Long-Term Seagrass Monitoring in Coastal Bend Ecosystems

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EXECUTIVE SUMMARY

This study is part of the Texas seagrass monitoring program, with specific focus on Corpus Christi Bay (CCB), Baffin Bay (BB), and the Upper Laguna Madre (ULM), following protocols that evaluate seagrass condition based on landscape-scale dynamics. This work is a continuation of the efforts set forth by Dunton et al., 2011 to implement long-term monitoring to detect environmental changes with a focus on the ecological integrity of seagrass habitats. This approach follows a broad template adopted by several federal and state agencies across the country, but which is uniquely designed for Texas (Dunton et al. 2011) and integrates plant condition indicators with landscape feature indicators to detect and interpret seagrass bed disturbances. The purpose of this study is to provide insight regarding the ecological consequences of environmental changes, and help decision makers (e.g., various state and federal agencies) determine if the observed change necessitates a revision of regulatory policy or management practices. The primary questions addressed in the 2024 annual Tier-2 surveys include: 1) "What are the spatial and temporal patterns in the distribution of seagrasses over annual scales?", 2) "What are the characteristics of these plant communities, including their species composition and percent cover?", and 3) "How are any changes in seagrass percent cover and species composition related to measured characteristics of water quality?". Seagrasses covered a significant portion of sampled Tier-2 sites, with greater average cover in Corpus Christi Bay (71.1%) than Upper Laguna Madre (66.1%) or Baffin Bay (55.6%). Seagrass coverage in CCB increased from 2022 (68.5%), with a mean seagrass cover of 71.1%. Additionally, seagrass canopy height has increased in some subregions in 2024 (mean = 19 cm), especially since 2023 (mean = 15 cm), indicating continued recovery after Hurricane Harvey and Winter Storm Uri. Many sites on the western ULM shore were deep (>1.5 m), which is near the light limit for seagrasses in the region. Only 5% of sites were barren in ULM when Tier-2 sampling began in 2011, compared to 16% in 2024. Nonetheless, seagrass in ULM seems to be recovering due to increased water quality. Seagrass coverage has also increased in BB since 2022 (25.4%), particularly near ULM, likely due to decreased water depth and better water quality. However, among the three systems, BB exhibits lower optical quality than ULM and CCB due to higher suspended solid concentrations. *Halodule wrightii* and *Syringodium filiforme* were the most widely distributed seagrasses in all regions. *Thalassia testudinum* was only found in CCB, while *Ruppia maritima* and *Halophila engelmannii* were rarely found in all systems.

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INTRODUCTION

In 1999, the Texas Parks and Wildlife Department (TPWD), along with the Texas General Land Office (TGLO) and the Texas Commission on Environmental Quality (TCEQ), drafted a Seagrass Conservation Plan that proposed, among other things, a seagrass habitat monitoring program (Pulich & Calnan, 1999). One of the main recommendations of this plan was to develop a coast wide monitoring program. In response, the Texas Seagrass Monitoring Plan (TSGMP) proposed a monitoring effort to detect changes in seagrass ecosystem conditions prior to actual seagrass mortality (Pulich et al., 2003). However, implementation of the plan required additional research to specifically identify the environmental parameters that elicit a seagrass stress response and the physiological or morphological variables that best reflect the impact of these environmental stressors.

Numerous researchers have related seagrass health to environmental stressors; however, these studies have not arrived at a consensus regarding the most effective habitat quality and seagrass condition indicators. Kirkman (1996) recommended biomass, productivity, and density for monitoring seagrass whereas other researchers focused on changes in seagrass distribution as a function of environmental stressors (Dennison et al., 1993, Livingston et al., 1998, Koch 2001, and Fourqurean et al., 2003). The consensus among these studies revealed that salinity, depth, light, nutrient concentrations, sediment characteristics, and temperature were among the most important variables that produced a response in a measured seagrass indicator. The relative influence of these environmental variables is likely a function of the seagrass species in question, the geographic location of the study, hydrography, methodology, and other factors specific to local climatology. Because no generalized approach can be extracted from previous research, careful analysis of regional seagrass ecosystems is necessary to develop an effective monitoring program for Texas. Conservation efforts should seek to develop a conceptual model that outlines the linkages among seagrass ecosystem components and the role of indicators as predictive tools to assess the seagrass physiological response to stressors at various temporal and spatial scales. Tasks for this objective include the identification of stressors that arise from human-induced disturbances, which can result in seagrass loss or compromise plant physiological condition. For example, stressors that lead to higher water turbidity and light attenuation (e.g., dredging and shoreline erosion) are known to result in lower below-ground seagrass biomass and alterations to sediment nutrient concentrations. It is therefore necessary to evaluate long-term light measurements, the biomass of above- versus below-ground tissues and the concentrations of nutrients, sulfides, and dissolved oxygen in sediment porewater when examining the linkages between light attenuation and seagrass health.

This study is part of the Texas seagrass monitoring program, with specific focus on Corpus Christi Bay (CCB), Upper Laguna Madre (ULM), and Baffin Bay (BB) following protocols that evaluate seagrass condition based on landscape-scale dynamics (Figure 1). Secondary bays within each system that have high seagrass coverage were also included (e.g., Nueces Bay, Alazan Bay). The program is based on a hierarchical strategy for seagrass monitoring outlined by Neckles et al. (2012) to establish the quantitative relationships between physical and biotic parameters that ultimately control seagrass condition, distribution, persistence, and overall health. This approach follows a broad template adopted by several federal and state agencies across the country but is uniquely designed for Texas (Dunton et al., 2011) and integrates plant condition indicators with landscape feature indicators to detect and interpret seagrass bed disturbances.

The objectives of this study were to (1) implement long-term monitoring to detect environmental changes with a focus on the ecological integrity of seagrass habitats, (2) provide insight to the ecological consequences of these changes, and (3) help decision makers (e.g., various state and federal agencies) determine if the observed change necessitates a revision of regulatory policy or management practices. We defined ecological integrity as the capacity of the seagrass system to support and maintain a balanced, integrated, and adaptive community of flora and fauna including its characteristic foundation seagrass species. Ecological integrity was assessed using a suite of condition indicators (physical, biological, hydrological, and chemical) measured annually on wide spatial scales.

The primary questions addressed in the 2024 annual Tier-2 surveys include:

1) What are the spatial and temporal patterns in the distribution of seagrasses over annual scales?
2) What are the characteristics of these plant communities, including their species composition and percent cover?
3) How are any changes in seagrass percent cover and species composition, related to measured characteristics of water quality?

METHODS

Sampling Summary

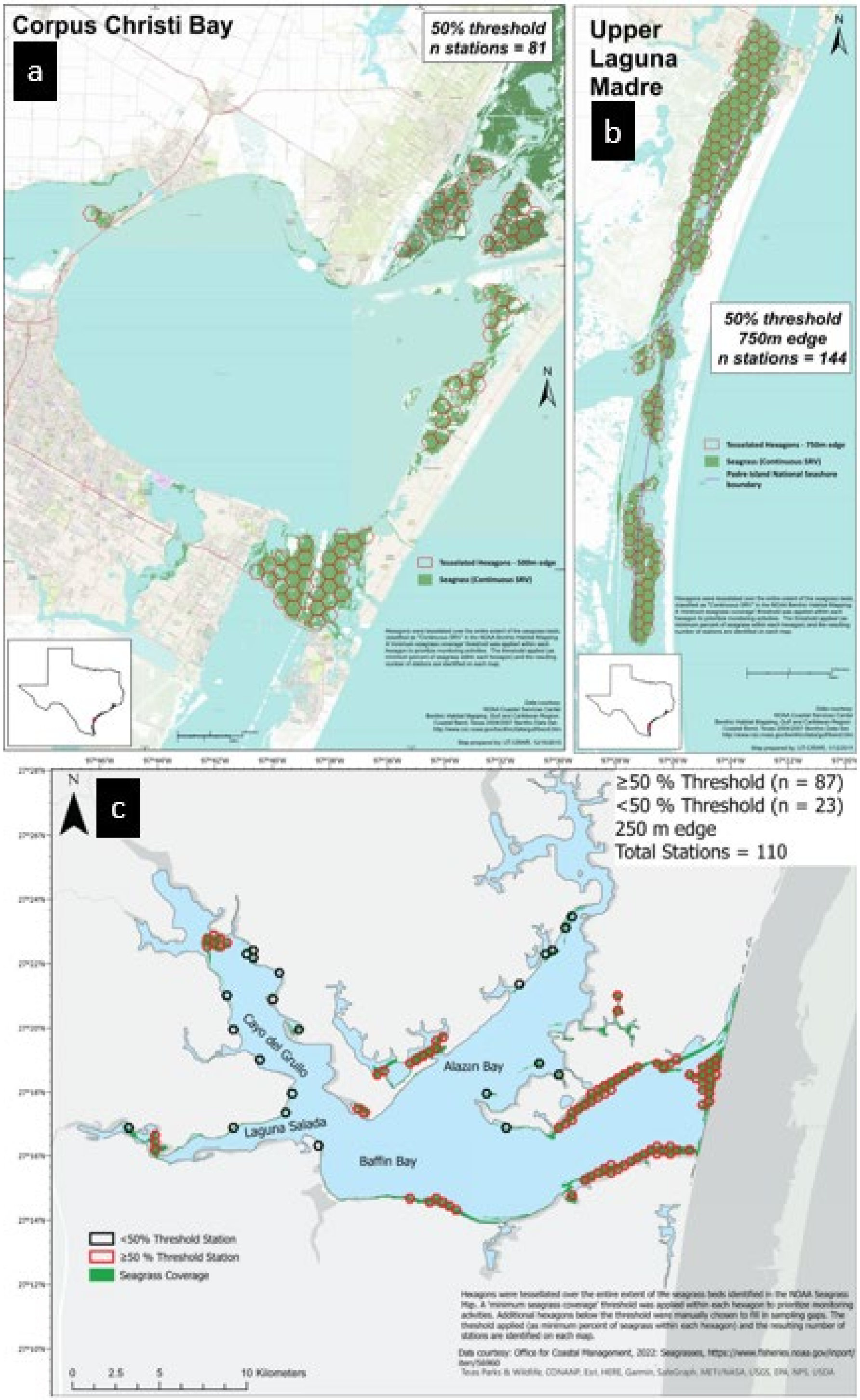
Tier-2 protocols (rapid assessment sampling methods) are adapted from Neckles et al. (2012). We sampled seagrasses using Tier-2 protocols from July to November 2024. Stations in Corpus Christi Bay were sampled in July (24), August (29), October (23, 25) and November. Stations in the Upper Laguna Madre were sampled in July (30), October (24, 31), and November (6, 8, 11, 13, 15). Stations in Baffin Bay were sampled in October (22) and November (8, 13, 15, 22). For statistical rigor, a repeated measures design with fixed sampling stations was implemented to maximize our ability to detect future change. Neckles et al. (2012) demonstrated that the Tier-2 approach, when all sampling stations are considered together within a regional system, results in > 99% probability that the bias in overall estimates will not interfere with detection of change.

Site Selection

The Tier-2 sampling program compliments ongoing remote sensing efforts. Therefore, we selected sites from vegetation maps generated with aerial and satellite imagery during the 2004/2007 NOAA Benthic Habitat Assessment (ULM/CCB) and the 2022 NOAA Seagrass Database (BB). The vegetation maps were then tessellated using hexagons, and sample locations were randomly selected within each hexagon (Figure 1). Only hexagons containing > 50% seagrass cover were included in 2023 sampling efforts for ULM and CCB. Additional stations with < 50% cover were included in BB to fully sample the extent of seagrasses in the system.

Water Quality

All sampling stations were located using a handheld GPS device to be within a 10 m radius of the pre-determined station coordinates. Upon arrival to a station, hydrographic measurements including water depth, conductivity, temperature, salinity, dissolved oxygen, chlorophyll fluorescence and pH were collected with a YSI 6920 data sonde. Water samples were obtained at each station for determination of Total Suspended Solid (TSS) concentration. Water transparency was derived from measurements of photosynthetically active radiation (PAR) using two LI-COR spherical quantum scalar sensors attached to a lowering frame. All sonde measurements and water samples were obtained prior to the deployment of benthic sampling equipment.



Hexagons were tessellated over the entire extent of the seagrass beds identified in the NOAA Seagrass Map. A "minimum seagrass coverage" threshold was applied within each hexagon to prioritize monitoring activities. Additional hexagons below the threshold were manually chosen to fill in sampling gaps. The threshold applied (as minimum percent of seagrass within each hexagon) and the resulting number of stations are identified on each map.

Data courtesy: Office for Coastal Management, 2022: Seagrasses, https://www.fisheries.noaa.gov/inport/item/56960

Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA

Figure 1. Tessellated boundaries of submerged vegetation delineated during the 2004/2007 NOAA Benthic Habitat Assessment (a, b) or the 2023 NOAA seagrass dataset (c). Resulting stations in a) Upper Laguna Madre (n = 144), b) Corpus Christi Bay (n = 81), or c) Baffin Bay (n = 110) are identified in text on map. Stations outside the National Park Service boundary in Upper Laguna Madre are funded by CBBEP (n = 92) and are delineated by the light purple line on the map. Stations must have >50% seagrass coverage in CCB and ULM, but BB stations in black have less <50%.

Seagrass Cover

Species composition and areal cover were obtained from four replicate quadrat samples per station at each of the four cardinal locations from the vessel. Percent cover of areal biomass was estimated by direct vertical observation of the seagrass canopy through the water using a 0.25 m^2 quadrat framer subdivided into 100 cells. Previous research has demonstrated that the probability of achieving a bias is less than 5% of the overall mean when using only four subsamples (Neckles, pers. comm.).

Spatial Data Analysis and Interpolation

ArcGIS software (Environmental Systems Research Institute) was used to manage, analyze, and display spatially referenced point samples and interpolate surfaces for all measured parameters. An inverse distance weighted method was used to assign a value to areas (cells) between sampling points. A total of 12 sampling stations were identified from a variable search radius to generate the value for a single unknown output cell (100 m^2). All data interpolation was spatially restricted to the geographic limits of the 2023 NOAA USA Seagrass Distribution database.

RESULTS

Water Quality

Baffin Bay

Stations in Baffin Bay had a mean water depth of 98.5 ± 33.8 cm (Table 1). BB was the coolest (23.3 ± 3.4°C) but most saline (48.8 ± 4.8) estuary sampled during 2024 (Table 1). Hypersaline conditions are common in this area due to the low freshwater inflow and high evaporation rates (An & Gardner, 2002). Regions in BB that were particularly isolated (e.g., Alazan Bay) had the highest salinity ranges, with values of up to 70.7. Overall, the stations were warmer and less salty than in 2023. The mean dissolved oxygen concentration was 7.1 ± 1.9 mg L^{-1} with a saturation of 111 ± 26.8% (Table 1). No sites showing hypoxia (≤ 2 mg L^{-1}) or low oxygen concentrations (< 3 mg L^{-1}) were documented in the region. The mean pH was 8.1 ± 0.1 (Table 1).

Corpus Christi Bay

Corpus Christi Bay stations had a mean water depth of 84.2 ± 19.4 cm (mean ± standard deviation), water temperature of 27.4 ± 1.5°C, and salinity of 34.2 ± 1.5 (Table 1). Overall, stations were warmer, deeper, and less salty in 2024 than in 2023 (Capistrant-Fossa et al., 2024). Dissolved oxygen concentrations were 6.8 ± 2.1 mg L^{-1} with an oxygen saturation of 104.3 ± 32.3% (Table 1). Four sites with low oxygen (≤ 3 mg L^{-1}) were recorded in Redfish Bay, but no sites were hypoxic (≤ 2 mg L^{-1}). The mean pH value for CCB was 8.1 ± 0.1 (Table 1). Many stations had pH < 8 including East Flats, Shamrock Bay, Redfish Bay, and the Nueces Bay Causeway.

Upper Laguna Madre

Stations had a mean depth of 121.8 ± 35.2 cm and water temperature of 26.3 ± 1.8 °C (Table 1). The system was hypersaline because mean salinity (41.1 ± 3.4) was greater than typical oceanic conditions (Table 1). Overall, waters were deeper and less saline than 2023 (Capistrant-Fossa et al., 2024). Nine Mile Hole has returned to normal salinities (~40) over the past year. This area is notorious for extremely hypersaline conditions during periods of low rainfall which ultimately causes high physiological stress on the plants, even for a tolerant species such as *Halodule wrightii.* The ULM typically experiences hypersaline conditions because of its limited connection to Gulf waters and the lack of any significant freshwater source. However, salinity has been relatively low the past few years due to large amounts of precipitation. The mean dissolved oxygen concentration and saturation was 7.1 ± 1.4 mg L^{-1} (Table 1) and 111.2 ± 21.9% (Table 1), respectively. No sites were hypoxic or had low oxygen. The mean pH was 8.1 ± 0.1 (Table 1), with highest values on the eastern shore across from the mouth of Baffin Bay.

Table 1. Summary of water column hydrographic parameters by region.

		Depth (cm)	Temperature (°C)	Salinity	Dissolved Oxygen (mg L^{-1})	Dissolved Oxygen (%)	pH
BB							
	Mean	98.5	23.3	48.8	7.1	111	8.1
	Std. Dev.	33.8	3.4	4.8	1.9	26.8	0.1
CCB							
	Mean	84.2	27.4	34.2	6.8	104.3	8.1
	Std. Dev.	19.4	1.5	1.5	2.1	32.3	0.1
ULM							
	Mean	121	26.3	41.1	7.1	111.2	8.1
	Std. Dev.	35.2	1.8	3.4	1.4	21.9	0.1

Water Column Optical Properties

Baffin Bay

The downward light attenuation coefficient (K_d) had a mean value of 1.4 ± 0.4 m^{-1} (Table 2), with higher values located near the mouth of BB. The mean TSS concentration for the region was 22.1 ± 10.5 mg L^{-1}, but the standard deviation indicates high intrastation variability. Similar variability was seen in the Secchi depth (68.9 ± 25 cm) measurements (Table 2). On average, the water visibility was within 30 cm of the vegetated or sediment surface. Overall, the water conditions were optically better compared to 2023 (Capistrant-Fossa et al., 2024).

Corpus Christi Bay

The mean downward light attenuation coefficient (K_d) was 1 ± 0.6 m^{-1} for the CCB region (Table 2). Light attenuation was greatest near Redfish Bay, which coincided with higher pH values in the area. The average TSS (9.1 ± 6.7 mg L^{-1}) was substantially lower than for BB or ULM (Table 2). Mean Secchi depth varied among stations (79.9 ± 16.7 cm) but overall, visibility at most stations was near the entire depth of the water column or within 10 cm of the vegetated or sediment surface (Table 2). Overall, water quality conditions were similar in 2023 to 2022 for CCB (Capistrant-Fossa et al., 2024).

Upper Laguna Madre

Monitoring in 2023 revealed a lower and less variable mean downward light attenuation coefficient (K_d; 1.1 ± 0.4 m^{-1}) than in 2023 (Table 4, Capistrant-Fossa et al., 2024). Higher light attenuation coefficients were observed near the JFK Causeway, Baffin Bay, and Nine Mile Hole. The mean Secchi depth was variable (91.1 ± 23.9 cm; Table 2) and water transparency was much greater than 2023 (Capistrant-Fossa et al., 2024). At most stations, visibility was within 30 cm of the vegetated or sediment surface, on average.

Table 2. Summary of water transparency property indicators by region.

		K_d (m^{-1})	Secchi (cm)	Chlorophyll *a* ($\mu g\ L^{-1}$)	Total Suspended Solids ($mg\ L^{-1}$)
BB					
	Mean	1.4	68.9	-	22.1
	Std. Dev.	0.4	25	-	10.5
CCB					
	Mean	1	79.9	-	9.1
	Std. Dev.	0.6	16.7	-	6.8
ULM					
	Mean	1.1	92.1	-	12.9
	Std. Dev.	0.4	23.9	-	7.5

Seagrass Cover and Species Distributions

Baffin Bay

The mean seagrass cover for sites in Baffin Bay was 55.6% for all species. The seagrass percent cover was 10.8% higher than in 2023 and 25.4% higher than in 2022, due to the increase of *Halodule wrightii* in seagrass meadows (Capistrant-Fossa et al., 2024). Overall, BB was mainly composed of *Halodule wrightii* (52.7 ± 42.3%; Table 3, Figure 2), with the highest abundance located on the mouth of the bay, along the southwest and northwest shore near Upper Laguna Madre. Other species like *Syringodium filiforme* (1.6 ± 10.2%; Table 3, Figure 4), *Ruppia maritima* (0.3 ± 2.7%; Table 3, Figure 5), and *Halophila engelmannii* (1.1 ± 4.8%; Table 3, Figure 6) had minor contributions with small patches in different regions of the system. *Syringodium filiforme* and *Ruppia maritima* had an increase of 1% and 0.2% respectively, although patches of these species were found in the same stations as in 2023 (e.g., *S. filiforme* in the mouth of the bay, and *R. maritima* in Cayo del Grullo). *Halophila engelmannii* was located on the mouth of the bay near Upper Laguna Madre, with an increase of 0.5%. *Thalassia testudinum* was not found in any of the stations. Additionally, seagrass was not found in twenty-nine stations (29.6% of stations) located near Laguna Salada, Alazan Bay, and Cayo del Grullo (Figure 7). These regions coincide with the bare patches reported in 2023. Canopy height was highest in *Syringodium filiforme* with a mean of 34.3 ± 7.4 cm (Table 4), followed by *Halodule wrightii* (19 ± 7.2 cm), *Ruppia maritima* (8.6 cm), and *Halophila engelmannii* (2.4 ± 0.3 cm). Both *Halodule wrightii* and *Syringodium filiforme* had longer blades in 2024 (*H. wrightii* = 19 cm; *S. filiforme* = 34.3 cm) than in 2023(*H. wrightii* = 17.2 cm; *S. filiforme* = 13.7 cm).

Corpus Christi Bay

The mean seagrass coverage for sites sampled in the CCB region was 71.1%. The seagrass assemblage (Table 3) in CCB was dominated by *Halodule wrightii* (41.4 ± 39.1%; Figure 2), followed by *Thalassia testudinum* (17.8 ± 29.2%; Figure 3) and *Syringodium filiforme* (9.7 ± 20.7%; Figure 4), with minor contributions from *Halophila engelmannii* (1.1 ± 4%; Figure 6) and *Ruppia maritima* (1.1 ± 4.5%; Figure 5). *Halodule wrightii* was most widely distributed within the CCB region relative to the other seagrass species (Figure 2). However, minimal cover was observed in the western portion of Redfish Bay, which was dominated by *Thalassia testudinum*. Twenty stations in the CCB did not have vegetation present, a significant increase from 2023. Low seagrass cover was observed in southern Redfish Bay near Ingleside and Aransas Pass, and northeast of the JFK causeway (Figure 7). Canopy height (Table 4) was greatest in *Thalassia testudinum* (27.3 ± 10 cm), followed by *Syringodium filiforme* (27 ± 8.8 cm), *Halodule wrightii* (18.2 ± 4.2 cm), *Ruppia maritima* (6.1 ± 1.2 cm) and *Halophila engelmannii* (2 ± 0.3 cm). Interestingly, *Thalassia* was observed growing just north of the JFK causeway, which is an uncommon location for it.

Upper Laguna Madre

The mean seagrass cover for all species was 66.1%, the highest coverage since 2021 because of *Syringodium filiforme* (4.8%). *Halodule wrightii,* the dominant seagrass, also increased since 2023 (5.4%; Table 3; Figure 2). *Ruppia maritima* was found in Nine Mile Hole (Figure 3) and no *Thalassia testudinum* was present during sampling. Twenty-four sampling stations were devoid of vegetation compared to thirty-five sampling stations in 2023 and 2022. Typically, stations that were bare or had low seagrass cover corresponded with greater water depths (>1.5 m) especially those located along the northwestern shore of Laguna Madre (Figure 4). *Syringodium filiforme* has maintained high cover near the JFK Causeway and the mouth of Baffin Bay (Figure 5). *Halophila* was rarely found in northern ULM and Nine Mile Hole (Figure 6). Little rooted wrack (dead seagrass) or attached macroalgae was found in ULM (Figures 7, 8). The highest canopy height values were observed in *Syringodium filiforme* (35.2 ± 10.3 cm; Table 4), followed by *Halodule wrightii* (22.3 ± 7.4 cm), *Ruppia maritima* (6.9 ± 0.1), and *Halophila engelmannii* (2.4 ± 0.6 cm).

Table 3. Summary of plant areal cover by species and region.

		H. wrightii **(% cover)**	***T. testudinum*** **(% cover)**	***S. filiforme*** **(% cover)**	***R. maritima*** **(% cover)**	***H. engelmannii*** **(% cover)**	**Bare (% cover)**	**Wrack (% cover)**	**Other (% cover)**
BB									
	Mean	52.7	0	1.6	0.3	1.1	44.3	0.1	0
	Std. Dev.	42.3	0	10.2	2.7	4.8	43.2	0.3	0.1
CCB									
	Mean	41.4	17.8	9.7	1	1.1	28.7	0	0.2
	Std. Dev.	39.1	29.2	20.7	4.5	4	31.2	0	1.4
ULM									
	Mean	51.6	0	13.6	0.3	0.9	31.2	0.6	0.8
	Std. Dev.	43.2	0	30.2	3.7	4.2	40.1	3.2	4.9

Table 4. Summary of plant canopy height by species and region.

		H. wrightii (cm)	*T. testudinum* (cm)	*S. filiforme* (cm)	*R. maritima* (cm)	*H. engelmannii* (cm)
BB						
	Mean	19	-	34.3	8.6	2.4
	Std. Dev.	7.2	-	7.4	-	0.3
CCB						
	Mean	18.2	27.3	27	6.1	2
	Std. Dev.	4.2	10	8.8	1.2	0.3
ULM						
	Mean	22.3	-	35.2	6.9	2.4
	Std. Dev.	7.4	-	10.3	0.1	0.6

CONCLUSIONS

Corpus Christi Bay

In south Redfish Bay, we observed a greater presence of *Thalassia testudinum* in the west portion while *Halodule wrightii* dominated the area to the east (Harbor Island). The average water depth is lower in east Redfish Bay than in the west portion and this difference may explain seagrass distribution within the CCB region. Overall, the mixed assemblage of seagrasses covers approximately 71.1% of the seabed in CCB which has increased from the post Hurricane Harvey (2017) value of 65% (Reyna & Dunton, 2019). The increase in seagrass cover is encouraging given the immense impact of Hurricane Harvey in 2017 (Congdon et al., 2019). *Thalassia testudinum* and *Halodule wrightii* cover have increased since 2018, as well as average canopy height for both have increased. Seagrass coverage was low in 2023 probably because of large amounts of drift macroalgae. Seaweeds may smother seagrasses, compete for nutrients, and decrease available light for photosynthesis (Kopecky & Dunton, 2006). Spatial patterns suggest that *Syringodium filiforme* extended its range further north into Shamrock Cove and *Halodule wrightii* decreased in cover near Shamrock Cove and East Flats.

Upper Laguna Madre

Overall, water quality across the ULM region was better for seagrass growth in 2024 than 2023 (Capistrant-Fossa et al., 2023). Decreased total suspended solid concentrations likely lowered the light attenuation coefficients. Decreases in light availability are one of the major drivers of seagrass loss worldwide and likely contributed to the decreased height. However, canopy cover continues to increase suggesting ecosystem resilience. Additionally, the number of completely barren locations has reached ~25% of all monitoring sites within ULM. Seagrass cover was lower along the western shore of Laguna Madre, likely because of diminished light availability in deeper waters (Capistrant-Fossa & Dunton, 2024). In contrast, seagrasses were particularly prevalent in shallower areas along the eastern shore of Laguna Madre into Nine Mile Hole. *Halodule wrightii* cover increased in Nine Mile Hole which we attribute to higher salinities because of decreased precipitation. Due to minimal flushing and freshwater inflow, the ULM is susceptible to periods of hypersaline conditions during extended periods of aridity. Overall, seagrass covered approximately 66.1% of the seabed in the ULM, which was the same coverage found in 2018. This significant growth in seagrass coverage suggests large-scale seagrass recoveries are occurring within the ULM, possibly from climatic drivers or increased water quality (Capistrant-Fossa & Dunton, 2024). Future monitoring efforts will be able to document and identify the expansions and contractions of *Syringodium filiforme* and *Halodule wrightii* within the ULM that are largely driven by changes in water quality, climate, and species competition (Wilson and Dunton, 2018; Capistrant-Fossa & Dunton, 2024).

Baffin Bay

Seagrass coverage has significantly increased since 2022, reaching over 50% in 2024 compared to 30% in 2022. Additionally, seagrass meadows have extended their distribution throughout the estuary, with fewer bare sites (29.6% of stations) compared to 2022 (40% of stations). This can be mainly attributed to the significant increase in *Halodule wrightii*. In addition, water quality in 2024 was of better quality than in previous years, with lower attenuation coefficients likely due to the decrease in TSS values compared to 2023. High light availability and low turbidity can control the seagrass composition in the system (Duarte, 1991). This could also explain why BB is the estuary with the least seagrass percent cover out of all the systems in this study. Water quality in Corpus Christi and Upper Laguna Madre had better optical conditions than Baffin Bay, essential for seagrass growth and survival. Salinity also plays an important role in the distribution of seagrass in BB. Baffin Bay is often hypersaline due to its low riverine input and oceanic exchange (Beecraft & Wetz, 2022). *H. wrightii* is a pioneer species that can survive high salinity conditions (ranges from 4 – 114; McMillan & Moseley 1967), compared to climax species such as *S. filiforme* and *T. testudinum* (Koch et al. 2007, Wilson & Duarte 2018). Drought periods and water quality drive the distribution and abundance of seagrass in Baffin Bay. Nonetheless, the significant increase in seagrass suggests a large-scale recovery, potentially from the increased water quality and an increase in precipitation events during 2024 (National Oceanic and Atmospheric Administration's, National Centers for Environmental Information, 2025).

Summary

Differences in water quality trends help explain the significant variation in seagrass meadow coverage between bay systems. The water column in BB had optically low quality due to high light attenuation coefficients and suspended solid concentrations, which resulted in low light penetration. Consequently, seagrass meadows were sparser and more barren in BB compared to other systems. However, significant growth in seagrass coverage and fewer bare sites from 2022 to 2024 suggests large-scale seagrass recoveries are occurring within BB and ULM. Increased water quality and decreased drought periods can be the main drivers for the increased seagrass abundance and shifts in the seagrass species in both systems. Furthermore, this positive relationship between optical properties and meadow coverage is highlighted when comparing CCB with ULM and BB. CCB has had consistently fuller seagrass meadows for the last 3 years, with *Thalassia testudinum* prevalent only in this system out of the three. *T. testudnium* not only does not tolerate variable salinity, but its light requirements are higher than *S. filiforme* and *H. wrightii*

(Fourqurean et al., 2001). This further highlights the better optical properties of CCB. Furthermore, environmental conditions within ULM appear to be degrading. Only 5% of sites were barren in ULM when Tier-2 sampling began in 2011, compared to 16% in 2024 (Capistrant-Fossa & Dunton, 2024). Research suggests this is related to rising sea levels in the Upper Laguna Madre (Capistrant-Fossa & Dunton, 2024).

FIGURES

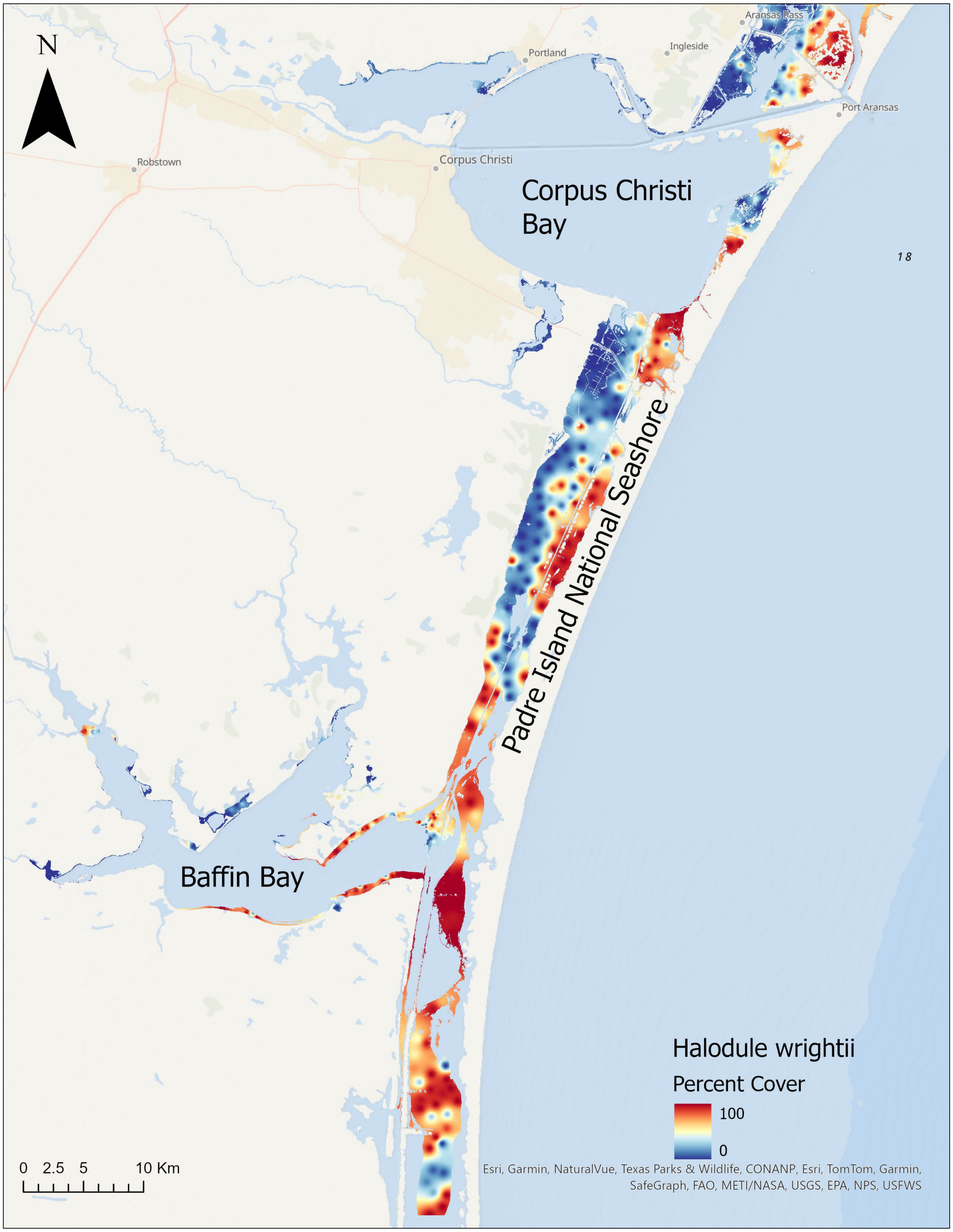


Figure 2. Spatial representations of percent cover for *Halodule wrightii* for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

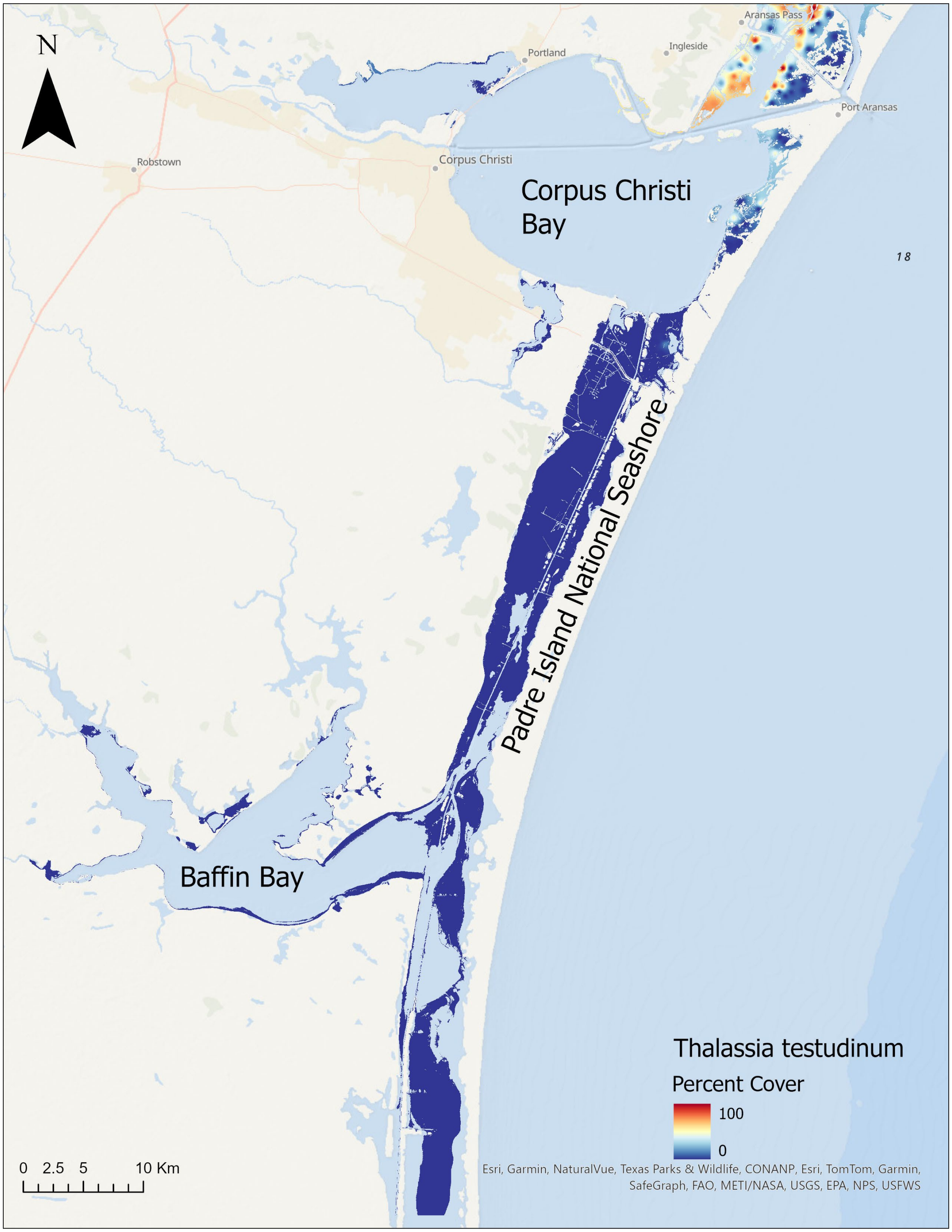


Figure 3. Spatial representations of percent cover for *Thalassia testudinum* for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

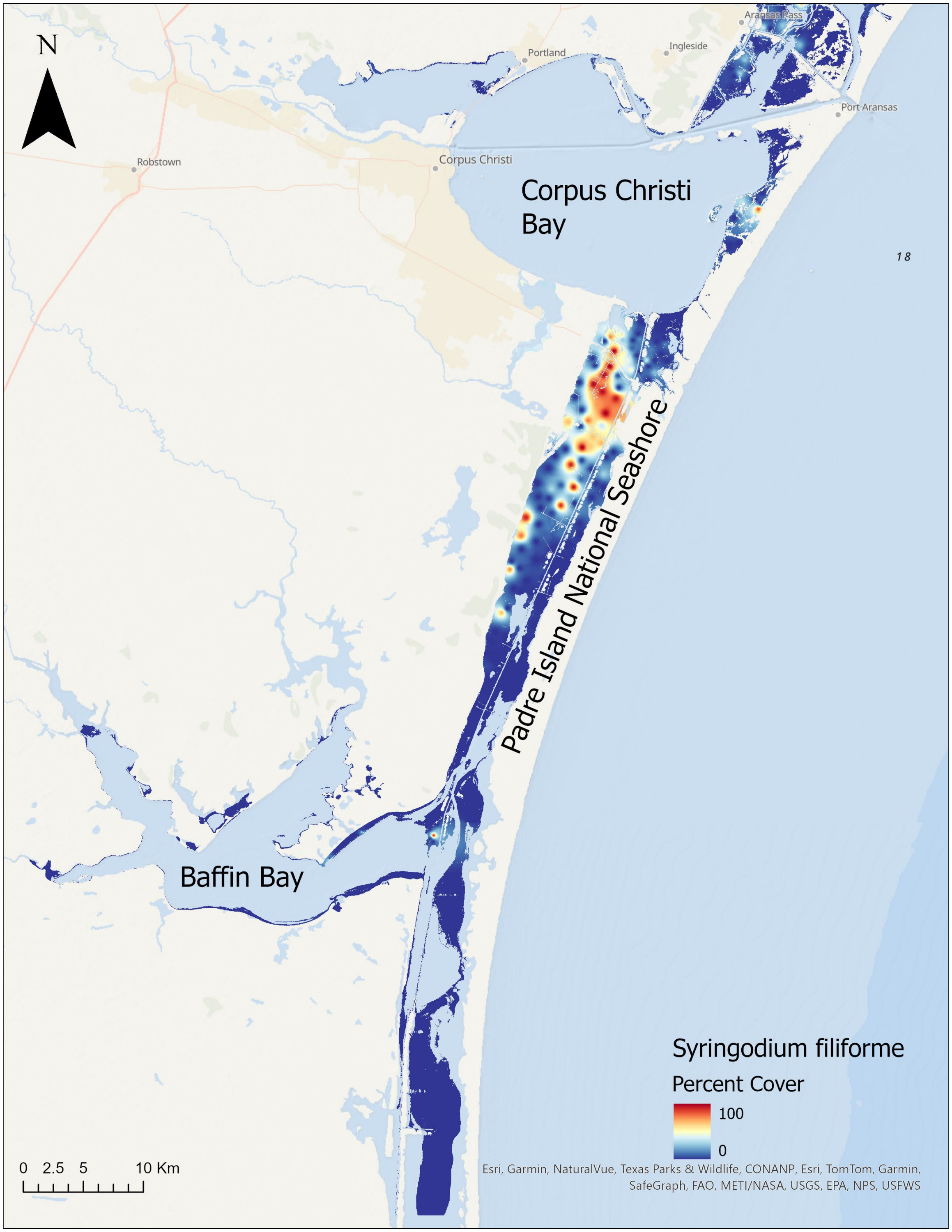


Figure 4. Spatial representations of percent cover for *Syringodium filiforme* for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

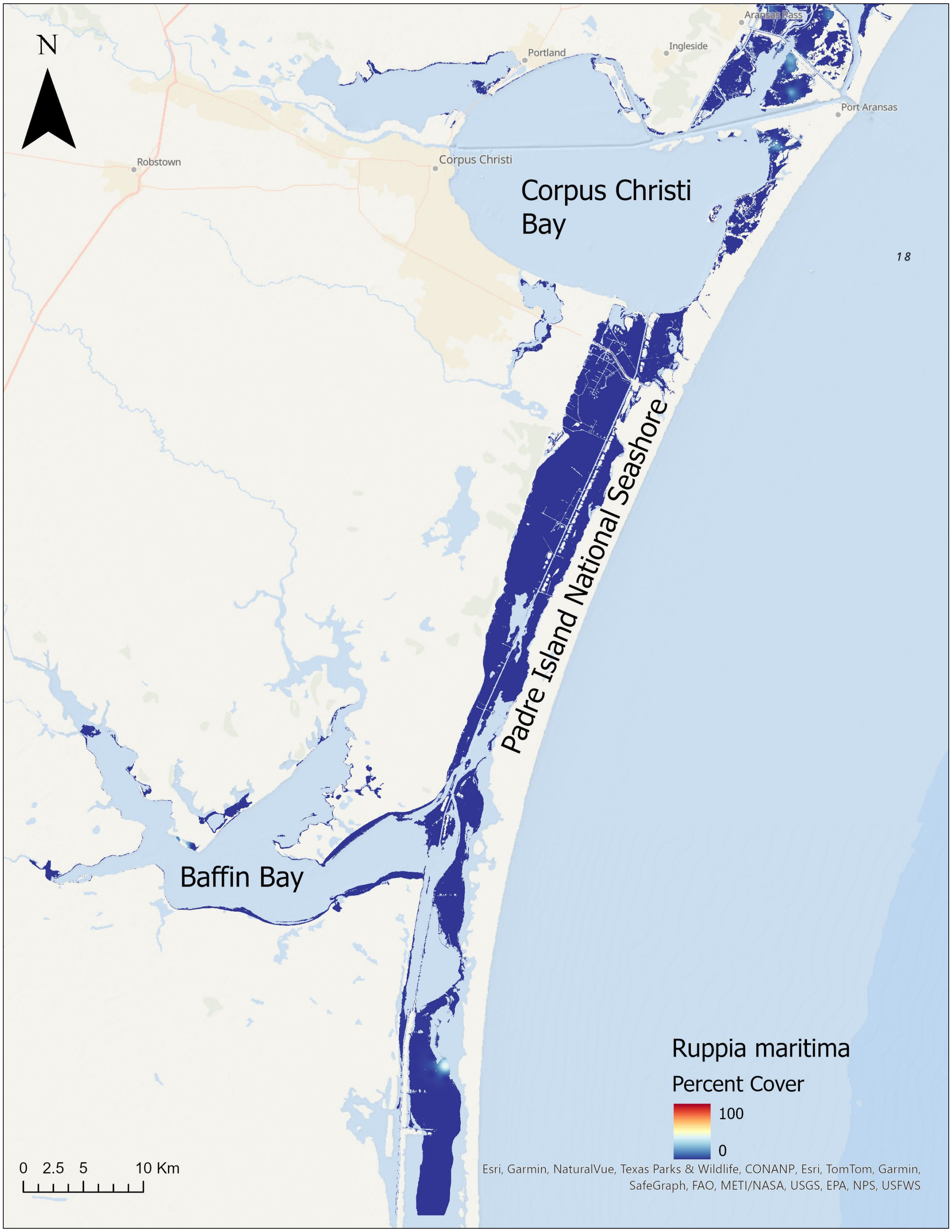


Figure 5. Spatial representations of percent cover for *Ruppia maritima* for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

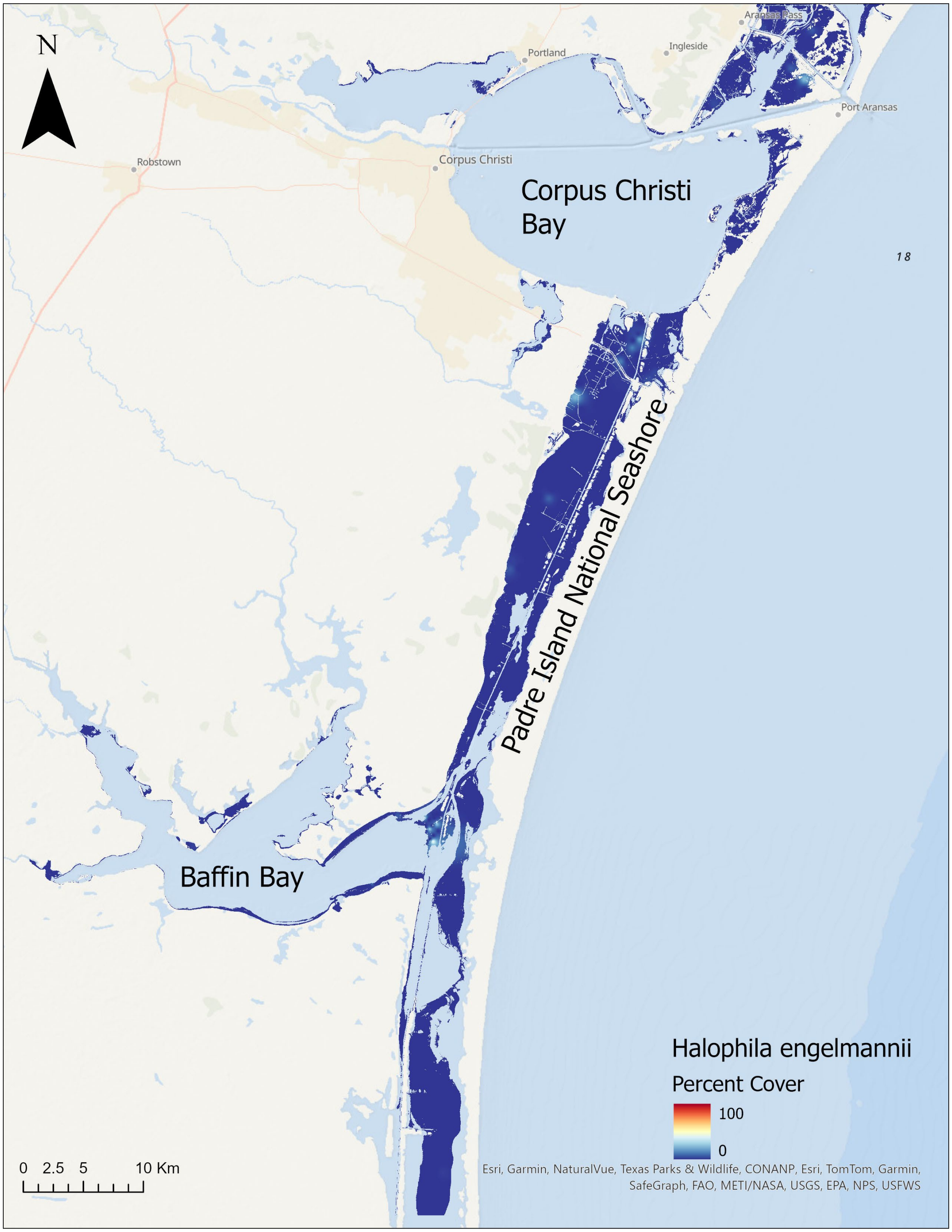


Figure 6. Spatial representations of percent cover for *Halophila engelmannii* for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

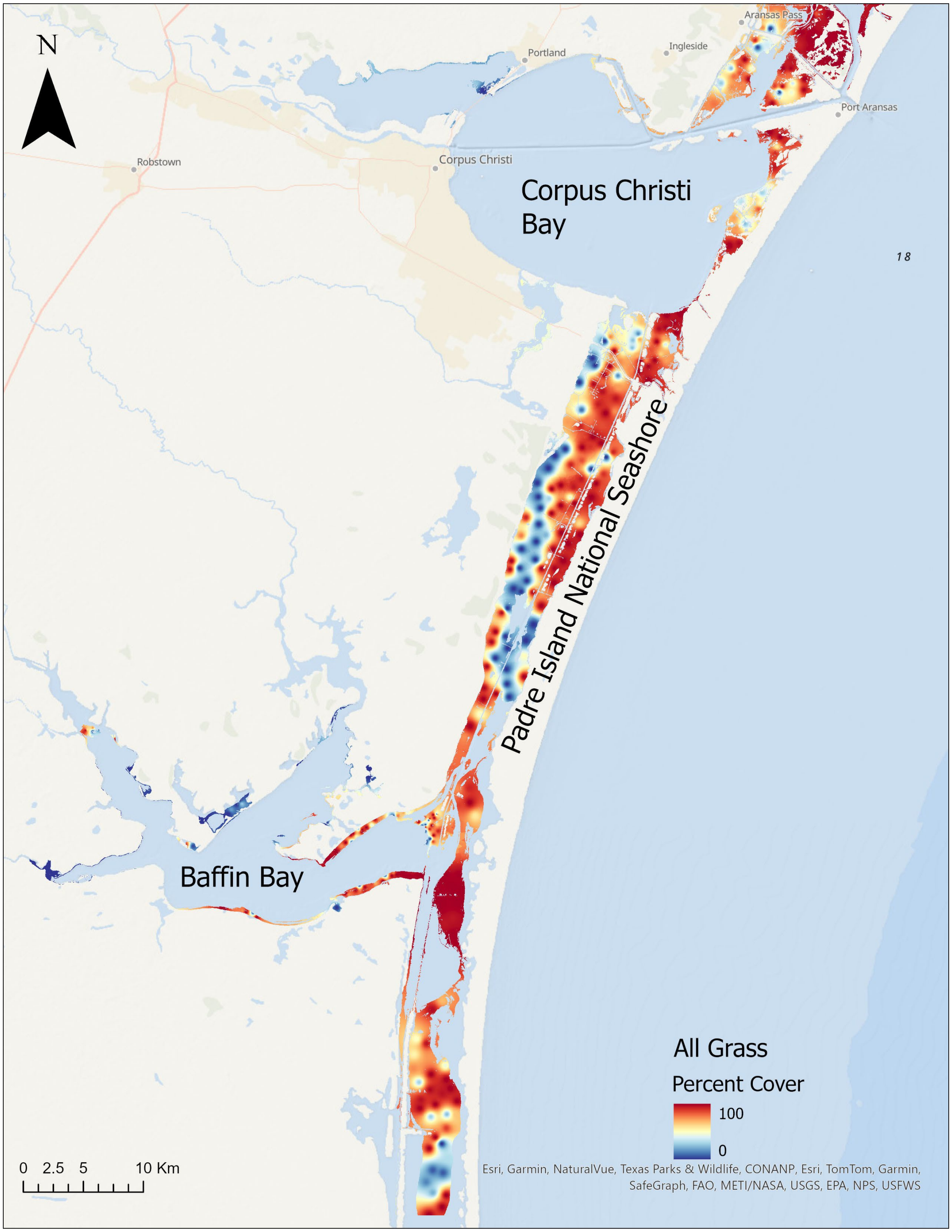


Figure 7. Spatial representations of percent cover for all seagrass species for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

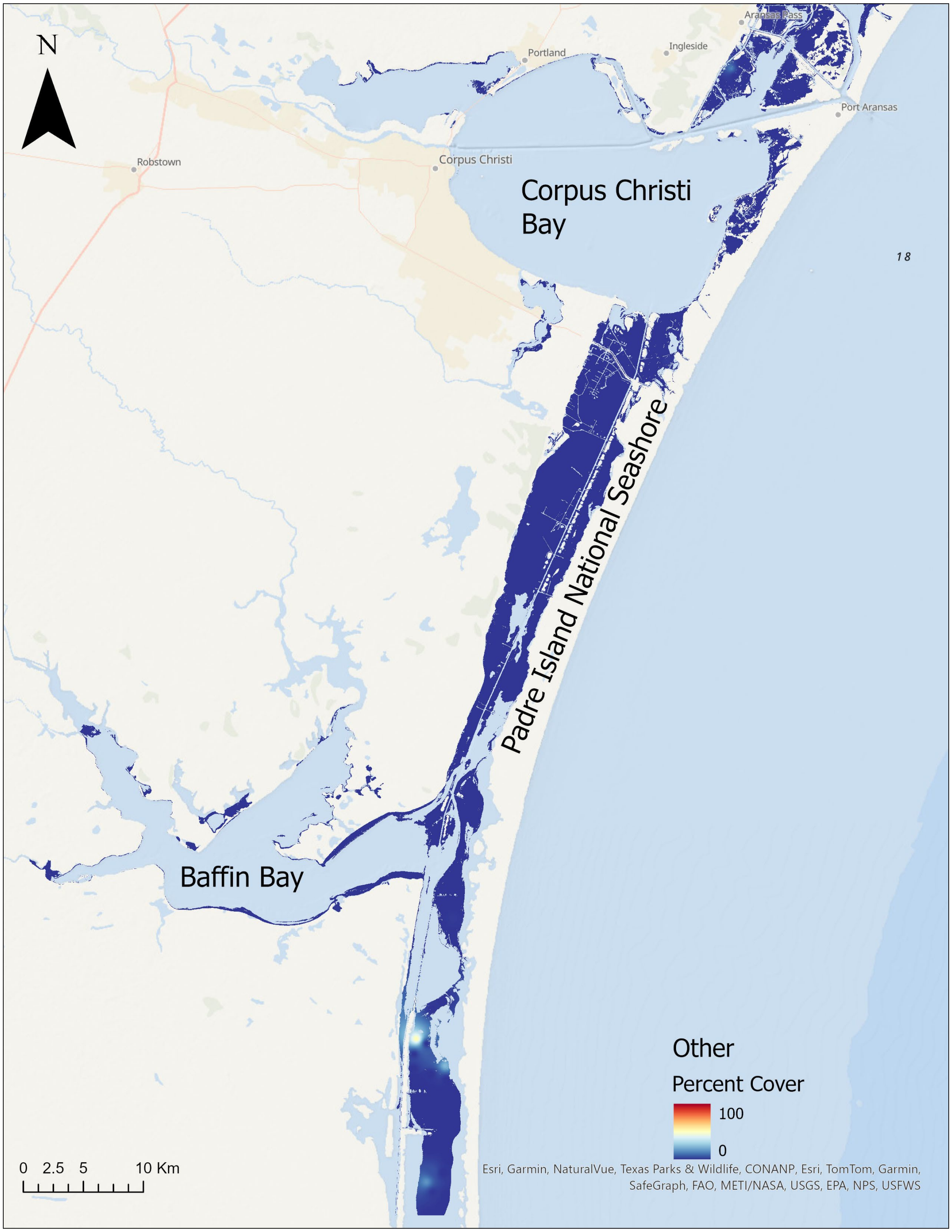


Figure 8. Spatial representations of percent cover for living, non-seagrass, ecosystem components (e.g., macroalgae) for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

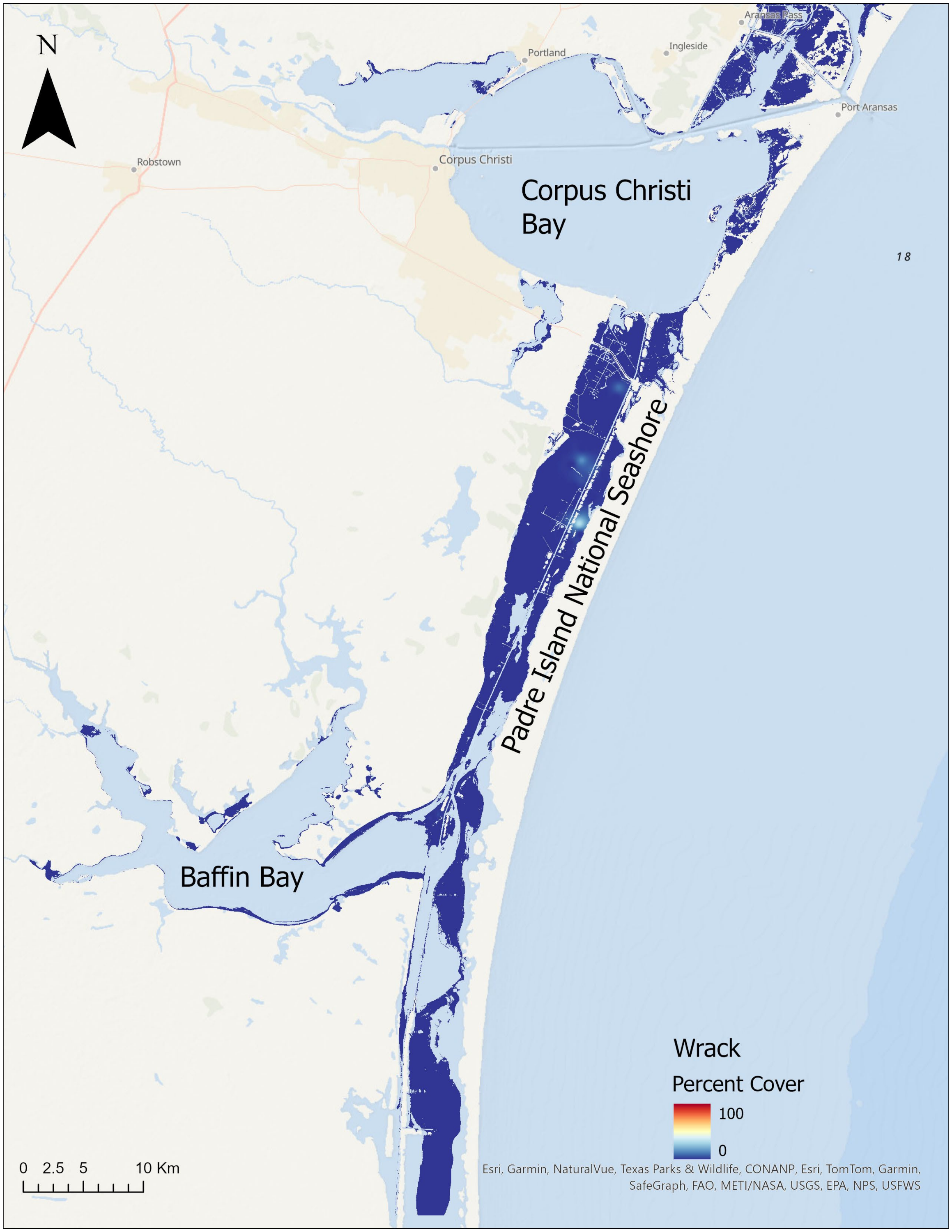


Figure 9. Spatial representations of percent cover for seagrass wrack for 2024. The spatial data interpolation is limited to the boundaries of seagrass habitat delineated by the 2022 NOAA USA seagrass distribution database.

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