Analysis of Erosion and Subsidence in Texas Coastal Wetlands: Effects of Vegetation Type and Historic Freeze in Feb. 2021

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Co-Principal Investigators: Drs. C. Edward Proffitt & Donna J. Devlin

Texas A&M University – Corpus Christi

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Introduction

The Texas coastal zone is experiencing erosion that threatens the economy, ecology and the quality of the quality of life. The main drivers of erosion are Sea Level Rise (SLR) and extreme storm events. These threats are not unique to Texas as coastlines across much the globe are retreating; however, the condition in Texas vary dire. Coastal management will be most effective if it is based on the latest data regarding SLR provided by NOAA, USGS and local experts. To understand what is happening in Texas, it is essential that we compare the SLR along the Texas coast with SLR on global and continental scales.

Incontrovertible data clearly indicate that the rate of global mean SLR has been increasing more rapidly during the recent years than over the last century. Over a period of just nine years, from 2006–2015, sea level rose at a rate *two and a half times the average that occurred throughout most of the twentieth century* (NOAA Center for Operational Oceanographic Products and Services). Satellite data 2021, indicate that global mean sea level was 97 millimeters (3.8 inches) above 1993 levels, making it the highest annual average in the satellite record from 1993 to 2021 (Fig. 1) (NOAA Center for Operational Oceanographic Products and Services).

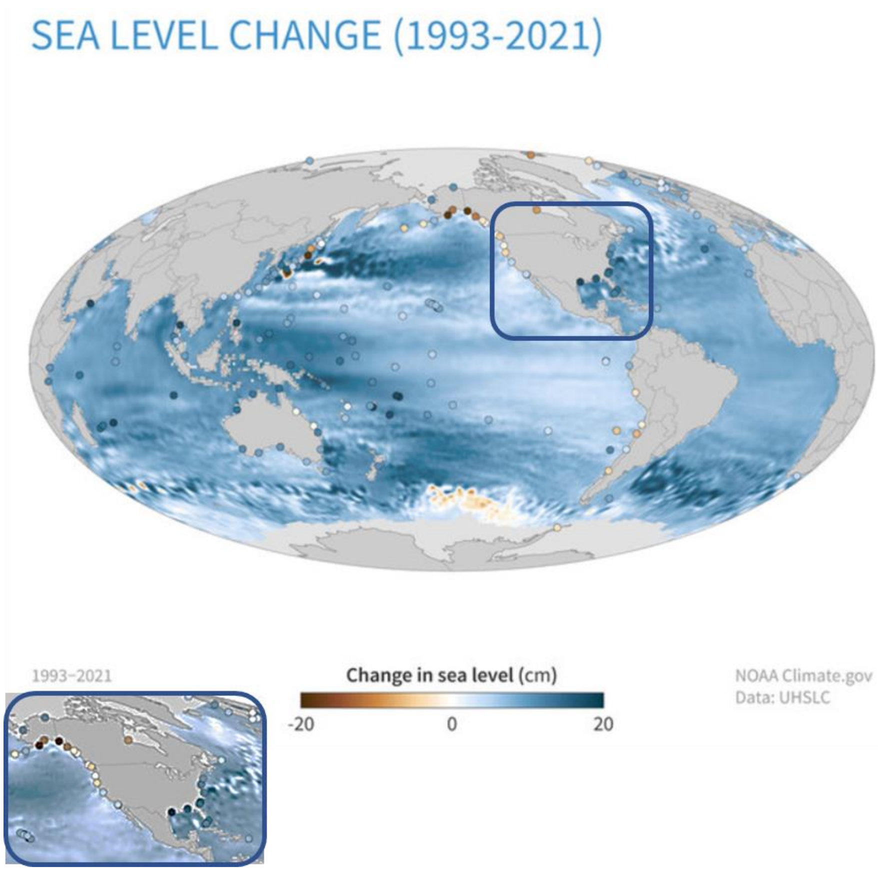

Figure 1. Sea level change from 1993-2021 measured since the start of the satellite record (https://climate.nasa.gov/vital-signs/sea-level/) modified with inserted box and magnified cut-out of United States, Mexico and Central America.

The greatest rates of SLR, 15-20 cm (6-8 in.) were measured along the Texas coast, and the Louisiana coast west of the Mississippi Delta (Figure 1); some regional differences occur as a result of variability in the strength of winds and ocean currents, that influence where heat is stored in the deeper layers of the ocean and thus thermal expansion of water (NOAA Center for Operational Oceanographic Products and Services). Estimates of 2050 Sea level in the western Gulf of Mexico give likely increase of approximately 40.5- 45.7 cm (16-18 inches), a level about 15 cm (almost a ½ foot) higher than the national average. (Lindsey, 2022).

Local consequences of SLR can be quite different because factors that influence SLR, such as subsidence (from water, oil and gas extraction) erosion, trapping of sediments by dams, etc. often vary substantially over relatively short distances (see Nichols et al. 2021 for a recent review and global perspective). In Texas, most geodetic on-the-ground assessments of subsidence were concentrated in the few larger urban areas, for northern parts of the Coastal Bend (Corpus Christi/Nueces Bay northward through Victoria area) rates of flooding are higher as a result of increased subsidence caused by both the extraction of hydrocarbons and water and faulting (Haley et al. 2022). In Galveston, where there's a very accurate long-term tide gage, sea level has risen 71 cm since 1900 (Liu et al. 2020). A remarkable number that foreshadows substantial and significant changes to come in the upcoming decades, not only in Galveston Bay but elsewhere in coastal Texas.

Texas coastal zone is retreating an average of 1.25 m/yr and is largely exacerbated by erosion associated with extreme events such as hs Harvey (GLO 2017) and hard freezes (Sherrod and McMillan 1985). High resolution models indicate the degree of warming in the tropical Atlantic compared to the global ocean is a key factor controlling Atlantic major hurricane activity in the Gulf of Mexico appears to be the degree to which the tropical Atlantic warms relative to the rest of the global ocean. Further they conclude that future warming will translate into greater numbers of major hurricanes in future years. There is also evidence that hard freezes may be more common in south Texas in the coming years, this is because in recent decades, the polar vortex has been breaking down more frequently, than it did in the past, this creates the potential to bring Arctic blasts of cold air deeper into the U.S. (Cohen et al. 2021). Although freeze events are likely to occur less frequently than hurricanes, but have the potential to to affect a much greater extent of the coastal zone (Proffitt and Devlin, in preparation).

Coastal vegetation, salt marsh and mangrove, can reduce erosion and shoreline retreat. A review of the value of salt marsh vegetation for coastal hazard mitigation concluded that salt marsh vegetation reduces wave height and lateral erosion, and increases accretion and marsh surface elevation (Leonardi et al.2018). Mangrove-vegetation can reduce erosion rates in high wave energy sites and result in accretion at low energy sites (Sánchez-Núñez et al. 2019). At Harbor Island, Texas, experimental plots with mangrove densities as low as 10% in a matrix of salt marsh effectively prevented erosion from Hurricane Harvey; while shoreline retreat occurred in salt marsh plots (Pennings et al. 2021). Among mangrove species, *Avicennia* are especially effective in accreting sediment, as their root systems as slow currents from tidal exchange and fresh water discharge, thus they consolidate the soil and build up land (Othman 1994).

Clearly, the potential for coastal vegetation to reduce the consequences of SLR and subsidence and erosion in intertidal wetlands and other systems are profound. Both salt marshe and mangroves have value for coastal hazard mitigation and climate change adaptation (Sánchez-Núñez et al. 2019). (Krauss et al (2020). We initiated a study of elevation change and egetation composition at sites along a latitudinal gradient from the Lower Rio Grande Valley – Boca Chica State Park (26° 0' north) to Port O'Connor (28° 27'). Study sites are each described more fully and the experimental design detailed, in the Methods.

Texas coastal wetlands are changing in many locations from dominance by herbaceous salt marsh species to dominance by tropical mangroves due to climate change. Our study factored in the effects of vegetation type on elevation change in order to assess the consequences of vegetation change on surface elevation, erosion, and shoreline retreat. In the midst of our study, a historic freeze occurred the week of February 14, 2021. Mangrove vegetation was eliminated in some sites and substantially reduced in most others. So, our focus also became the effects of this massive disturbance on the vegetation and the cascade of effects to surface elevation.

Materials and Methods

Surface Elevation Table – Marker Horizon Methods

Surface Elevation Tables and Marker Horizons (hereafter abbreviated SET-MH) is an accepted standard method for assessing to measure elevation change, accretion and erosion, and subsidence used worldwide (Cahoon et al. 2000; Lynch et al. 2015; Cahoon et al. 2020). Different forms of SET are used to address different questions. We restrict our discussion to the typical deep Rod SET (sometimes referred to as RSET) as that we used, as did the Mission-Aransas National Estuarine Research Reserve (see report by Cressman et al. 2020) and the USGS for 5 northern Texas National Wildlife Refuges (Moon et al. 2022). A diagram of SET-MH from Lynch et al. (2015) (Fig. 2.)

The SET-MH uses a portable **arm** and **collar** (Fig. 3a) that are placed on a **receiver** (Fig. 3b) which has been cemented onto the uppermost of a series of 1.2 m threaded steel rods driven into the sediment to the depth of "refusal" (i.e., will not move further downward even with continued pounding) that forms a permanent benchmark sometimes called a SET mark.

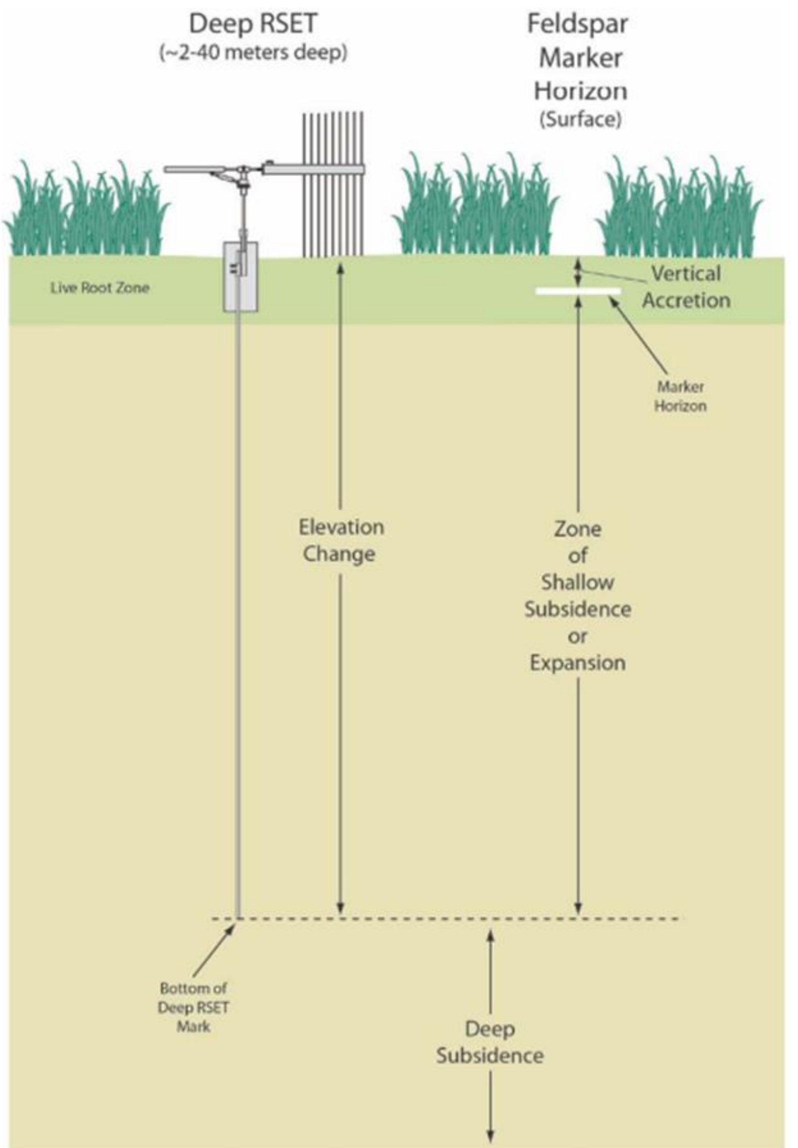

Figure 2. Diagram of deep rod SET and marker horizon from Lynch et al. (2015). The SET measures elevation change relative to be bottom of the steel rod benchmark and the MH (often feldspar) measures vertical accretion. SET minus MH provides a measure of deep subsidence (below the SET rod benchmark.

Figure 3a (left) the removable arm sitting on the collar (held steady by pink clamp), with the collar attached to the permanent receiver. 2b (right) the permanent receiver attached to the uppermost steel rod shown before cement is added to fill the hole. Picture on the left shows the pvc core after the receiver is cemented in. The photograph of the arm was taken at our Padre Island National Seashore site, and the receiver (right) is from our Boggy Creek / Port O'Connor site.

The arm is carefully machined (Nolans Machine Shop, Lafayette, LA) and can be leveled in X, Y, and Z dimensions to ensure placement at different measurement times. Numbered pegs and holes on collar / arm also allow the user to be sure that he/she are measuring the same exact location (or "arm placements") every time. Typically, multiple arm placement locations are measured for each SET. In our project, we used 4 arm placements per SET. Fiberglass pins are inserted through holes in the arm and gently lowered to the sediment surface (see Fig. 3a). Our arm uses 9 pins and distances from top of pin to arm are measured to the nearest mm. The 9 values are averaged to get a single value per arm placement. A feldspar marker horizon (Fig. 4a) established at one of our sites, and an illustration of a core taken through a marker horizon (Fig. 4b), illustrate the MH methodology.

Figure 4a. (left) Feldspar set on the wetland surface as a marker horizon (PINS site). b. (right) a core showing s
above the marker horizon (from: https://www.tidalmarshmonitoring.net/monitoring-methods-marker-horizons.

Vegetation

Our method for quantifying vegetation included establishing fixed quadrat plots, usually 5x5 m in size (Fig. 5) but at some sites the intertidal range was smaller and so smaller quadrats were used. These plots were located a minimum of 5 m from SET-MH plots. Along with these, we also established other plots at random in the vicinity after the freeze in order to better assess vegetation patchiness. Densities and sizes (height and canopy diameters) of all live and dead mangrove shrubs were measured. Counts of seedlings were also collected at multiple 1x1 m subplots. Percent cover was recorded for all marsh plants by species in entire plots when visible, but in subplots where visibility was impaired by mangroves.

Fig. 5. Establishing permanent vegetation plots at The Nature Conservancy's Cohn Preserve on Mustang Island.

Experimental Design

Our study design for SET-MH and vegetation plots is depicted in (Fig. 6). SET benchmarks were established at the border between mangrove dominated (canopy edge) and marsh dominated portions of each site where both habitats existed (at all except PINS site, where there were few mangroves). A MH was located in both marsh and mangrove dominated areas as well near each SET. Two SET arm placements were used in both the marsh and mangrove dominated areas of each SET. Each study site had 3 SET-MH and vegetation plots established, however 2 of the SETs at Boggy Creek in Port O'Connor were destroyed by vandals. Establishment at some sites was delayed because of COVID-19 protocols, therefore periods of measurements are not all the same.

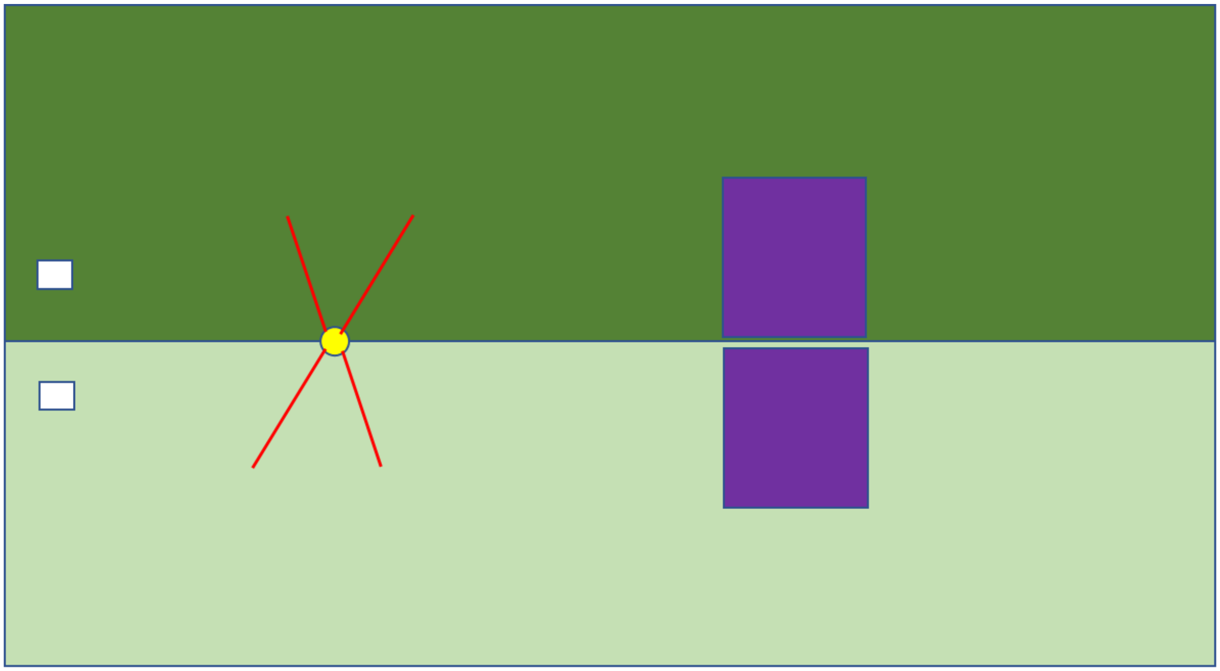

Figure 6. Illustration of the study design. Dark green signifies mangrove dominance, light green marsh dominance. The yellow circle is the receiver and SET mark. Red lines illustrate are placements (2 in mostly mangrove, and 2 in mostly marsh areas). Large purple squares signify vegetation plots.

Study Sites

The 7 Sentinel Sites spanned a large segment of the Texas coastal zone (Fig. 7) designed to complement without duplicating the spatial coverage of two other studies employing SET methods: a) USGS study of 5 National Wildlife Refuges ranging from Aransas NWR to McFaddin NWR the Louisiana border and b) a Mission-Aransas National Estuarine Research Reserve assessment of elevation change in their reserve and the Nueces Delta Preserve. After the February 2021 freeze, addition vegetation stations were added, but no SET-MH, in order to better assess marsh-mangrove vegetation changes (Fig. 7). These sites span a substantial range of environmental factors that influence vegetation type (Gabler et al. 2017).

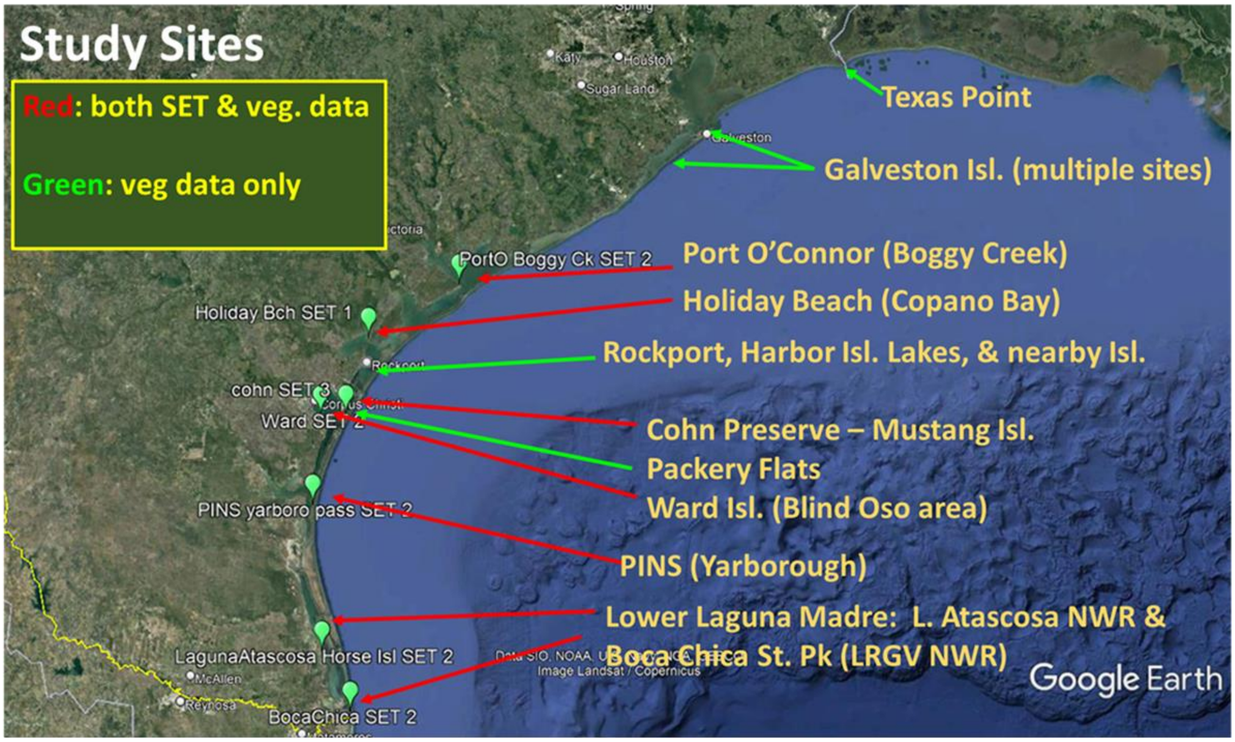

Figure 7 . Locations of SET-MH sites (with vegetation plots) are indicated by red arrows. Additional vegetation plots added after the Feb. 2021 freeze are designated by green arrows.

Description of vegetation and ecological characteristics

Two SET-MH sites are located as follows, two in the Lower Laguna Madre (NWR's), one in the Upper Laguna Madre (PINS), two in Corpus Christi Bay (Mustang Island, The Nature Conservancy's Cohn Preserve) and Oso Bay (Ward Island), one in Copano Bay (Holiday Beach at the Coastal Bend Bays and Estuaries Program property), and one in Matagorda Bay (Boggy Creek Nature Park at Port O'Connor). Details of location and installation are given in Table 1. These groups of sites vary in temperature and precipitation, two primary drivers of vegetation (Gabler et al. 2017).

The Laguna Madre is hypersaline because evaporation exceeds precipitation (Tunnell 2002), and salinities frequently exceed that of ocean waters. Wind-tidal flats and marshes dominated by succulent species (e.g., *Batis maritima, Sesuvium portulacastrum,* and *Sarcocorina virginica*) are common. The black mangrove *Avicennia germinans* has become a dominant or co-dominant in the Lower Laguna Madre, but is less abundant in most of the Upper Laguna Madre (Proffitt and Devlin, in press).

The Cohn Preserve is in Corpus Christi Bay on Mustang Island. The Ward Island site is in the “Blind Oso” part of Oso Bay part of the broader Corpus Christi Bay system. Nutrients are relatively high in the Blind Oso, and substantially lower at the Cohn Preserve (based on data downloaded from nearby water quality stations, and not detailed herein). Mustang Island has salinities are somewhat stable and similar to much of eastern Corpus Christi Bay because of the proximity of Gulf of Mexico waters entering through Packery and Aransas Passes. In the Blind Oso, salinities vary substantially based on season (hot, dry summers) and urban discharges. Rainfall is greater than in the Laguna Madre, but less than that of estuaries further north.

Holiday Beach on Copano Bay is primarily dominated by a mixture of *Spartina alterniflora* and *Batis maritima*. There was sparse mangrove coverage at this site at the start of the study. Rainfall is higher, and salinities typically somewhat lower than further south.

Port O’Connor’s Boggy Creek Nature Park on Mategorda Bay has a dense coverage of mangroves, mixed with *Batis maritima* in the middle and *Spartina alterniflora* on the west and north ends. Rainfall is higher in this region of Texas (Gabler et al. 2017), and winter temperatures can often include freezes although many are not cold enough to kill most mangroves.

Table 1. Locations (decimal degrees) of each SET, the date established, vegetation type, and number of four foot long threaded steel rods used in the benchmark.

Site	SET	Lat (deg dec)	Long	date_setup	Veg type	Num. of 4 foot rods
Mustang_Cohn	1	27 43	97 09 882	6-Mar-20	two zones of marsh_mangrove. SET at edge of mangrove zone	16.5
Mustang_Cohn	2	27 43	97 09 912	8-Mar-20	two zones of marsh_mangrove. SET at edge of mangrove zone	6
Mustang_Cohn	3	27 43	97 09 929	8-Mar-20	two zones of marsh_mangrove. SET at edge of mangrove zone	6
Ward_West	1	27 42	97 19 914	10-Jan-21	day is approx	5.5
Ward_West	2	27 42	97 19 875	10-Jan-21	day is approx	6
Ward_West	3	27 42	97 19 680	10-Jan-21	day is approx	6
PINS_YarboroPass	1	27 12	97 23 233	9/2/2020	mostly marsh only several mangr	9
PINS_YarboroPass	2	27 12	97 23 188	9/2/2020	mostly marsh only several mangr	9
PINS_YarboroPass	3	27 12	97 23 135	9/2/2020	mostly marsh only several mangr	8
PortOc_BoggyCk	1	28 27	96 24 954	1/11/2021	mangr msh (destroyed by vandals)	8
PortOc_BoggyCk	2	28 27	96 24 970	1/11/2021	mangr msh (destroyed by vandals)	7.5
PortOc_BoggyCk	3	28 27	96 25 004	1/11/2021	ok (mostly mangr some Batis)	7
HolidayBch	1	28 09	97 00 795	1/27/2021	marsh sparse mangr	4
HolidayBch	2	28 09	97 00 769	1/27/2021	marsh sparse mangr	3
HolidayBch	3	28 09	97 00 795	1/27/2021	marsh sparse mangr	3
BocaChica	1	26 00	97 09 486	10/17/2020	marsh & mangr	14
BocaChica	2	26 00	97 09 463	10/17/2020	marsh & mangr	11
BocaChica	3	26 00	97 09 440	10/17/2020	marsh & mangr	11
LagunaAtascosaNWR	1	26 21	97 20 183	10/16/2020	mangr. Some msh and mudflat	7
LagunaAtascosaNWR	2	26 21	97 20 186	10/16/2020	mangr. Some msh and mudflat	12
LagunaAtascosaNWR	3	26 21	97 20 194	10/16/2020	mangr. Some msh and mudflat	12

The February 2021 Historic Freeze Event Associated with Winter Storm Uri

The extensive mangrove mortality at some sites and severe loss of living aboveground mangrove plant tissue at most sites during winter storm Uri a reassessment of our primary vegetation-related goals. Before the freeze disturbance we were focused on how different marsh and mangrove dominated locations (within and between sites) would develop and how these different vegetation types would affect surface elevation change. **After the freeze, our focus shifted to assessing if: a) mangrove dominated sites (recovering more slowly) would lose elevation at a greater rate than marsh dominated sites (not as greatly affected by the freeze); and b) if marsh plants would quickly recolonize dead mangrove sites and reset successional patterns**. This new analysis allows an unprecedented assessment of marsh and mangrove vegetation dynamics and effects on surface elevation following massive disturbance. As such, it will be widely cited by scientists, managers, and we, expect, policymakers alike.

Assessing the frequency of hard freeze events

Projections are for increasing temperatures over coming decades regionally and globally (Marcott et al. 2013). It appears that warmer winters may be facilitating the spread and dominance of *A. germinans* populations, with much of the expansion coming since two "killing" freeze events in the 1980's. We analyzed historical temperature and rainfall data to determine if ecologically significant warming has occurred over a number of decades that would support the continued increase in mangroves. Daily temperature and rainfall data were obtained from NCEI (National Centers for Environmental Information within NOAA), and monthly and annual minimum and maximum temperatures, rainfall totals, and counts of days below freezing and days above 35 C were calculated.

The time series data in Corpus Christi were analyzed for evidence of warming over the last 7 decades that might provide conditions conducive to increasing dominance of *Avicennia germinans* in this and an estuary further north also experiencing expanded mangrove population (Port O'Connor, 118 km north). We analyzed historical data (Naval Air Station, Corpus Christi:1945 – 2018) and airport (Port O'Connor: 1943 – 2019) to determine if there was any evidence for reduced freezes and general warming over time that could lead to the increases in mangrove abundance. A similar analysis was done for Galveston. Mangroves also respond to increasing rainfall, and we analyzed these data at both locations as well.

We used Mann-Kendall Tau to assess temporal trends in the data. Once that was established, we use linear and quantile regression to determine if there were patterns of increasing values over the >7 decades of data. For counts of days that were positive integers or zero, generalized linear modeling testing against the Poisson and Negative Binomial distributions was used. Quantile regression tests different subsets of the dataset for slope and intercept, for example, the 10% of all years with the coldest winter temperatures (minimum annual temperature or MAT) would be the subset tested for the 0.1 quantile, while the 0.9 quantile would include only those 10% of the years with the warmest MAT.

Results

Vegetation Assessments

Historic vegetation and temperature analyses:

Unfortunately, there have been no quantitative studies of mangrove abundance or size pre or post the 1980's freezes. After the last "killing freezes" in the 1980's mangrove recovery of dominance proceeded as a logarithmic function (Fig. 8, using data from Guri and Long 2014 remote sensing study) we calculate that there is an excellent relationship between time since massive freeze disturbance and cover of mangroves: Log(proportion mangr. Cover = 1.677 log(years since disturbance + 1) – 5.9062; R^2 = 0.99. From this equation, proportion mangrove cover throughout Texas could be estimated and tested using future data. However, the Guri and Long (2014) analysis does not separate out the different effects of latitude on recovery. In fairness, the 1989 freeze was so intense that mangroves were reportedly killed as far south as Rio Soto in Mexico! So, although quantitative data are lacking along the latitudinal gradient, it seems very possible that there was near-total destruction of mangroves in Texas by the combination of these two freeze events in the 1980's. Guri and Long (2014) opine that 5x5 m resolution of aerial/space images would be required to determine colonization by seedlings. We disagree with Guri and Long (2014) on this point. Our on-the-ground surveys suggest that no resolution other than on-the-ground m^2 or smaller plots will adequately show the densities of colonizing seedlings.

	Estimate	Std. Error	t	P	
(Intercept)	-5.90619	0.13324	-44.33	1.10e-07	***
logyrplus1	1.67695	0.05071	33.07	4.75e-07	***

$F_{1,5}$ = 1094, R^2 = 0.99

Log(pro.mangr.cov) = 1.677 * log(years since disturb.+1) -5.9062

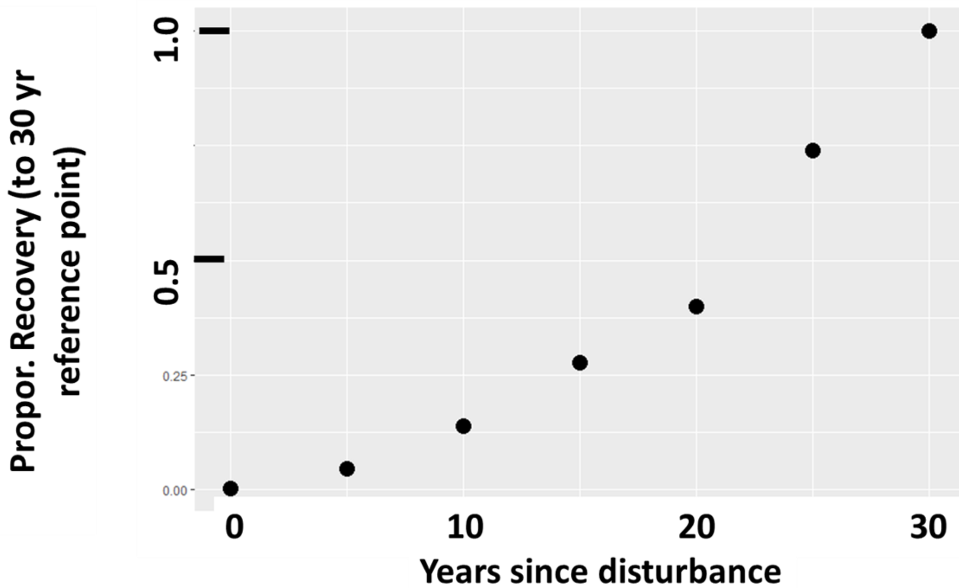

Fig. 8 Analyses of % mangrove cover from Guri and Long (20xx). The regression analysis allows calculation of % mangrove cover at different points in time following the catastrophic 1983 and 1989 freezes.

Freeze frequency analysis

A key question for researchers and natural resource managers is: How likely is another hard freeze? Our analysis of the NCEI temperature and rainfall data indicate that overall mean temperatures are rising and that freezes are infrequent (Fig. 9 [Corpus Christi example] and Table 2 [including Brownsville, Corpus Christi, and Port O’Connor]).

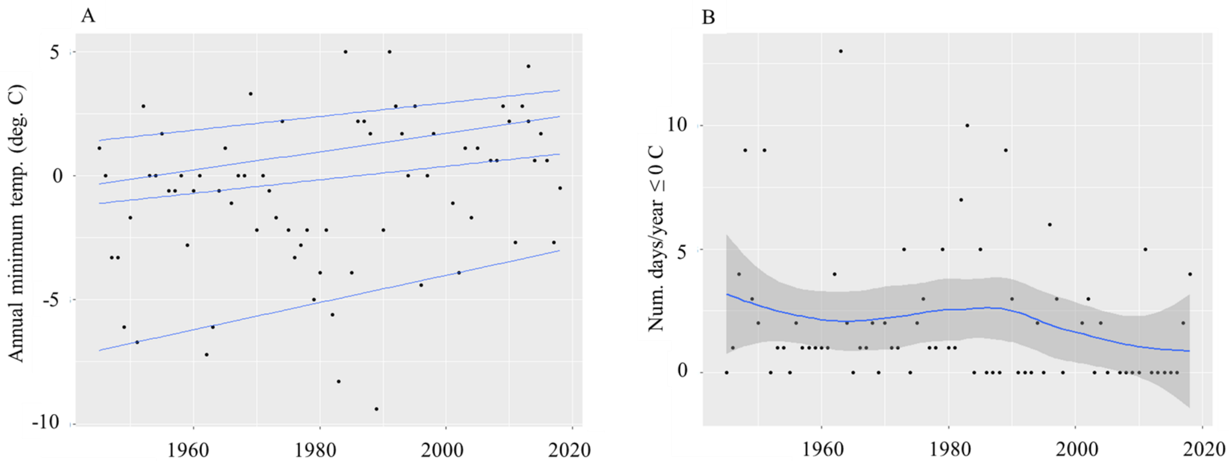

Figure 9. Temperatures from the Naval Air Station in Corpus Christi from 1945 – 2018. A. Quantile regression lines for tau = 0.1, 0.5, 0.7, and 0.9 are shown top to bottom respectively. Quantile regression was significant although slopes of the lines were not different from one another indicating that the one for tau = .5 (simple linear regression) suffices to indicate the pattern of increasing minimum temperatures over time. B. the loess pattern of number of days at or below freezing show a decreasing trend.

Table 2. Mann-Kendall tests of trends over time for MAT (minimum annual temperature), number of days below zero C, number of days per year above 35 C, and total annual rainfall at both CC (Corpus Christi Bay) and PO (Port O'Connor) an estuary 118 km further north. For those variables with significant temporal trends, slopes were determined using linear regression (MAT) or generalized linear modeling (days below zero). The days below zero was modeled against the Poisson and the negative binomial, and the latter was the better model.

	Mann-Kendall test of trend over time			modeling & assessing slopes			
	tau	p		slope estimate	slope SE	P value	test
CC MAT	0.162	0.049		0.036	0.016	0.029	linear regression
CC Number of days below zero C	-0.189	0.031		-0.014	0.007	0.069	generalized lin. Model (negative binomial)
CC Number of days > 35 C per year	0.121	0.175					
CC Annual total rainfall	0.111	0.172					
PO MAT	0.181	0.023		0.034	0.014	0.016	linear regression
PO Number of days below zero C	-0.245	0.002		-0.01	0.003	0.0007	generalized lin. Model (negative binomial)
PO Number of days > 35 C per year	0.03	0.714					
PO Annual total rainfall	0.031	0.695					

Analyses of our vegetation data

At our study sites, mangroves appear to have been reducing marsh cover likely because of shading as illustrated by data collected over time and plotted in Fig. 10. This is important because reduced marsh abundance in mangrove-dominated areas meant slower recovery of marsh after Uri removed or substantially reduced mangrove canopy cover. The lack of living plant cover, especially roots, produced conditions that could be conducive to erosion and land loss.

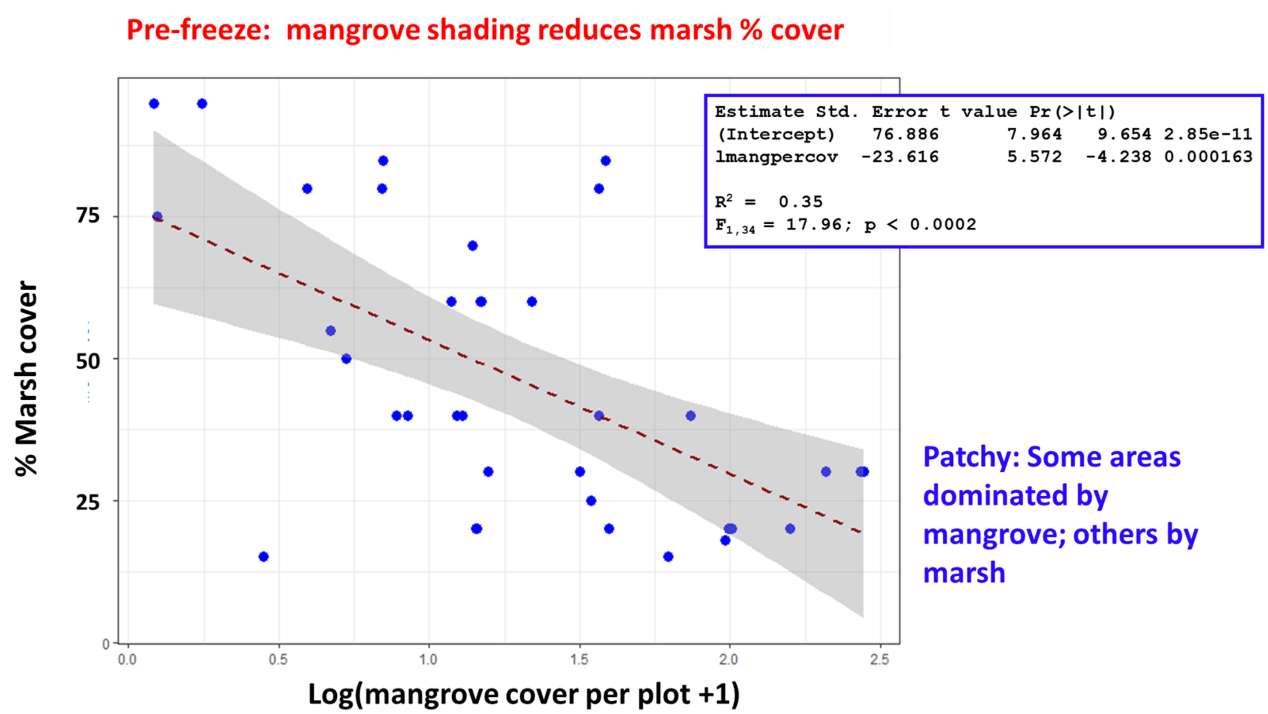

Figure 10. Before winter storm Uri, locations with greater mangrove canopy cover had reduced marsh cover, probably because of competition for light.

Pre-and – post freeze

Mangrove mortality was very high in the north and near zero at the southernmost site (100 minus the "recovery" column in Table 3). Surviving mangroves at the Laguna Atascosa National Wildlife Refuge Sentinel Site resprouted from some of branches, indicating incomplete "top-kill." At all sites north of Laguna Atascosa, all resprouting was from the base of the plant indicating near 100% loss of above ground mangrove plant matter. This difference is probably reflected in the more rapid recovery of canopy area and height at Laguna Atascosa.

A key factor is population recovery is numbers of plants per unit area (density). Mangrove recovered densities post-freeze as a relatively linear function of the minimum temperature encountered (Fig. 10). Recovery of height and canopy area (not shown) followed somewhat similar patterns but the curves were generally non-linear. Suffice to note that mangrove recovery was largely a function of the lowest temperature attained during the historic freeze. Recovery of canopy area will take a number of years which will vary by the degree of damage and levels of reproduction in upcoming years (since very little reproduction and new seedlings recruitment in the first two years).

Table 3. Mangrove density and size parameters pre and post freeze at the 7 Sentinel Sites, arranged from south to north. Percent recovery indicates the degree of pre-freeze values attained in the number of months indicated. ND for Boca Chica for canopy area notes missing data.

	Pre freeze		Post freeze		% recovery	No. months
	Shrubs/m^2	sd	Shrubs/m^2	sd		
Boca Chica/LRGVNWR	2.7	0.79	2.7	0.8	100	15
Laguan Atascosa NWR	3.44	2.24	3.64	2.22	105.8	15
Padre Isl. Nat. Seashore	0.067	0.03	0.05	0.04	74.6	15
Ward Island	1.21	0.97	0.79	0.87	65.3	16
Cohn Pres - Mustang Isl.	3.52	0.39	1.37	1.09	38.9	12
Holiday Bch - Copano Bay	1	0.3	0		0.0	10
Boggy Ck Park -Port O'Connor	2.44	2.87	0.1	0.3	4.1	14

	Height (cm)	sd	Height (cm)	sd		No. months
Boca Chica/LRGVNWR	71.3	36	71	34	99.6	15
Laguan Atascosa NWR	117.8	62	86.6	45.5	73.5	15
Padre Isl. Nat. Seashore	15.8	6	15	7.1	94.9	15
Ward Island	116	56.1	82	22.1	70.7	16
Cohn Pres - Mustang Isl.	75.5	24	53.6	15.5	71.0	12
Holiday Bch - Copano Bay	72.8	10				10
Boggy Ck Park -Port O'Connor	91.1	12.2	13.2	24.5	14.5	14

	Canopy Area (m^2)	sd	Canopy Area (m^2)	sd		No. months
Boca Chica/LRGVNWR	ND		ND		near 100	15
Laguan Atascosa NWR	2.13	0.9	1.43	1.98	67.1	15
Padre Isl. Nat. Seashore	0.01	0.002	0.008	0.01	80.0	15
Ward Island	1.14	0.85	0.17	0.34	14.9	16
Cohn Pres - Mustang Isl.	2.73	4.1	0.14	0.5	5.1	12
Holiday Bch - Copano Bay	1.43	1.98				10
Boggy Ck Park -Port O'Connor	0.94	2.05	0.014	0.028	1.5	14

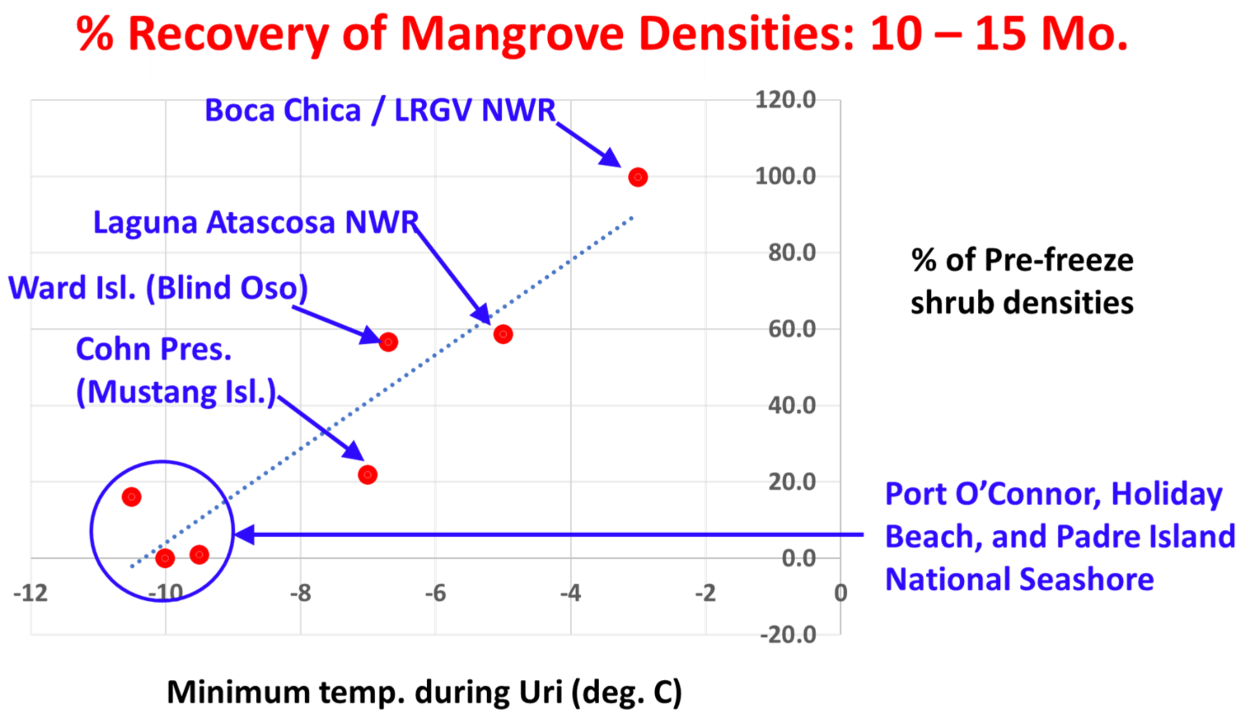

Figure 11. Recovery of mangrove densities at sites that varied by minimum temperature attained during Uri. Note, that colder areas recovery densities way more slowly than slightly warmer sites.

Batis maritima dominated the salt marsh vegetation at all of our Sentinel Sites. There was little to no change in marsh cover in sites in the hypersaline Laguna Madre (Boca Chica, Laguna Atascosa, and Padre Island National Seashore) (Table 4). At Boca Chica, there was very little freeze damage and both marsh and mangrove populations remained largely stable. At Laguna Atascosa freeze damage defoliated mangroves, but many rapidly recovered from stem sprouts. At PINS, there were few mangroves to begin with and they were small, so there had been little impact by mangroves on the marsh plants.

Table 4. Marsh % cover (*Batis maritima*) pre and post freeze at all sites. Percent recovery of pre-freeze values is also presented.

	Pre freeze			Post freeze		% recovery	No. months
	Marsh % Cover	sd		Marsh % Cover	sd		
Boca Chica/LRGVNWR	65	42		65.1	41.7	100.0	15
Laguan Atascosa NWR	6.1	14.2		5.6	13	91.8	15
Padre Isl. Nat. Seashore	78	8		78.3	7.6	100.4	15
Ward Island	26.7	20.9		40.1	37.5	150.2	16
Cohn Pres - Mustang Isl.	20.2	27.8		18.9	27.9	93.6	12
Holiday Bch - Copano Bay	18.3	7.6		20	8.7	109.3	10
Boggy Ck Park -Port O'Connor	20.6	6.9		41.9	32	203.4	14

Mangrove population recovery depends on reproduction, propagule dispersal, and seedling recruitment. Reproduction was absent at all sites except Boca Chica (where it was still much less than we've seen in previous years [EP and DD field observations]) the first year as surviving mangroves expended energy on vegetative regrowth. In 2021, within weeks of the freeze, a few propagules floated in at several sites and a small number of seedlings recruited. Some of these were most likely from reproduction on site before the freeze, and in the water dispersing at time of the freeze and were spared, others may have traveled on ocean currents from more distant locations. In 2022, there have still been almost no propagules seen stranding in the sites because of reduced reproduction the previous 2021 season.

Resulting seedling densities were relatively low or zero at most sites (Table 5). YOY seedlings colonized at Boca Chica but there were no other older seedlings in our plots at that site. No seedlings occurred at either of the other two Laguna Madre sites. Holiday Beach also had no seedlings recruit since the freeze. Older seedlings (the ones recruiting in summer of 2021 a few months post-freeze) occurred at Ward, Cohn, Holiday, and Boggy (Table 5), but none of these sites except Boggy Creek had any YOY seedlings recruiting in 2022 because of a lack of reproduction at nearly all sites the previous season. At Ward Island, older seedlings established at 56.3% of pre-freeze seedling densities. At Boggy Creek and Cohn Preserve older seedling densities recovered to 77.7 – 100% of pre-freeze levels. Reduced reproduction has led to low numbers of dispersing propagules and thus low seedling recruitment at most sites. There is somewhat better reproduction in the Summer-Fall of 2022 and in future years seedlings from these maternal trees as well as from maturing older seedlings will aid in the population recovery. Some recruitment from distant sources (e.g., the Caribbean, Louisiana) may also occur.

Table 5. Older and young-of-the-year (with cotyledons attached) seedling densities / m^2 pre and post Uri at all sites. Percent recovery of pre-freeze values is indicated as well.

	Pre freeze		Post freeze		% recovery	No. months
	Mang. Older Seedlings /m^2	sd	Mang. Older Seedlings /m^2	sd		
Boca Chica/LRGVNWR	0		0			15
Laguan Atascosa NWR	0		0			15
Padre Isl. Nat. Seashore	0		0			15
Ward Island	0.16	0.08	0.09	0.12	56.3	16
Cohn Pres - Mustang Isl.	1.1	2.2	1.1	1.36	100.0	12
Holiday Bch - Copano Bay	1	3.1	0		0.0	10
Boggy Ck Park -Port O'Connor	3.19	1.9	2.48	2.07	77.7	14
	Mang. YOY Seedlings /m^2	sd	Mang. YOY Seedlings /m^2	sd		
Boca Chica/LRGVNWR	0.53	0.41	0.33	0.58	62.3	15
Laguan Atascosa NWR	0		0			15
Padre Isl. Nat. Seashore	0		0			15
Ward Island	0		0			16
Cohn Pres - Mustang Isl.	0		0			12
Holiday Bch - Copano Bay	0		0			10
Boggy Ck Park -Port O'Connor	0.8	0.87	0.59	0.82	73.8	14

Surface elevation change (SET-MH) analyses

After installing the SET-MH units at all sites we waited 4 – 6 months to ensure that the SET mark settled. However, COVID-19 lockdown also produced delays in sampling some sites as we could do day-trips locally but not the more distant sites that would require overnight stays. We finally developed protocols for the field team to camp out and drove multiple vehicles in order to prevent infection of participants. This worked, as no one on our team caught the disease while installing or gathering data. As a consequence of all the delays in installation and first readings, one site (the Cohn Preserve) has a longer period of data than the others. Also, Padre Island National Seashore has the shortest period of record because as we were set to read the instruments there, hurricane Ian was passing to the east and the national seashore staff closed access to the site. These data will be gathered a week or two after the grant period and data will be added to the web site.

To date, with the most recent readings taken August-September 2022, many mangrove dominated locations show a trend of losing elevation (Fig. 13). Salt marsh areas were more variable in trends. Some sites lost elevation, some gained, and several showed little trend over the time period. Our next data point will be taken in January 2023 to support the invited paper that we are writing for a Special Issue of **Estuaries and Coasts**, "*Current Advances in Coastal Wetland Elevation Dynamics*" edited by Don Cahoon and Glenn Guntenspergen.

In a number of instances our marker horizons were lost suggesting more surface erosion than we anticipated. Thus, shallow subsidence values are not included herein until we have a longer record of intact MHs.

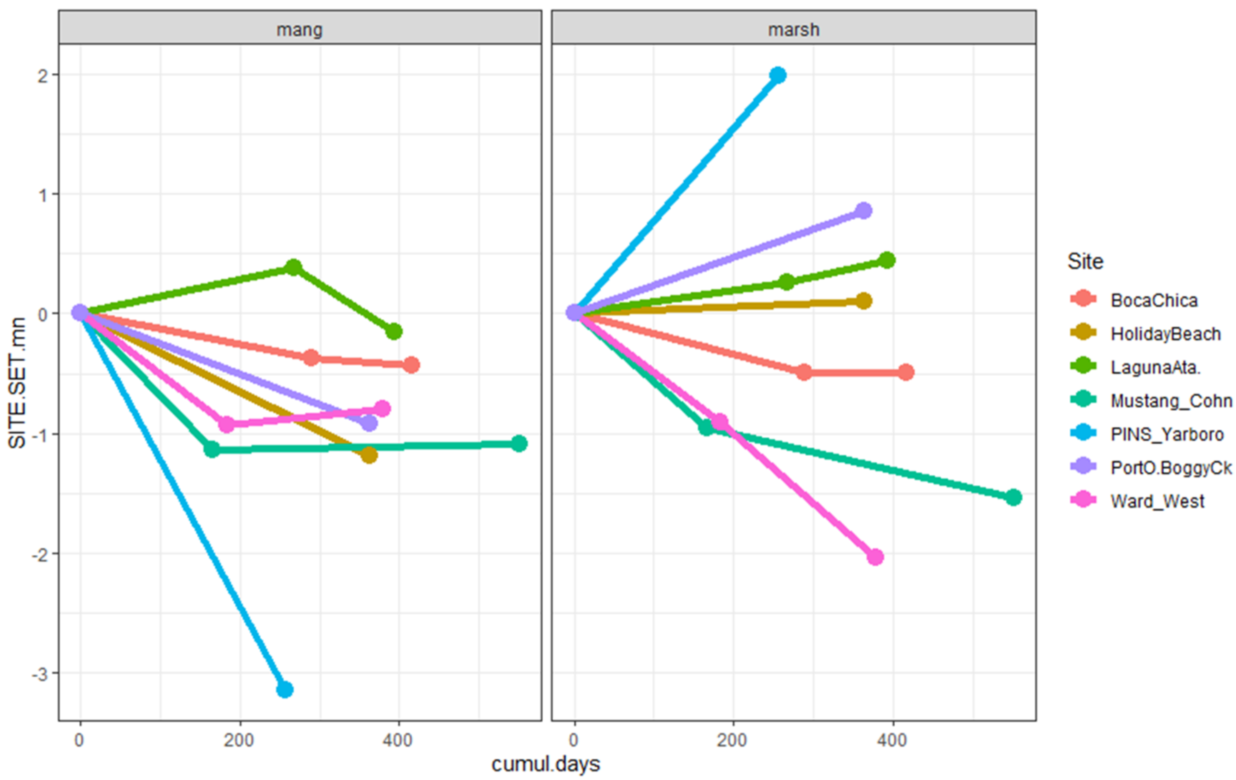

Figure 12. Elevation change (mm) by mangrove (left) and salt marsh (right) paired locations since study initiation. Plotted points are means of the (usually) 3 SETs at each site. Note that the Cohn site has a longer period of time because the SETs at that site were installed just before COVID-19 lockdown.

Discussion

Historic development of mangrove populations and climate patterns:

Sherrod and McMillan (1985) reviewed the historical and paleontological evidence for occurrence of mangroves in the Gulf of Mexico. Mangroves appear to have been in our region for millions of years. These authors report earlier studies summarized here. Berry (1916), Berry (1924), and Ball (1931) all reported various mangrove species in the fossil record from the late Eocene that included a site in Texas. A long period of cold climate ending near the end of the Pleistocene likely eliminated all or most mangroves from the Gulf of Mexico. New records of mangrove peat in some areas of southern Florida date from about 3000 to 4000 years ago and indicates that populations were expanding northward again.

The earliest verified collection of a mangrove in Texas was in 1853, but reports in various parts of the Gulf of Mexico date back to the 1500's (Sherrod and McMillan 1985). Following the end of the "Little Ice Age" about 1850 and the general warming co-occurring with the Industrial Revolution, mangrove expansion again proceeded but the population advance has been punctuated by periodic freezes. Sherrod and McMillan (1985) reported that in 1983, there were 9 days of temperatures as low as -6 to -10 C. At Harbor Island, one of the largest populations of mangroves along the mid-Texas coast, they recorded 85% mortality (noted in a otherwise unpublished survey by Sherrod in 1984). They estimate >95% loss in Galveston and 60-70% in Brownsville. They report that shorter plants survived better than tall ones, which is consistent with our findings reported here.

Unlike our findings from the 2021 freeze, Sherrod and McMillan (1985) reported that many propagules survived and recruited the following year. They also note that extended periods of drought such as occurred in the 1950's produced long periods of hypersaline conditions in the Laguna Madre.

Our analysis of temperature patterns in different parts of the Texas coastal zone suggest that warming will continue and hard freezes will decline in frequency. This latter prediction is consistent with the findings of Landgren et al. (2019) project that marine cold-air outbreaks (MCAO) from the north pole region will decline in the future, which suggests that the intervals between freeze events such as Texas experiences in 1983, 1989, and 2021 will lengthen and their effects on tropical species such as mangroves will be lessened.

Interactions between marsh and mangrove plants:

Our observational data that well-developed stands of mangroves outcompete marsh understory plants is consistent with our results from a separate field experiment that we have on-going from 2017 (Proffitt and Devlin, in prep). In that study, we found that not only do mangroves shade out marsh, but that fertilization with nitrogen increased this effect. Guo et al. (2017) reported that experimental removal of mangroves on Harbor Island resulted in recovery of a number of species of marsh plants within 2 years. Recovery following the freeze does not appear to be that rapid in many of our sites although at several there may be a level of marsh recovery similar to that reported by Guo et al. (2017). Kangas and Lugo (1990) opined that the southern limit of salt marsh dominance was set by competition with mangroves, but that mangrove poleward distributions were set by frost.

Mangrove propagules and seedlings are influenced by environmental conditions and their plant neighbors. Hoffman and Proffitt (in press) found that *Avicennia* propagules can have as high as 20% survival (with subsequent rooting and shoot production) even when exposed to -8 C for 5 hours. Mangrove seedlings that recruit also interact with marsh plants at many sites. Further, these interactions likely vary in strength and possibly direction (e.g., facilitative or competitive) along environmental gradients, such as the freeze effect gradient studied here. For instance, Coldren and Proffitt (2017) reported that salt marsh plants competitively excluded *A. germinans* seedlings under experimentally produced freezing conditions, but the mangrove seedlings survived at higher salinity (40 psu) treatments. Milbrandt and Tinsley (2006) stated that *B. maritima* had a positive effect on mangrove recruitment; yet, McKee et al. (2007) found no benefit from *Batis*, but did find that *Distichlis spicata* and *Sesuvium portulacastrum* facilitated mangrove recruitment. The possible difference in Batis effects in these two studies are microclimate associated with latitude: Milbrandt and Tinsley (2006) worked at the Sanibel – Captiva NWR in Pine Island, Fl while Mckee et al. (2007) conducted studies in Belize. These results suggest that some marsh species (or combinations of marsh species) will promote survival of mangrove seedlings under some environmental conditions but not others. Further study is clearly warranted.

Where not eliminated by shading by mature mangroves, salt marsh species may facilitate seedling recruitment. Following the freeze, some seedlings that recruited may have been so facilitated. This may substantially influence the rate of mangrove population re-establishment following winter storm Uri. Because many sites have little living intertidal wetland plants following the freeze, anything that enhances marsh and/or mangrove population expansion will reduce the likelihood of catastrophic erosion if a large storm strikes the coast in the next few years.

Mangrove population recovery:

Our data show that population recovery at Sentinel Sites has been limited by low reproduction in the first two years following freeze disturbance. However, our graduate student, Jake Doty, scouted 3 sites (Boca Chica, Ward, and Boggy Creek) more broadly than in just our established plots and found YOY seedlings that he tagged and tracked survival, growth, and reproduction of for his masters thesis (Doty 2022). He found 100% survival of all tagged seedlings and similar growth rates at all sites. He also found that these seedlings at northern sites (Ward Island and Boggy Creek) reproduced at 16 months of age, but the ones at Boca Chica did not. This precocious reproduction may facilitate population growth at more heavily disturbed sites.

Shoreline protection: Our SET data support our initial hypothesis that mangrove vegetation, especially belowground material, can reduce elevation loss. The interactions among marsh and mangrove plants are crucial components of the intertidal system in ecotonal areas where subtropical and temperate systems intermingle Coldren and Proffitt 2017). As the climate generally warms, increasing dominance by tropical mangroves is expected at the expense of declining salt marsh cover and biomass (Coldren et al. 2019). In most typical cases this should be viewed as a natural consequence of a warming climate and changes to the ecosystems and community dominants should be considered normal and even beneficial. For example, Silliman et al. (2019) used field experiments and meta-analyses to show that intertidal wetlands protected these regions from erosion and that root systems, rather than above ground structures, were the key element by increasing sediment cohesion and shear strength. More locally, Pennings et al. (2021) demonstrated using large experimental clearings in Corpus Christi Bay (Harbor Island) that even a small amount of mangrove cover (11%) provided substantially greater protection to erosion and shoreline retreat than did salt marsh. They also reported that soil shear strength was greater in mangrove plots than in marsh plots.

The National Synthesis of NERR SET data report (Cressman et al. 2020), and data presented by Kim Cressman project lead at our Workshop September 23, 2022, indicates that many estuaries in the nation, are not increasing in elevation at a rate that would allow them to keep up with relative sea level rise (SLR). The Mission-Aransas National Estuarine Research Reserve is the only one in Texas. Some of their SET data were showing increasing elevation that could maintain wetland surfaces in the face of SLR while others were not.

Moon et al. (2022) compared long-term SLR rates in mid-and-northern Texas and more recent (last 19 years) at USGS sites several northern National Wildlife Refuges. The Rockport gauge had 5.77(0.49) mm/yr long term SLR and 9.74 (1.78) mm/yr in recent years. The Freeport gauge had 4.21(0.72) mm/yr long term SLR and 6.81(1.72) mm/yr in recent years. The Sabine Pass gauge had 6.05(0.74) mm/yr long term SLR and 11.36(1.89) mm/yr in the most recent two decades. Their SET data as well suggested that many salt marshes in northern Texas will not be able to offset the effects of SLR.

Severe disturbances can disrupt the intertidal wetland communities and lead to greater erosion and surface subsidence (Cahoon et al. 2003). Proffitt and Travis (2014) found that disturbance by hurricane Charley disrupt mangrove reproduction (and thus recruitment).

Conclusions

Addressing TGLO Goals:

Our project was designed to address the GLOs coastal goals, especially “To protect, preserve, restore, and enhance the diversity, quality, quantity, functions, and values of (CNRAs).” The over-arching conceptual model we considered is illustrated in the path diagram shown in Fig. 13). There, since mangroves over time develop dense stands and reduce marsh cover, once mangroves are largely killed by freeze disturbance, there is neither mangrove nor marsh roots left to stabilize the sediments until one or the other or both recolonize dense populations. A large storm striking at the time before substantial plant recovery could result in near-immediate loss of sediments and land retreat.

Our SET results are consistent with this hypothetical model. Where mangroves were largely removed by the freeze, there tends to be greater elevation loss than in other areas, or in the same area in marsh plots “paired with” the mangrove plots. However, where mangroves were patchey and less abundant, marsh will persist because of lack of competition and marsh roots will function to reduce the effects of SLR. We continue to assess these trends over time.

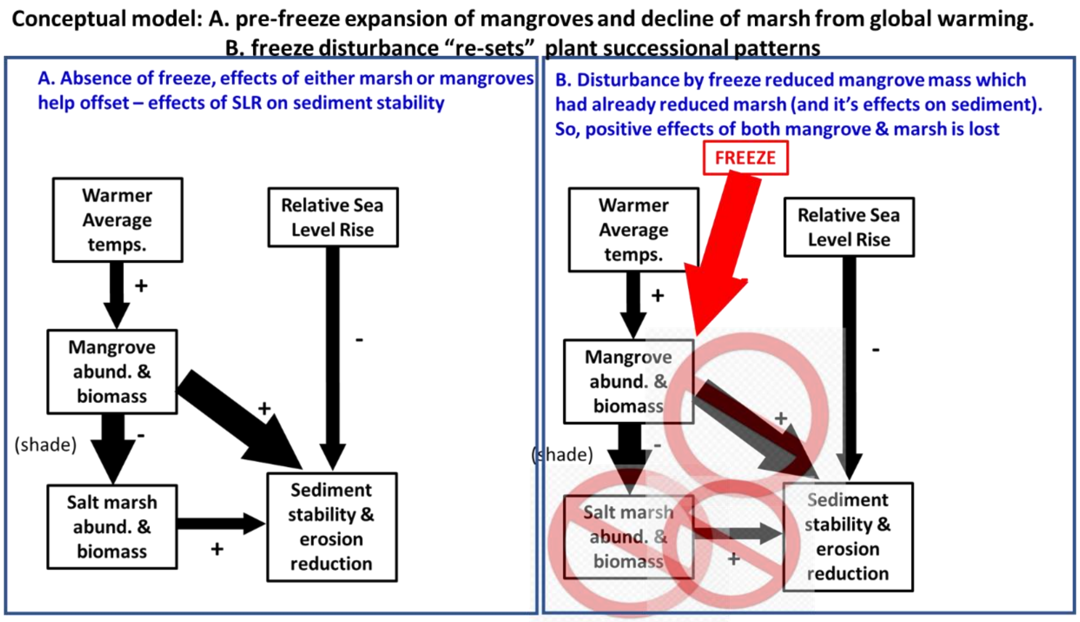

Figure 13b. A) shows the typical effect of warmer winters. Increasing mangrove (+ slope of temperatures affecting mangroves). And positive effects of mangrove and marsh (where it occurs!) abundance and mass on the stability of sediments in the root zone. SLR is shown having a negative effect on sediment stability, and to avoid graph clutter effects of SLR on vegetation are not indicated, neither is the effect of warming temperatures on SLR. Sediments have the best ability to offset SLR. B) Severe freeze adversely affects mostly mangroves (red arrow) negatively. That removes the + effects of mangrove abundance and mass on sediments, as well as indirectly much of the effects of salt marsh on sediment stability since mangroves had already resulted in the deterioration of marsh.

Recommendations:

1) Land managers should assess wetland vegetation at their sites. The best and least time consuming method would be to run transects from open water through all or much of the intertidal zone. Visual estimates of percent cover by plant species and mangrove height rankings (<30 cm, 30 – 60 cm, >60 cm) would provide a good indication of how well a particular site is recovering. Alternatively, drones have come down in price. Flying transects across the intertidal zone would give a fair idea of recovery, although probably would not capture the smaller mangrove plants which are an indicator of a burgeoning population.
2) Active restoration may be necessary at some sites. This might be sites that are recovering particularly slowly compared to other sites in the vicinity. Or it might sites where shoreline erosion is observed to be progressing. Or it might include sites that are recovering but are in regions where there is a long fetch that could magnify the effects of storms on erosion. Restoration could take the form of planting various wetland species, especially those marsh species that exhibit relatively rapid clonal growth. Some sites where there is substantial elevation loss and/or particularly high rates of SLR might need thin-layer dredge and fill. This must be carefully done with minimal depths of fill added in order to reduce the smothering of plants already in the site. See Slocum et al. (2005) for an experimental test of sediment

slurry deposition on a *Spartina alterniflora* marsh. See Proffitt et al. (2005) for rates of colonization by marsh plants of large flats created from dredge and fill. It would be best if any such sediment slurry deposition was done at first over small scales as experimental tests because how plants other than *S. alterniflora* will respond to even shallow burial is unknown.

3) All future actions would benefit from a Wetlands Coordinator position best housed at one of the state agencies or perhaps a cooperative between an agency (Agrilife, for example) and a university. The Coordinator could develop and maintain a large database of results from recommendation #1 and studies by various researchers. Further, the Coordinator could analyze these data and produce periodic reports that show the progression of wetland development and succession coast-wide and over time.
4) Increase educational efforts at all levels from elementary school through college and to the general public. Changes will be coming that will eventually require informed decisions to be made by elected leaders and voters.
5) Ensure continued support for studies of SLR and erosion/subsidence. Long term quantitative data will be beneficial to planners and policymakers in the future.

Acknowledgments

We appreciate field and planning help by Dr. Carolyn Weaver early in the project. Jacob Doty has been instrumental in all phases of field work and we gratefully thank him for his tireless efforts. Ryan Fukawa, Max Portmann, Caleb Carr, and Phil Rivera from our lab assisted in the field. Elena Flores (MS student) and Asael Rodriguez (BS student) from UTRGV assisted in the field at the Boca Chica site. Staff at the Laguna Atascosa NWR took us to their site by airboat at time of SET installation! Stephanie Bilodeau of the Coastal Bend Bays and Estuaries Program provided boat rides to our Laguna Atascosa site a couple of times as well. Jake Herring and Travis Muckleroy provided assistance at the Holiday Beach site.

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OUTREACH

Our Outreach actions were conducted at several levels, both general at TAMUCC and on broader academic, scientific, federal, state and local agencies and with the general public. At TAMUCC activities included adding modules to undergraduate and graduate classes at TAMUCC, exhibits, discussions and workshops regarding sea level rise and storm surge potential on campus.

TAMUCC

Teaching Module- The SET-MH and Salt Marsh/Mangrove Vegetation Data Method for Measuring Sea Level Rise Module*. In fall of 2020, this module was added to Dr. Proffitt's Marine Botany stacked undergraduate and graduate level Course that is taught annually*. There are approximately 25 students in each class. Therefore, approximately 75 students have participated in or are currently participating in this hands-on module.

Figure 14. Students measuring height and canopy dimensions of mangroves near a SET-MH Station on TAMUCC Campus before the February 2021 freeze event.

The aim of this Module is to train students in the appropriate way to collect scientific, publishable data from SET-MH and Salt Marsh/Mangrove Vegetation Data for the purpose of measuring sea level changes and how to use the SET-MH method to differentiate among erosion, subsidence and accretion. these methods and in. The module consists of lecture, field and laboratory work. SET-MH is installation and reading methods are studied and demonstrated in the classroom, students set up vegetation plots on campus to learn to record vegetation data in the field. Samples of vegetation are taken into the laboratory for identification.

Figure 15. Students measuring height, percent cover and density of salt marsh vegetation near a SET-MH Station on the TAMUCC Campus after the February 2021 freeze event.

This is a valuable tool for students to have in their toolbox, as students who are seeking jobs in coastal wetlands will have experience in these methods that are accepted and employed worldwide to access sea level rise. In fact, all National Estuarine Research Reserves either have sentinel SET-MH sites installed at present or have plans to install them.

Figure 16. Photograph from above of students working on a vegetation plot at the Ward Island Sentinel Site.

Graduate Education (thesis research occurring at the Sentinel Sites) -
Simen Kaalstad [mangroves and freeze thesis completed and MS degree awarded – collaborative with the USGS], Jake Doty [completed MS work and thesis at 2 Sentinel Sites, and is now working on PhD at the sites], Max Portmann [recovery of belowground roots, a spin-off project funded by Seagrant, is occurring at two of the Sentinel Sites], Caleb Carr [seedling quantification and influence of nutrients and herbivory on recovery at 2 of the sites, funded by a grant from the Center for Coastal Studies at TAMUCC], Molly McGuigan [decomposition of mangrove and marsh litter and use by marine invertebrates, at 2 of the sites, also funded in part by the Seagrant award], Jessica Peterson [effects of fiddler crab burrowing on seedling survival and growth at one of the Sentinel Sites], Sophia Hoffman [seedling growth at high and low salinity sites used one of the Sentinel Sites in her thesis work. She was awarded the MS degree, has a paper in press, and now works as a technician at the Virginia Long Term Ecological Research site], Phil Rivera [undergraduate, is conducting a study of survival and recovery at two sites as part of his Honors thesis, will graduate in December 2022, and plans to attend graduate school probably at Villanova University working under noted mangrove ecologist Dr. Samantha Chapman].

Earth Day Exhibits/Field Trips-We prepared an exhibit (2021) and field trip (2020) for the TAMUCC Earth Day celebration.

Meeting with representatives from USFWS and Facilities Dept at TAMUCC on 9/2021 to discuss conserving shoreline vegetation coordination with the USFWS Pollinator Program.

Environmental Council Meetings-Dr. Devlin is member of the Council and has presented information regarding the value of the SET-MH sites located on campus to the council members.

The Nature Conservancy Gulf of Mexico Program Meeting-We discussed our SET-MH and Vegetation Plot findings with members of the TNC-GOM Program in July 2021.
Oso Bay Wetlands Preserve-Drs. Proffitt and Devlin gave an invited Climate Change Presentation on July 15, 2021. This talk included information about SETs and concentrated on work at the local SET-MH sites at the Cohn TNC Preserve and TAMUCC (Fig. 17).

Preliminary Report for The Nature Conservancy Cohn Preserve- In March, 2022, at TNC's request, we conducted a preliminary analysis of the SET-MH and vegetation plot data from the Cohn Preserve and prepared a Preliminary Report for Cohn Preserve (Appendix x). The TNC management staff used the report in the decision-making process for restoration of the Preserve.

Figure 17. A flyer about the presentation by Drs Proffitt & Devlin at the Oso Bay Wetlands Preserve.

TNC Cohn Preserve Stakeholder Meeting- We participated in the Cohn Preserve Stakeholder in July, 2022, and shared our meeting and shared our SET-MH and vegetation data with the attendees. Our data will help engineers determine appropriate methods for protection of the Preserve.

Web site – On the project web site, which we will maintain in the future, are our SET data in Excel form and summaries of all other data in a copy of this report. Also, numerous pictures of our lab members installing and measuring SET-MH and quantifying vegetation changes are presented. Students whose thesis topics relate to, and use, all or some of the Sentinel Sites are highlighted. The link to the web site is included in Proffitt's signature line on all emails.

COLLABORATIONS

University of Texas – Rio Grande Valley - We strengthened the link between labs at two Minority Serving Universities (TAMUCC AND UT-RGV). We located our SET-MH Stations close to Dr. Alejandro Fierro Cabo's existing Fertilization Experiment and Carbon Emissions Experiment at LRGV-NWR. Thus, both their and our experiments (by PIs and students) will be strengthened by collaborations. An associate scientist, two graduate students and one outstanding undergraduate from the Fierro Cabo lab were trained in installation of and taking readings at SET-MH stations (see acknowledgments).

Figure 18. Asael Rodriguez, (undergraduate student, UT-RGV), Ryan Fukawa (MS student, TAMUCC) and Elena Flores (MS student, UT-RGV) working together to install SET at LRGV-NWR.

Further, in person field meetings and discussions were especially important during COVID years, as most scientific meetings were all conducted virtually until 2022, and there was little opportunity for students to interact with professors and fellow students from other institutions. For instance, as well as working, we shared meals in the field and a comradery was established. Our PhD student gave advice to MS and graduate students at UT-RGV. The students engaged with Drs. Devlin and Proffitt. The UT-RGV team worked with our team at both southern sites, LA-NWR and LRGV-NWR, usually for three days/trip, so this provided a real opportunity for networking.

Dr. Proffitt also served as a committee member for one of the UT-RGV MS student (Ms. Elena Flores) who helped in the field. He has helped her with statistical analyses for her project.

Serendipitous Outreach USGS & TAMU-Galveston- Since we had vegetation plots (and transects at some sites-transects were not set-up pre-freeze we were able to closely monitor damage and recovery and participate in the Gulf-wide Mangrove Freeze Damage Study. One of the MS students in our lab served as the data coordinator for the project.
We participated in virtual weekly meetings for several months following the February 2021 freeze with USGS-WERC, TAMUG and UT-RGV to discuss findings after the freeze and best method for making comparisons among all sites. Determined that even though PRISM data isn't as accurate on small scales, that for Gulf-wide comparisons, at present it is the most applicable meth

TAMU- We are collaborating with Dr. Yina Liu, Assistant Professor of Oceanography, Team Lead, Marine and Environmental Geochemistry, GERG and Dr. Michael Shields Assistant Research Scientist, to design a study of shallow and deep blue carbon at the SET-MH sites. We have met with them virtually on several occasions and they have also visited several of the SET-MH sites. Dr. Liu is taking the lead on this work and is currently working on the first draft of a grant proposal.

NEWSPAPER ARTICLE

Moon B12

The Elephant in the Room

By Ed Proffitt

Usually, I generally focus on native plants as a local response to offset the effects of drought. But that's really only one small facet of the larger problem which involves other aspects of climate change and local ecosystems as well as human communities. This is the "elephant in the room" that is difficult to adequately understand and to devise workable solutions to counter the worst of the effects. But, as you have seen in the news almost daily, climate change is not something that's coming "down the road," but is indeed amongst us now. Here, we have extended periods of drought. Wildfires or flooding threaten other parts of the globe. Storms are projected to become more intense and frequent. Oceans are warming, glaciers are melting, and perhaps major currents like the Gulf Stream are changing. But, as much as I usually focus on drought, and using native plants to conserve water, an issue that's at least as pressing for us is sea level rise and coastal shoreline retreat. Global, or eustatic, sea level rise is in progress and will flood many locations around the world within decades. In the Coastal Bend, this problem is compounded by subsidence and shifting of the continental plate that magnifies the global effects to produce the nation's greatest "relative" sea level rise, which in some places exceeds 3 mm per year. In a few decades, the landscape of Padre Island will be vastly different as land will be lost to the sea. The first habitat to suffer likely will be our intertidal wetlands that are key to fish and bird populations and hence our quality of life.

Devising workable solutions for coastal wetland conservation requires a full understanding the problems. Can wetlands here "build land" beneath them by trapping sediments and successive root production and decay? This happens in some coastal wetlands but not all. If so, do both marsh and mangrove vegetation contribute equally to land building? What will be the consequences for wind-tidal flats often dominated by thin layers of algal mat? These flats certainly do not build land at any rate that would offset even mild sea level rise. How do all these intertidal wetland types respond to major disturbances such as hurricanes and intense "hard" freezes like we had in 2021? Hurricanes are projected to become more frequent and intense, and what does that mean for intertidal wetlands? Climatologists are unsure in their projections of future hard freeze events – some saying that polar outbreaks will be more frequent, some saying the opposite. If they're more frequent, that'll drive vegetative communities of intertidal wetlands more toward salt marsh. If less frequent, then that'll favor tropical mangrove dominance.

Some of these questions, and other topics as well, will be subjects of presentations and panel discussions this week at two scientific meetings in Port Aransas. The first meeting is the Texas Bays & Estuaries annual symposium, which will cover a variety of important topics and include speakers from many different subdisciplines and career paths. The meeting will be held Wednesday and Thursday at the University of Texas Marine Science Institute and is hosted by UTMSI and the Mission-Aransas National Estuarine Research Reserve. The second meeting is the next day, Friday September 23 from 9 AM to 1:00 PM, at the same location. This workshop will focus on defining the issues, research needs, and solutions to problems associated with sea level rise, intertidal vegetation loss (and recovery) post freeze. My lab at Texas A&M University – Corpus Christi and colleagues at UTMSI-MANERR will co-host this one. Not only will there be technical presentations of research findings but also a panel discussion that will include biological and geological researchers, coastal engineers, and both public and private natural resource land managers (see attached agenda for details of the meeting). The broad goal of this second meeting is to clarify and quantify the major problems, and put forth some solutions.

Figure 19. Article by Dr. Proffitt for the Island Moon weekly newspaper.

September 22, 2022 | Island Moon | B12

Workshop: Friday September 23, 2022 (9 AM – 1 PM)

Subsidence, erosion, and shoreline retreat: Assessing the roles of sea level rise, storms/freezes, and shifts in vegetation dominance in loss of Texas intertidal wetlands

Convened by: Ed Proffitt & Donna Devlin, Texas A&M University-Corpus Christi

Jace Tunnell & Katie Swanson, Mission-Aransas National Estuarine Research Reserve

Venue: University of Texas Marine Science Institute, 750 Channel View Drive, Port Aransas, TX 78373. Meeting will be in the Seminar Room on second floor of the Estuarine Research Center building

RSVP please, as a box lunch will be provided, to: ed.proffitt@tamucc.edu

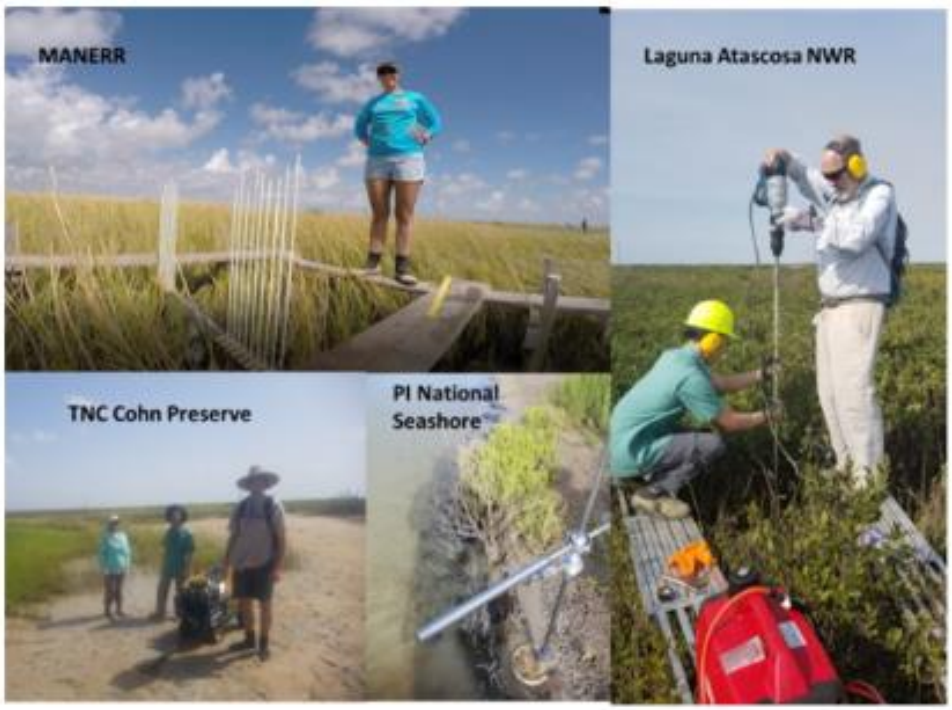

Figure 20. A flyer advertising the Workshop held September 23, 2022.

Dr. Proffitt wrote an article (Fig. 19) for the Island Moon weekly newspaper published on north Padre Island that highlighted the Workshop held September 23, 2022 at the University of Texas – Marine Science Institute at Port Aransas (Fig. 20). The article (reprinted in Fig. 19) informed the general public about some of the important issues that will be faced by residents in the future and that some potential solutions would be discussed by an invited panel and workshop attendees.

A7 Island Moon September 29, 2022

The Island Outdoors

On the Rocks

By Jay Gardner

Hurricane Ian will have slogged ashore somewhere along the gulf coast by the time this hits your hot little fingers. I was in contact with our friends Matt Palmtag and Emily Lumsden over there in Tampa, and they were expecting a 10-foot storm surge. While Matt lives a good 10 miles inland, Emily and Randy live right on the water inside Tampa Bay. One of the issues is that they are also experiencing their "king tides" that happen in the fall at the same time (we call them "bull tides" over here). Emily was telling me that if those two hit at the same time, it would put about five feet of water over their pool and through the first story of their house. I hope everyone is safe over there, and we'll be watching the news.

Also by the time this gets in your hands, the beaches will likely be closed, and the tides will already have been to the dunes and should be receding. Hopefully this won't impede the efforts of the contractor working on the Packery jetties too much. One thing that this storm will do, however, it will put water over the parking lot under the JFK Causeway next to the boat ramps and Packery Flats. This is yet another reason why the Bond 2018 project needs to get going.

North wind and high tide

The north wind had already filled up the Oso and Laguna by Wednesday, which is coinciding with our high tides as well. This will have floated off some of your dock boards, so be careful when stepping off your bulkhead on to your dock. You might go right through! Also there will be debris floating off the shorelines into the channels and waterways that will pose a hazard like happens every time. Be careful out there.

When the water stops sloshing around in the gulf, our water will drop out like a bad habit from the bays through the passes. This will pull all the mullet out, and the redfish and flounder will be right behind them, and the kingfish, Spanish mackerel, and a host of other predatory fish will be waiting for them on the outside. The fishing will be off the chain for the next couple of fronts like this. Our buddy Dan has already been hitting a few pompano south of Bob Hall, and we're all looking forward to that.

Teal season

Well folks, our attempt at teal season at the lake last weekend was met with mediocre success. My attempt at mounting the mud motor on the johnboat and getting it to perform was mostly a failure, but at least we had the Yamaha to fall back on. The lake was up, way up, and at 88%, not only was most of the good meadows flooded, they were very flooded. We hunted the first morning in a small pocket off the main channel that I had hunted before, however it was really deep. Deep to the point where when we threw the decoys out, they just floated around with their heads down because the lines were too short. They wound up floating into a corner all together in a big wad. Ha!

Well folks, I have to cut it short this week folks, I'm in a workshop down in Kingsville regarding the Baffin Bay Water Quality Management Plan. Y'all get out and do some fishing and I'll see you next week here On the Rocks.

A wave at Bob Hall Pier during Hurricane Katrina

Turtle Count

Donna J. Shaver, Ph.D.

Going Native

By Ed Proffitt

September 28 2022 wetlands sea level rise and hurricanes

Ian is stalking Florida and very possibly will cause substantial damage to humans and coastal environments. If a similar-sized storm were to come here now (heaven forbid!) the Coastal Bend would not have a couple of advantages that Florida has. At the workshop we co-hosted last week some of the presentations and discussions brought that into clarity. First, relative sea level rise is greater here. In the past +4 mm / year has been mentioned as a high rate of rise. However, a presentation by the USGS focused on the most recent 19 years. Relative sea level rise in some parts of Texas exceeded 11 mm/year. That's nearly ½ inch per year…oh my. In other nearby locations it was greater than 6 mm/year. Presentations by the NOAA-sponsored National Estuarine Research Reserve and the USGS found that rates of accretion of elevation produced by coastal wetlands were not likely to "keep up" with these higher rates of sea level rise. Florida's advantage here is a substantially lower rate of relative sea level rise meaning that wetlands there may be able to better offset such a rising sea than can ours.

Our second disadvantage is a substantial reduction in cover and dominance by black mangroves caused by the extremely low temperatures produced by winter storm Uri in February 2021. Florida did not suffer such a loss. A presentation by Dr. Anna Armitage of Texas A&M University – Galveston and her colleagues highlighted how even a moderate covering by mangroves greatly reduced coastal erosion and shoreline retreat in their experimental plots on Harbor Island caused by Hurricane Harvey and other lesser storms – pre-freeze. My lab's post-freeze data from other sites in Texas show a trend toward wetland surface elevation loss in areas where many mangroves were lost. Our hypothesis is that stands with the most dense mangrove canopy pre-freeze had shaded out much of the salt marsh understory. Thus, when the freeze killed a large fraction of the mangroves, there was little live marsh (or mangrove) plants left with a well-developed root system to hold the sediment. Slow and steady loss has resulted in mangrove-dominated sites, but that would be greatly magnified if we suffered a storm surge and waves that would accompany a storm of Ian's magnitude. On the plus side, salt marsh plants are vigorously recovering some (but not all) sites we've looked at, and there's been patchy survival and re-sprouting of mangrove shrubs. What's really needed on the mangrove side now is a couple of good years of reproduction and seedling recruitment, followed by another few good years as those seedlings grow into shrubs with a large enough root system to begin recovering lost elevation. We think active restoration would help, but we'd need a source of seedling propagules to disperse and person-power to do so over a large enough scale to really make a difference. Other ideas were discussed formally or informally at the meeting and some of these may be useful on a case-by-case basis.

So, think of it as a race now. Both marsh and mangrove plants recovering in sites while elevation is slowly being lost in some (but not all) areas and we hope larger storms miss much of the Texas coast for our near future. Therefore, in addition to using native plants to offset the effects of drought, we need to encourage native marsh and mangrove plants to quickly recover our coastal wetland habitats. Natural resource managers at the meeting recognize that wetland recovery is critical and I'm sure will be doing what they can to assist that recovery. One simple project that the public (e.g., boy and girl scout troops, school groups, birdwatchers, fishermen, etc) could engage in that would help is collecting and dispersing marsh and mangrove "propagules" when they begin to arrive on our beaches in November through January. Pick up some buckets full and take them to a nearby wetland and disperse. Some of those will take root…whereas none that clutter our sandy beaches will do anything other than die! This is another way to Go Native.

Our lab assessing mangrove and marsh recovery a year post freeze

Large areas of little marsh or mangrove recovery on Ward Island about 10 months post freeze

Figure 21. A follow-up Island Moon "Going Native" article (by Ed Proffitt) published 9/29/2022 that focuses on the Workshop presentations and panel discussions.

Additional Meetings - Educated managers as to the how of SET-MH's allow the measurement of SLR and subsidence

Zoom meeting: Boggy Creek Victoria Curto Mott-MacDonald, PE and county park board members Allan Berger, Oran Moses, Steve Dublin, Linda Bourias, Dwane Fishbeck, and Charlene Terrell attended.

WORKSHOP

Dr. Ed Proffitt (TAMUCC) and Dr. Donna Devlin (TAMUCC) organized a workshop to follow the Texas Bays and Estuaries Meeting (TBEM) in September 2022 in collaboration with Mr. Jace Tunnel and Ms. Katie Swanson of the Mission Aransas National Estuarine Research Reserve. The timing worked well for the workshop both because many of the stakeholders had attended the TBEM and were energized by the experience and because it was close to the end date for this CMP 24 TGLO Grant. The workshop gave researchers studying Sea Level Rise and a broad spectrum of stakeholders to interact directly with each other in a non-threatening, cordial environment.

The early morning session opened with a presentation by Phillippe Tissot (Conrad Blucher Institute at TAMUCC) titled: ***Global and Relative Sea Level Rise and Inundation*** and was followed by a series of three presentations on **Surface Elevation Table & Horizon Studies (SET).** The first of these presentations by Laura **Feher** of United States Geological Service Wetland and Estuarine Research Center (USGS-WERC) concentrated on **SET Research in northern Texas, Katie Swanson** (MANERR) followed with a presentation on **SET Research in the MANERR and Nueces Delta** and the final presentation before the coffee break was by C. Edward Proffitt (TAMUCC) **SET Research from Port O'Connor to Boca Chica.**

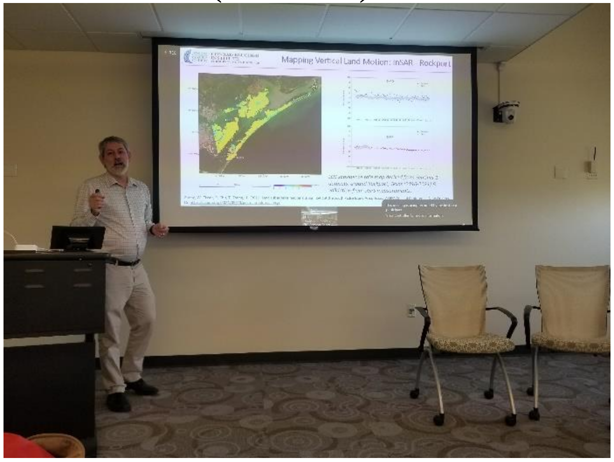


Figure 22 (Left). Dr. Phillippe Tissot and describing sea level rise in Texas. (Right). Laura Fehr showing SET data from USGS sites in northern Texas.

The first two talks of the second session addressed National **SET Research Programs.** The first presentation was given by **Kim Cressman** who addressed **The NERR National** data analysis of wetland elevation change compared to the rates of relative SLR. She was followed by **Phillippe Hensel** of NOAA who discussed **Alternative SET Methodologies.** The final speaker was **Anna Armitage** who talked about **Lessons from a Harbor Island Vegetation**

Clearing Experiment.

Following lunch, we had a rousing panel discussion moderated by **Jace Tunnel (MANERR).** Panelists represented a broad spectrum of stakeholders and that included;
Loretta Battaglia (Director, Center for Coastal Studies at TAMUCC),
Dr. Kiersten Stanzel (Executive Director of the Coastal Bend Bays and Estuaries Program),
Jesse Gilbert (Executive Director, Texas State Aquarium Exec. Dir.),
Dr. Lauren Williams (The Nature Conservancy),
Allan Berger (Boggy Creek County Park),
James Clement (King Ranch),
Phillip Blackmar (HDR coastal engineer),
Jackie Robinson (TPWD),
John Blaha (CCA).

Figure 23. Workshop panelists discussing Sea Level Rise Workshop, SET-MH, and needed "next steps."

Figure 24. Jace Tunnel moderating Panel during Sea Level Rise Workshop.

Appendix A

1. **Report to the Nature Conservancy: Cohn Preserve**

By Drs. Ed Proffitt & Donna Devlin
March 22, 2022

In this preliminary report submitted to support planning by the Nature Conservancy for possible restoration, we highlight changes in elevation over the 6 month period from March 2021 to September 2021 and also the changes in vegetation and bare ground at our study plots between February 2021 (at freeze) and Feb. 2022 (after 1 year).

There was no significant change in surface elevation (95% confidence interval overlaps zero) over a 6 month period in either marsh dominated or mangrove dominated sections of the 3 study plots (Table 1). This is not surprising because of the short time frame, data collection continues.

There has been a substantial change in the vegetation community at the Cohn Preserve following the hard freeze in early 2021. The mature mangrove shrubs (*Avicennia germinans*) dominating much of the site suffered 78% mortality (Table 1). Further, the area of mangrove canopy cover has only recovered by 17% over this first year. Surprisingly, salt marsh (mainly *Batis maritima*) has been slow to increase in cover (+ 6.4%) despite the reduction in shade from mangroves. As a combined consequence of mangrove loss and slow marsh recovery, the % unvegetated cover has increased 29.8% over the last year (Table 1).

Mangrove seedling numbers / m^2 have increased over the last year indicating some slow recovery of the mangrove population (Table 1). These seedlings recruited from propagules already in the water dispersing at the time of the freeze (field observations) and there was little if any survival of rooted seedlings during the freeze. However, this year there has been virtually no reproduction by any mangroves we've seen in the Corpus Christi Bay region (field observations), and consequently we've seen almost no recruitment of new seedlings this year and don't expect to see any. Further increase in population size will most likely occur when surviving saplings begin to reproduce this summer or next and can provide propagules for recruitment.

Table 1. Preliminary data on elevation change post freeze (not significant) and vegetation change pre-and post freeze.

Cohn Preserve Preliminary Report by E. Proffitt & D. Devlin					
Surface Elevation Change (in mm)	**Time frame**	**Mean**	**Lower 95% CL**	**Upper 95% CL**	**Comment**
Mangrove dominated	3/2021 - 9/2021	0.6	-1.24	2.42	No sig. change in first 6 mo. Since 95% CL overlap zero
Marsh dominated	3/2021 - 9/2021	0.5	-1.09	2.1	No sig. change in first 6 mo. Since 95% CL overlap zero
Vegetation (pre - post freeze)	2/2021 - 2/2022	**Mean**	**Stnd Dev.**		**Comment**
Marsh (*Batis maritima* dominant)	pre-freeze	23.4	1.5		no change over year 1
	Post-freeze (1 yr)	24.9	24.6		
Mangrove					
Live mangr. Shrubs / m2	pre-freeze	4.6	1.0		
	Post-freeze (1 yr)	1	0.9		78% loss of live mangroves
Live mangr. Height (cm)	pre-freeze	75.2	2.1		
	Post-freeze (1 yr)	42.2	12.7		56% recovery in yr 1
Live mangr. Canopy cover (m2)	pre-freeze	2.9	2.5		
	Post-freeze (1 yr)	0.5	0.9		17% recovery in yr 1
num. seedlings / m2	pre-freeze	1	0.5		
	Post-freeze (1 yr)	4.4	3.9		77% increase in yr 1
Unvegetated	pre-freeze	28.5	2.9		
	Post-freeze (1 yr)	40.6	10.2		29.8% increase over yr 1

2. **COVID-RELATED DELAYS & ACTIVITIES**

Picture of camping to promote social distancing after SET field work.

3. **Student Support**

Ryan Fukawa, Jacob Doty MS & PhD, Maxwell Portman, Caleb Carr

In Field Training distinct types of training in SET and Vegetation Monitoring

SETs

Trainees: a post doctoral researcher (TAMUCC), a research associate II (UT-RGV), 9 graduate students (TAMUCC-7. UT-RGV-2) and 6 undergraduate students

SET Location
SET Installation
SET Reading

Vegetative Plots (establishment and assessment)

Trainees: a technician (UT-RGV), 9 graduate students (TAMUCC-7. UT-RGV-2) and 6 undergraduate students

- Set Up-Random methods for locating plots
- Monitoring Plots
  - Subplot- Random Methods
  - Mangrove-
    - Reproduction and Seedling quadrats
    - Mangrove Canopy Estimations
    - Density and Cover Estimations
  - Salt Marsh-
    - Plant Identification
    - Growth forms-& strategies—under or over within salt marsh cover?
      --methods to find species that are not recorded using photographic methods.
    - Density and Cover estimations

Aquatic Botany Class and Lab

Numerous transects and plots within transects: 3 years ~70 sudents?