The winter freeze of Dec/2017- Jan/2018 caused defoliation and dry branches on ~ 89% (110 ha) of the black mangroves at Port Fourchon, but its recovery was relatively rapid (~1 year after the winter freeze) (Cohen et al., 2021). It contrasts with the impacts of Hurricanes Zeta and Ida (2020 – 2021) on Avicennia trees that caused relatively minor damages ~5% (6.32 ha) to these forests by erosion ~4.7% (6 ha) and sand accumulation ~0.32 ha (~0.25 %) along the back-barrier wetlands (Fig. 6). Thus, on the short-term scale, black mangroves are more resistant to hurricane landfalls than winter freezes. However, the impacts of winter freezes and hurricanes in mangrove areas must be considered from a long-term perspective. Although small, the losses of mangrove areas by hurricanes are permanent, as the ~6 ha of coastal zone was eroded due to Zeta and Ida, causing a permanent loss for mangroves. Assuming the progradation of mudflats with the establishment of Avicennia seedlings at low density and topographically lower surfaces, and a hurricane makes landfall once every 3 - 5 years along the Louisiana coastline (Roth 2012; NOAA 2021), these new mangrove zones will be vulnerable to the effects of the next hurricane, and will likely be lost as well. However, the natural trend of mangrove expansion (7.6 ha/yr) over areas previously occupied by saltmarshes should offset these mangrove losses caused by hurricanes (Fig. 5).

Among the factors that can determine the fate of mangroves in Port Fourchon (Fig. 8), the beach barrier retreat is the greatest threat to the mangroves in the study area. Shoreline recession is a product of hurricane overwash, relative sea level rise (~10 mm/yr) (Sweet et al. 2018), and reduction of fluvial sediment supply (Blum and Roberts 2012b). The landward sediment transport with wetlands loss (~15.6 ha along 4 km) in the study area had been occurring for decades until 2013 (Dietz et al. 2022), when a beach nourishment project replenished 2.8×10^6 m^3 of sediments along 9.5 km of coastlines near Port Fourchon (Dietz et al., 2018; Cohen et al., 2021). This nourishment project stabilized the beach barrier until Oct/2017, when shoreline erosion occurred again, threatening the wetlands by restarting the long-term process of shoreline retreat (Cohen et al., 2021). Between Nov/2019 and Nov/2021, a significant loss of >291,000 m^3 of sand sediment (Tab. 1) was recorded, causing a shoreline retreat of up to 64 m (Fig. 4), a decrease in the dune height and sandy flats elevation (Fig. 4c and Tab.1), and the destruction of back-barriers wetlands (~18.5 ha of saltmarsh and ~0.32 ha of mangroves) (Figs. 4c, 6b, 7c and Tab.1). This suggests a resumption of the effects of the beach barrier retreat and that its protection against the action of waves and currents may soon disappear and threaten the marshes and mangroves by intensifying erosion of their substrate. However, our data also revealed that mudflats are more protected against lateral erosion when occupied by dense mangroves

(Figs. 6b and 3c), which causes an increase in vertical sediment accretion and a natural elevation of their substrates (Fig. 3d). Then, the mangrove expansion over areas previously occupied by marshes progressively increases coastal protection against hurricanes. Protecting the hydrodynamic conditions, which favor muddy sedimentation through the Avicennia roots, is essential for mitigating the erosive effects caused by hurricanes.

The above findings are novel and essential for understanding the past and future dynamics of the Avicennia populations at their northernmost distribution limit along the Gulf Coast. The data imply that freezing events greatly impact mangrove areas, but mangroves will recover after ~1 year. Naturally, frequent winter freezes affect mangrove survival, a critical factor for the mangroves to protect the coast against the increased frequency of intense hurricanes. On the other hand, the hurricane impacts are minor but lasting. Considering a long period (10 years), hurricanes can accelerate beach barrier erosion and shoreline retreat and bury the back-barrier wetlands. If the barrier was breached, the muddy flats with mangroves and salt marshes would be more vulnerable to the erosive action of waves and currents generated by hurricanes. In this case, human interventions are needed to ensure the stability of the beach barrier.

4.6 Human intervention on coastal wetlands

Recent interventions involving machine dredging to the construction of earthen containment dikes (Fig. 6b) along the back-barrier have been implemented between June/2020 and June/2021 to protect the beach barrier and wetlands in Port Fourchon (Consultants 2020). This coastal engineering project has removed mangrove mudflats that destabilized adjacent mudflats, causing the collapse of other mangrove substrates and the loss of ~5.4 ha of mangroves (Fig. 6b). These damages are comparable to the mangrove loss caused by hurricanes between 2019 and 2021 (Table 1). The mudflats with mangroves were dredged and the earth was used to construct these dikes that were ~1.5 m high and ~15 m wide. The long-term effects of these dikes have to be monitored. It is possible that these dikes, associated with other interventions, will benefit the mangrove and marsh stability over the long term. In June 2022, a new beach renourishment project started with the transfer of sediments from the back to the front of the beach barrier, causing a coastal progradation of up to 26 meters (Fig. 4a and 4c). Our data did not indicate significant changes in the sediment volume between Nov/2021 and Jul/2022. An important issue that deserves to be discussed is the effectiveness of this costly undertaking in the face of future hurricanes.

Our findings imply that adding mud to the back-barrier zone to increase the mudflat area and planting *Avicennia* seedlings may be a more effective way of coastal protection at Port Fourchon. Some studies have suggested that the combination of breakwaters—similar to those that already exist in the study area in front of the beach barrier (Fig. 1c)—and the plantation of mangroves is efficient in protecting the shoreline against the action of waves and currents (Akbar et al. 2017; Ratri et al. 2021). Such measures would favor the accumulation of sandy sediments in front of the beach barrier and the preservation of muddy flats with mangroves and saltmarshes behind the beach barrier.

Conclusion

Hurricanes Zeta and Ida (2020 – 2021) caused only minor damage to Avicennia trees (~5%, 6.32 ha) relative to the extensive degradation caused by the winter freezes of Dec/2017- Jan/2018 (~ 89%, 110 ha) at Port Fourchon. However, though small, the losses of mangrove areas by hurricanes are permanent, while mangroves impacted by winter freezes can recover after ~1 year. In addition, the natural trend of mangrove expansion (7.6 ha/yr) over areas previously occupied by saltmarshes should offset the mangrove loss caused by lateral erosion during hurricanes, and the presence of mangroves in the marshes would also increase the resistance of the muddy flats to the action of waves and currents. The beach barrier retreat—controlled by the frequency and intensity of hurricanes, relative sea level rise, and reduction of fluvial sediment supply—is the greatest threat to the mangroves at Port Fourchon. This finding is novel and important because it implies that the mangroves growing along the Gulf of Mexico coast have low resistance but high resilience to winter freezes. Consequently, these extreme events have not prevented the mangrove expansion along their boreal limits. By contrast, the studied mangroves showed a high resistance and low resilience to hurricanes, primarily because hurricanes can cause permanent habitat destruction by forcing shoreline retreat and burying the back-barrier wetlands. In this case, beach renourishment, such as that developed in 2013 and currently underway since Jun/2022, coupled with the plantation of mangroves along the back-barrier wetlands and breakwaters, would favor the sandy sedimentation in front of the beach barrier and the preservation of muddy flats with mangroves and saltmarshes behind the beach barriers.

Our findings on the resistance and resilience of subtropical mangroves to climate extremes should inform decision-making on developing the best methods needed to protect the coast of Louisiana. Therefore, the effects of winter freezes, hurricanes, relative sea level rise, and decreased fluvial sediment supply on beach barriers and wetlands on the Gulf of Mexico coast associated with human interventions must be monitored on a high-resolution spatial and temporal scale, only possible through the methodology presented here.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

M.C. conceived the hypothesis, led the spatial-temporal analysis, fieldwork, wrote the manuscript and led the project.
Q.Y conceived the hypothesis, assisted in writing, editing, and field work. A.V.S assisted the spatial-temporal analysis and field work. K.B.L assisted in writing and editing and led the project. S.N. assisted analyses. E.R assisted analyses and field work. L.C.R.P assisted analyses. N.C. assisted analyses. All authors contributed to the discussion and finalization of the paper.

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Availability of data and materials

All datasets produced in this article will be stored at the PANGAEA Database (https://issues.pangaea.de/browse/PDI-33136) upon publication and accessible to the public for free.

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Figures

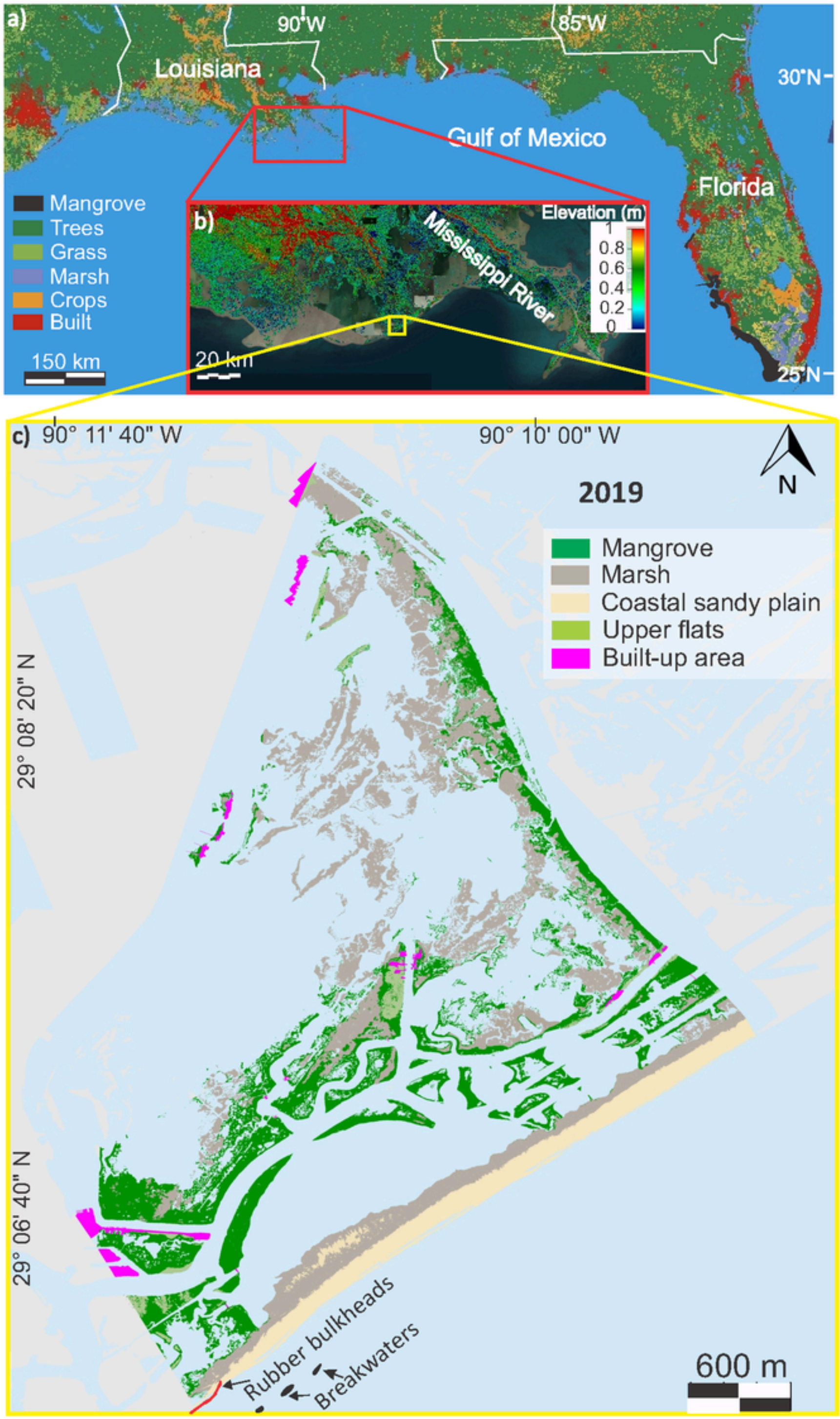

Figure 1

a) Study area with vegetation map based on Brown et al. (2022); b) topographic map of the Mississippi River delta plain near Port Fourchon based on Lidar data; c) study area showing the mangroves and salt marshes in 2019 with anthropogenic interventions (breakwaters and rubber bulkheads).

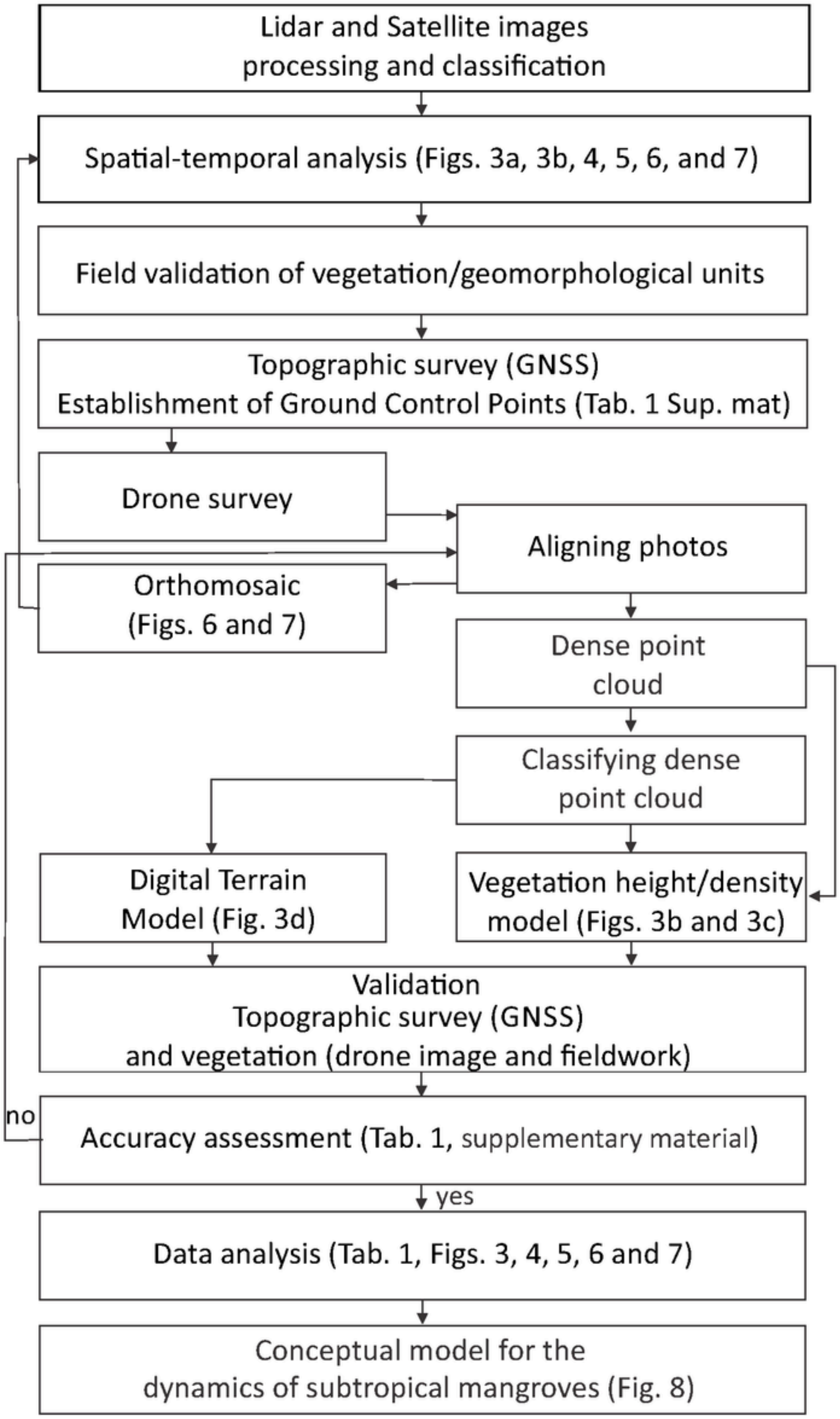

Figure 2

Methodology flow chart modified from Cohen et al. (2021).

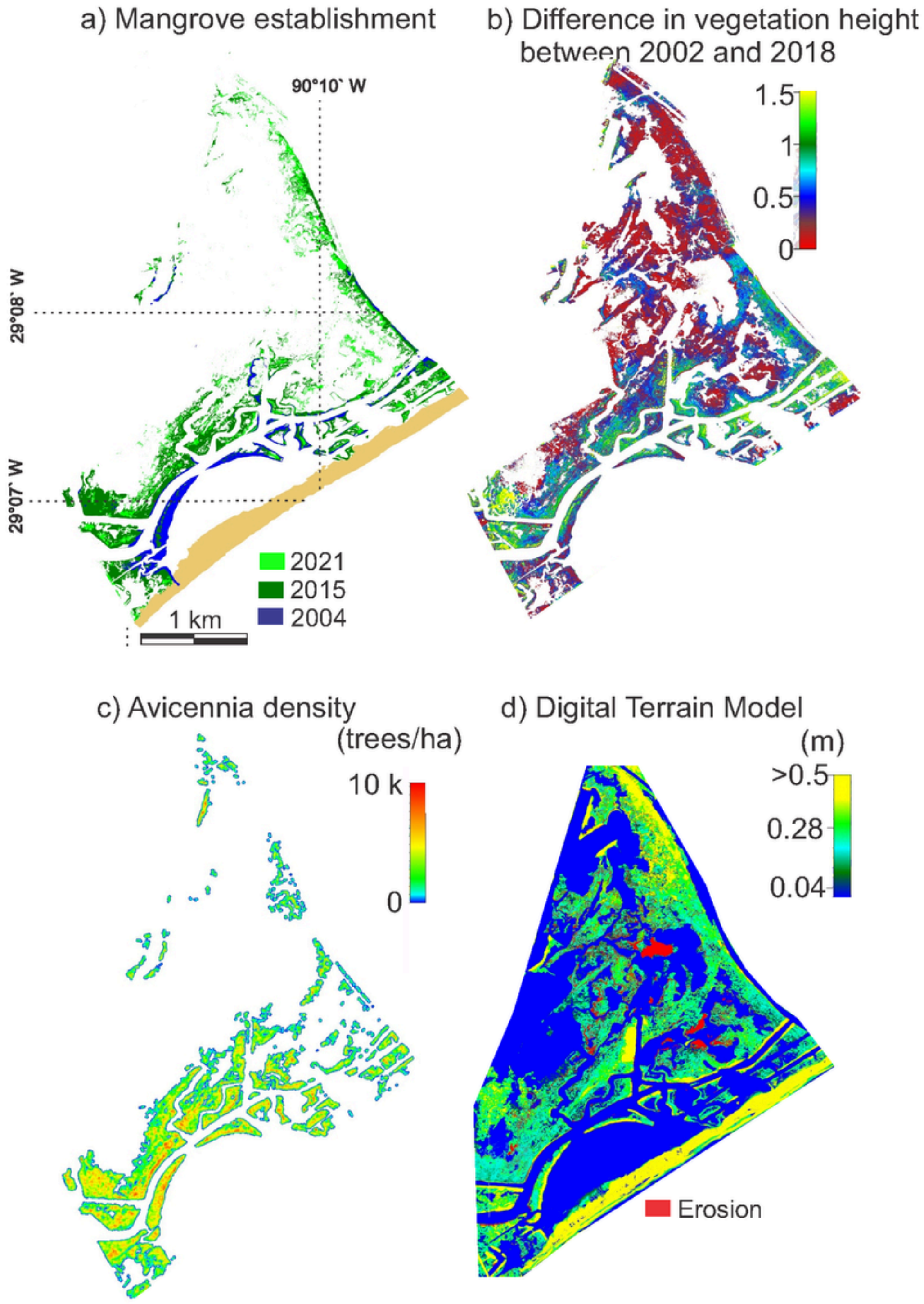

Figure 3

a) Spatial-temporal analysis based on satellite and drone images between 2004 and 2021, showing the mangrove expansion; b) difference in vegetation height between 2002 and 2018, based on Lidar and drone data, evidencing the increase in mangrove vegetation height; c) *Avicennia* density model; c) digital terrain model, based on drone data obtained in 2018, showing the mudflats erosion between Nov/2019 and Nov/2021.

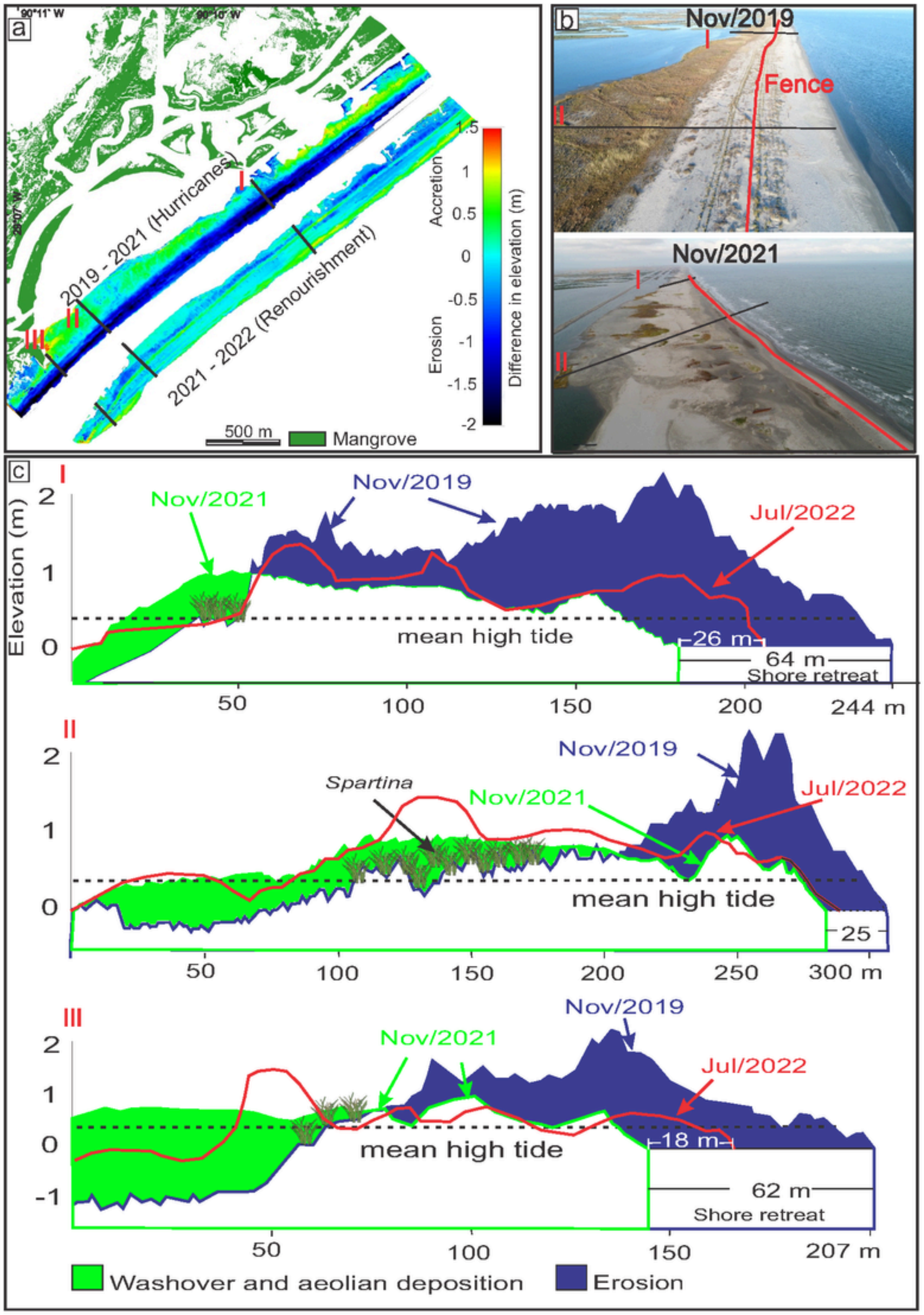

Figure 4

a) Planialtimetric analysis showing erosion and accretion in front of the beach-barrier and back-barrier between Nov/2019 and Jul/2022; b) panoramic photos showing erosion in front of the beach-barrier and sand accumulation on back-barrier wetlands between Nov/2019 and Nov/2021; c) planialtimetric profiles I, II, and III across the beach barrier, showing the dune crest positions, shoreline retreat, and buried saltmarshes, based on drone data.

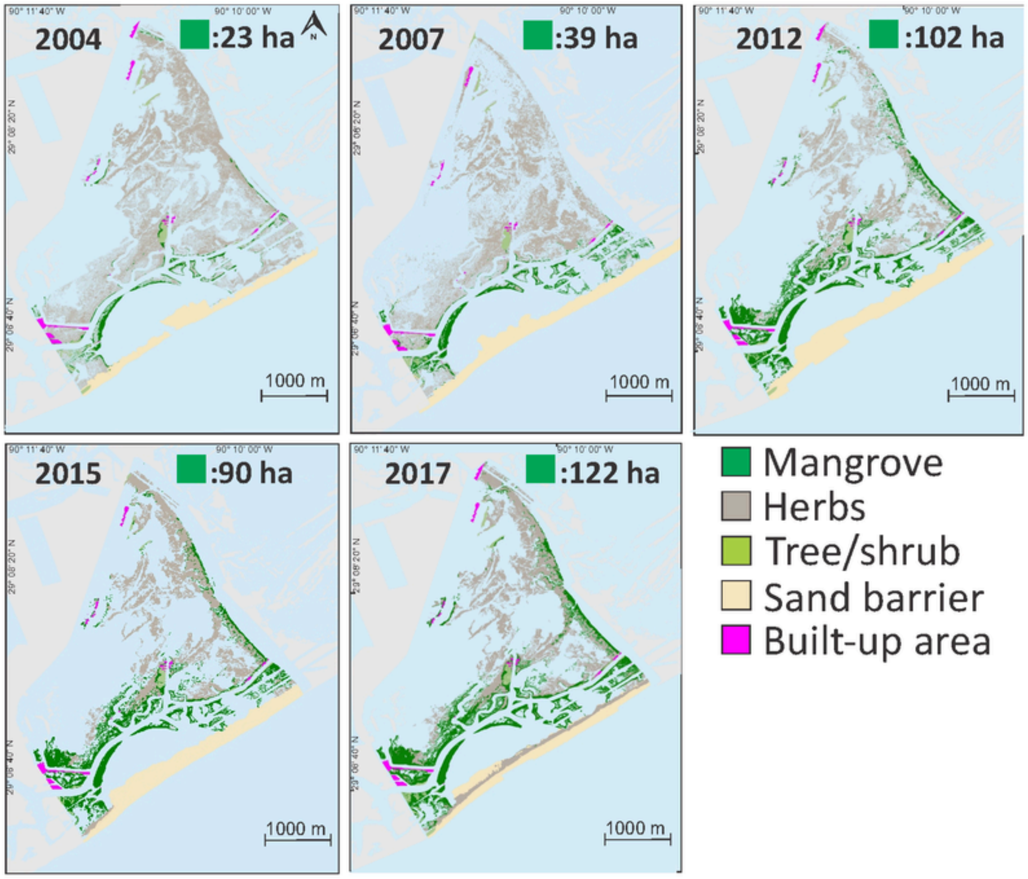

Figure 5

Spatial-temporal analysis based on satellite images between 2004 and 2017, showing the pattern of mangrove expansion.

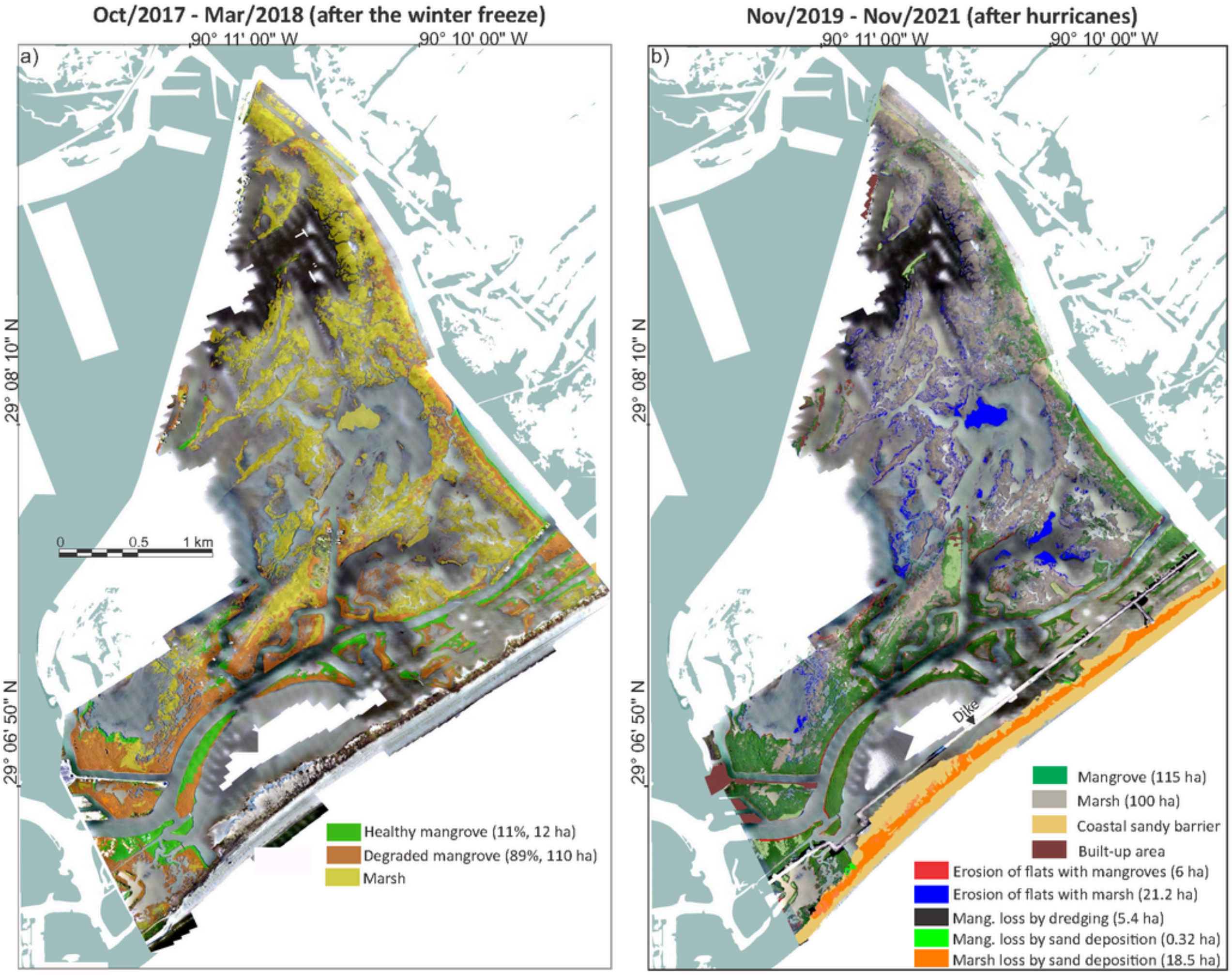

Figure 6

Spatial temporal analyses based on drone images comparing the impacts of a) a winter freeze with degraded (as evidenced by defoliation and dry branches on *Avicennia* trees) and healthy mangroves (Oct/2017 – Mar/2018) and b) hurricanes (Nov/2019 – Nov/2021) obtained from drone images.

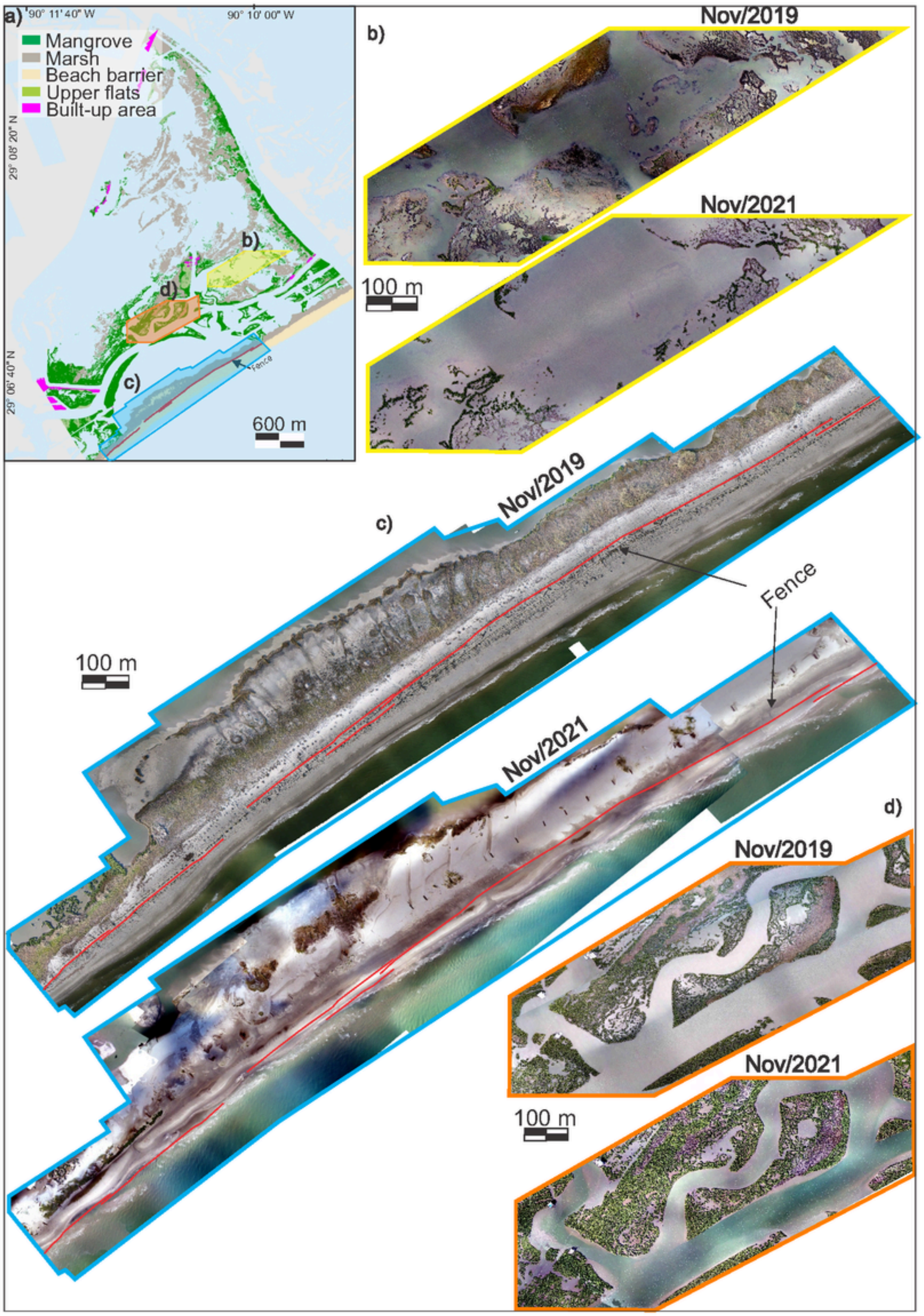

Figure 7

a) Vegetation map based on drone images highlighting b) orthophotos obtained in Nov/2019 and Nov/2021 with expressive mudflats erosion occupied by saltmarshes; c) beach barrier erosion and sand deposition on back-barrier wetlands. The red line represents fences built along the beach-barrier; and d) reduced mudflat erosion occupied by mangroves.

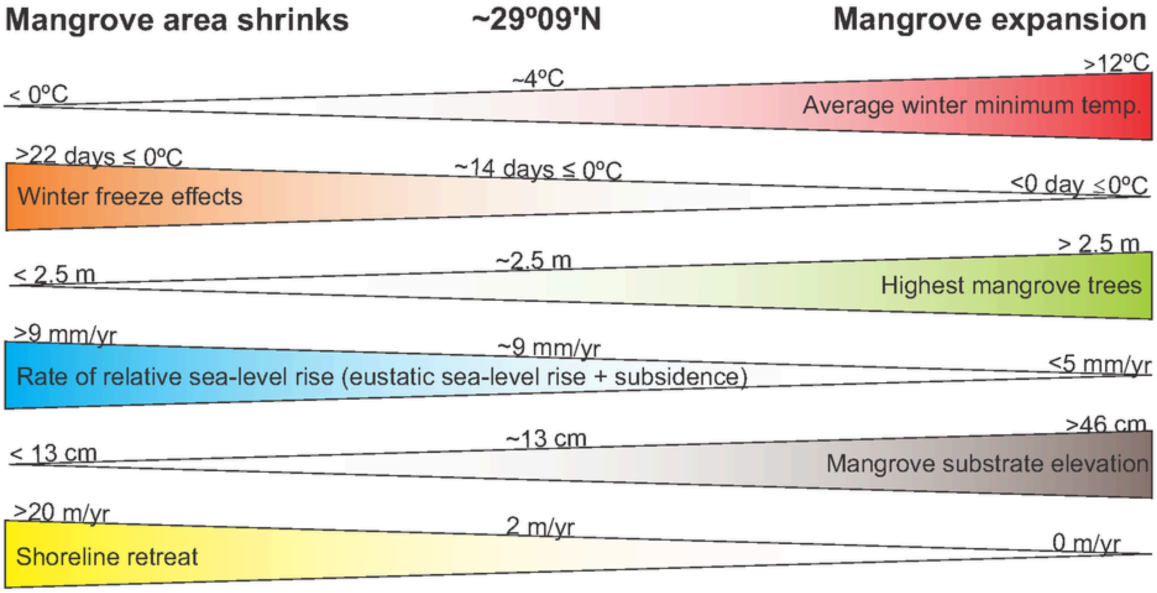

Figure 8

Conceptual model for the dynamics of subtropical mangroves at Port Fourchon (29^{o}09’N) under various scenarios of climate (winter freezes and hurricanes) and relative sea-level rise (eustatic sea level and local subsidence) changes. Color gradients represent the magnitude of change with values obtained for the study area (Cohen et al., 2021a; Cohen et al., 2021b).

Supplementary Files

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