In the wake of a major hurricane: Differential effects on early vs. late successional seagrass species

Victoria M. Congdon, Christina Bonsell, Meaghan R. Cuddy, Kenneth H. Dunton
Marine Science Institute, The University of Texas at Austin, Port Aransas, Texas

Scientific Significance Statement
Hurricanes and tropical storms can cause physical damage to coastal zones and their critical foundation plant species that include seagrasses. Submerged seagrasses are susceptible to wind and wave energy; however, it is not clear how seagrass species are differentially affected by storm energy and whether their variable susceptibility is more related to plant architecture or successional stage. Climax species have morphological traits (e.g., wide leaves, thick belowground tissues) that provide greater resistance to disturbances. Distinct life history traits (e.g., lower turnover) may translate to a slower ability to recover. We found that two species responded differently to a major hurricane and that the late successional species was more sensitive than the pioneer species as measured by greater reductions in cover and blade length. Our results suggest that species-specific responses are important when assessing hurricane effects on coastal habitats.

Abstract
At least 18 major storms have struck the Gulf of Mexico and Caribbean in the past 50 yr including Hurricane Harvey, a Category 4 storm that passed over extensive seagrass beds in the western Gulf of Mexico and became the second-most expensive U.S. hurricane. We sought to identify the effects of an extreme hurricane on sediment physicochemical characteristics and seagrass species with contrasting life histories and morphologies. Surprisingly, Harvey’s intense wind speeds resulted in decreases in blade length, vegetative cover, and greater overall loss of *Thalassia*, a persistent climax species relative to *Halodule*, a prolific pioneer species. Sediment ammonium and grain size changed, but not organic carbon. Our results indicate that effects of wind intensity are not only restricted to the differential impacts on seagrasses, but on the physicochemical characteristics of the sediments. These changes, coupled with the slow colonization abilities of *Thalassia*, may prolong recovery of disturbed seagrass meadows.

Disturbance is recognized as a major factor influencing the persistence of nearshore marine communities. In some cases, cyclones can produce intense winds and waves, torrential rainfall, and considerable storm surge that may impact a...
variety of coastal ecosystems including seagrasses, salt marshes, mangroves, coral reefs, and upland communities (Tilmant et al. 1994; Preen et al. 1995). These severe storms can defoliate and uproot vegetated communities, pummel underwater reef structures, and transport massive amounts of sediment that can affect habitat function. Seagrass meadows provide nursery habitat for recreationally and commercially important species, improve water quality, and sequester “blue” carbon (McLeod et al. 2011). Therefore, disturbances can disrupt the ecological functions of these foundation species by reducing carbon sequestration, releasing buried carbon (Macreadie et al. 2015), and altering habitat use by local fauna (Paperno et al. 2006).

The effects of severe weather phenomena on coastal habitats are variable and often differ in response to the individual characteristics of the storm. Tropical cyclones are typically large-scale disturbances but the environmental consequences can vary in magnitude and spatial extent (Smith et al. 1994; Paerl et al. 2001; Anton et al. 2009). Wind speed and direction, intensity, and storm proximity are all important determinants of impacts on the surrounding ecosystems. Post-hurricane investigations have documented catastrophic effects on mangroves located near the eyewall and storm track (Milbrandt et al. 2006). These high-energy wind and wave disturbances can also redistribute the substrate, causing substantial removal and deposition of sediments (Fourqurean and Rutten 2004).

In subtropical and tropical regions, ecological succession in seagrass beds typically culminate with *Thalassia testudinum*, where disturbed areas are first colonized by early successional macrophytes including seaweeds, *Halodule wrightii*, or *Syringodium filiforme* (Patriquin 1975). Differences in life history strategies determine species succession and ultimately their response to a disturbance. Colonizing or opportunistic species have lower resistance but the ability to recover quickly because of shorter turnover times, faster sexual maturation, and a high investment in the production of dormant seeds (Kilminster et al. 2015). The cited effects of hurricanes on seagrasses within the Gulf of Mexico and Caribbean illustrate the ephemeral nature of these acute disturbances and imply that seagrass ecosystems are resilient (Tilmant et al. 1994; Byron and Heck 2006; Steward et al. 2006). Hurricane-impact studies documented a range of responses, from no effect to species-specific losses (Fourqurean and Rutten 2004; Byron and Heck 2006; van Tussenbroek et al. 2008; Anton et al. 2009). Fourqurean and Rutten (2004) documented substantial thinning of *S. filiforme* (19%) and *H. wrightii* (11%) beds following a Category 2 hurricane. Interestingly, this same study only recorded a 3% reduction in the density of *T. testudinum*, which was attributed to species differences in plant architecture. To test this, Cruz-Palacios and van Tussenbroek (2005) simulated hurricane-like disturbances and concluded that differential growth forms such as a deeply anchored root-rhizome system, coupled with flexible leaf structure, buffered the effects of hurricanes. Field surveys conducted by van Tussenbroek et al. (2008) following a Category 4 hurricane documented significant declines in *S. filiforme* but minimal changes in *T. testudinum*, corroborating the findings of Fourqurean and Rutten (2004) and Cruz-Palacios and van Tussenbroek (2005). But the hearty architecture of long-lived seagrasses like *Thalassia* may not be advantageous across all environments. Individual storm characteristics, drag forces, and wave heights dictated by the proximity of the bed to physical barriers may influence distinct successional species differentially, particularly those (like *Thalassia*) that exhibit significant morphological plasticity.

In this study, we examine the susceptibility of seagrasses to a major storm event by asking two research questions: (1) what is the effect of a Category 4 hurricane on two common seagrass species characterized by very different life histories (e.g., turnover rate, age, resource allocation) and morphologies; and (2) how are the sediment characteristics altered in seagrass beds? We addressed these questions at 126 stations on the central Texas coast in the aftermath of Hurricane Harvey, a catastrophic storm that dropped over 60 in. of rainfall, caused approximately 68 deaths, and resulted in an estimated $125 billion in damages in late August 2017 (Blake and Zelinsky 2018). We used pre- and post-hurricane survey data from the Texas Seagrass Monitoring Program (http://www.texasseagrass.org) to document and compare the immediate impacts of this major disturbance on a pioneer, shoalgrass (*H. wrightii* = Halodule), and climax, turtlegrass (*T. testudinum* = Thalassia), species. We show that a major hurricane substantially affected established beds of the late successional species, *Thalassia*. Since seagrass recovery is a function of species-specific growth rates and the size of the disturbance, a slow-growing species such as *Thalassia* could require a decade or more to recover through vegetative regrowth or from new seedling propagation (Dawes et al. 1997).

**Methods**

**Storm and site description**

Hurricane Harvey rapidly intensified into a Category 4 hurricane before striking the Coastal Bend on 25 August 2017 (Fig. 1). Maximum sustained winds were 213 km h$^{-1}$ with highest peak wind gusts of 241 km h$^{-1}$. Extreme winds and disastrous flooding made Harvey the second largest natural disaster in terms of economic losses in U.S. history (Blake and Zelinsky 2018).

The Texas coast is composed of a series of shallow lagoons tucked behind barrier islands. The water depth of our stations ranges from 0.2 to 1.2 m (Coastal Bend) and 0.1 to 2.5 m (Laguna Madre). Seagrass assemblages in Texas are dominated by *Thalassia* (16–24% cover) and *Halodule* (34–43% cover). Sediment ammonium, organic carbon, and grain size composition ranges are, respectively: Coastal Bend: 4–481 μmol L$^{-1}$, 0.7–6.3%, and 71–100% shell/sand and 0.2–29% silt/clay; Laguna Madre: 7–535 μmol L$^{-1}$, 0.8–8.5%, and 49–97% shell/sand and 3–51% silt/clay.
Seagrass monitoring

As part of the Texas Seagrass Monitoring Program, a small team of trained observers has annually sampled 525 permanent stations along the Texas coast. We employed a restricted random sampling design where we generated one random, fixed station within a tessellated hexagon (Coastal Bend: 500-m edge; Laguna Madre 750-m edge) (Dunton et al. 2011; Neckles et al. 2012). Hexagons were created using the National Oceanic and Atmospheric Administration’s 2004/2007 Benthic Habitat Assessment (https://coast.noaa.gov/digitalcoast/data/) with a minimum threshold of 50% cover. In 2015 and 2017, we visited these same stations (± 10 m) along the same north-to-south gradient (Coastal Bend to Laguna Madre; Fig. 1) during peak seagrass growth (Coastal Bend: July/August; Laguna Madre: August/September/October/November). Prior to the landfall of Hurricane Harvey in 2017, we sampled 126 stations from 26 July to 22 August within the Coastal Bend.

Following the storm, the field team managed to resurvey the same 126 stations in the Coastal Bend from 18 September to 08 October. The remaining 399 Laguna Madre stations were surveyed from 18 October to 17 November 2017. Since we had not surveyed the Laguna Madre prior to Harvey’s landfall in 2017, we used pre-Harvey samples collected in 2015 for our pre- and post-storm comparison. For the Coastal Bend, our pre- and post-Harvey data were based entirely on samples collected prior to and immediately following landfall (126 stations). To determine seagrass composition at each of the 525 stations, we visually estimated percent cover by species using a 0.25 m² quadrat subdivided into 100 cells placed at four ordinal points around a shallow-draft vessel. Cover of seagrass species present in each quadrat was defined as the proportion of the frame obscured by vegetation. Immediately following each of the four cover observations, we collected five random shoots for all species present within the quadrat for measurements of blade length. Blade lengths were determined as the photosynthetic portion of the longest blade from each shoot. For subsequent analyses, we focused on the two dominant seagrass species, *Halodule* and *Thalassia*.

Sediment physicochemistry

In August 2011 and May 2012, sediment cores were collected from three fixed 50-m transects at a reference site within the Coastal Bend (27°54′N, 97°05′W) ranging in depth from 0.3 to 1.4 m. One core was collected at 10 permanent
points along each transect and processed for sediment ammonium. Additionally, at each transect, two cores were collected at the 0- and 50-m point for total organic carbon (TOC) and grain size analysis. Following Hurricane Harvey, we obtained two sediment cores from 16 stations \((n = 32)\), 0.5–0.75 km from the 2011/2012 reference site. From each of the 16 stations, we processed one of the cores for pore-water ammonium and the second core was subsampled for grain size and TOC. All sediment samples were collected within colonized or previously colonized sediments and extracted using a 10 cm (60 mL) syringe corer, placed on ice, and frozen prior to analyses. For pore-water ammonium, we thawed then centrifuged the sediment core, and processed the supernatant using the colorimetric techniques in Parsons et al. (1984). We determined sediment grain size fractions by weight using sieving and settling velocity to classify sediment particles (Folk 1961). Shell/sand fractions were classified as particles > 63 \(\mu\text{m}\). For the evaluation of organic matter, we used loss-on-ignition; samples were dried at 60°C to a constant weight, weighed, combusted at 550°C for 4 h, and reweighed.

### Spatial and statistical analyses

To illustrate continuous layers of changes in seagrass cover and wind speed, we used inverse-distance weighted (IDW) interpolation to assign values to areas between sampling points, weighted by distance. We used 12 sampling stations identified from a variable search radius \((100 \text{ m}^2)\) to generate a predicted value for each unknown point. We interpolated changes in seagrass cover using data from 525 stations, which were spatially restricted to the geographic limits of the submerged vegetation map (2004/2007 NOAA Benthic Habitat Assessment). Changes in seagrass cover \((\Delta C)\) caused by the hurricane were quantified as follows: \(\Delta C = [(C_{\text{post}} - C_{\text{pre}})/C_{\text{pre}}] \times 100\%\), where \(C_{\text{pre}}\) values were measured in 2015 (Laguna Madre: August–November) and 2017 (Coastal Bend: July–August). Since the Coastal Bend was exposed to major hurricane force winds, we focused on changes in cover at 126 stations within this region. For the interpolation of maximum sustained winds, we used 10-m maximum sustained wind gusts obtained from 70 weather locations reported by the National Weather Service (NWS; M. Buchanan) in the National Hurricane Center Hurricane Harvey tropical cyclone report (Blake and Zelinsky 2018). We used the tool “Extract Values to Points” to extract cell values from the interpolated wind raster to obtain an estimate of wind speed for each of the 525 seagrass sampling stations. All spatial analyses were performed in ArcMap 10.3 (Environmental Systems Research Institute).

We used maximum sustained winds derived from the IDW interpolations as a metric of wind intensity. We calculated the difference \((C_{\text{post}} - C_{\text{pre}})\) for cover and blade length for each of the 525 stations. Pre-Harvey data used in these calculations were obtained in 2017 and 2015 for the Coastal Bend and Laguna Madre, respectively. All seagrass post-Harvey data were from 2017. We then modeled the effect of wind intensity on differences in blade length and cover using linear regression for all 525 stations. We assessed whether species responded differently (i.e., change in slope) using analysis of covariance (ANCOVA) to test if models with an interaction between species and wind speed differed from those without an interaction term. For the 126 stations in the Coastal Bend, we tested for differences in cover and blade length of monospecific or mixed (species co-occur) beds using either Student’s \(t\)-test or Welch’s \(t\)-test (for unequal sample size). We tested differences in sediment grain size between pre-Harvey (2011/2012) and post-Harvey (2017) measurements using Student’s \(t\)-test for each size fraction after testing for normality. We examined for differences in sediment organic carbon and sediment ammonium via Wilcoxon rank sum test \((p < 0.05)\) after testing for homogeneity of variance using Levene’s test (cutoff value of \(p = 0.05)\). The data presented in this article are archived in the repository https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0187104 and https://doi.org/10.25921/9qkw-3w27.

### Results

Hurricane Harvey battered coastal habitats in Texas with copious rain and winds before weakening as it crossed toward the interior of the state; Category 3 and 4 winds associated with the storm’s eyewall were most prevalent in the Coastal Bend (Fig. 1, inset). There were significant albeit weak reductions in cover of *Thalassia* and *Halodule* at stations with higher winds but with greater explanatory power for *Thalassia* (Fig. 2A; linear regressions, \(F_{\text{Thalassia}(1205)} = 38.26, \text{adj. } R^2_{\text{Thalassia}} = 0.15, F_{\text{Halodule}(1388)} = 4.74, \text{adj. } R^2_{\text{Halodule}} = 0.01, \alpha = 0.05\)). The negative effect of maximum sustained winds on cover differed between species (ANOVA, \(F = 4.38, p < 0.05\)). Higher wind intensity led to significant decreases in blade lengths of both species with species-dependent effects (ANOVA, \(F = 12.18, p < 0.05\)) and lower explanatory power for *Halodule* (Fig. 2B; linear regressions, \(F_{\text{Thalassia}(1153)} = 105.7, \text{adj. } R^2_{\text{Thalassia}} = 0.40, F_{\text{Halodule}(1250)} = 15.91, \text{adj. } R^2_{\text{Halodule}} = 0.06, \alpha = 0.05\)).

Maximum winds corresponded with localized damage in *Thalassia* and *Halodule* beds (Fig. 1, inset; Fig. 3). In the Coastal Bend, the storm completely eradicated *Thalassia* at 12% of stations and 30% of stations displayed a > 50% reduction in cover \((n = 57)\; (\text{Fig. 3A})\). In comparison, 7% of stations lost *Halodule* with 13% of stations exhibiting > 50% decline \((n = 72)\; (\text{Fig. 3B})\). Cover differences \((C_{\text{post}} - C_{\text{pre}})\) per station of *Thalassia* \((\bar{x} \pm SD: -17.8\% \pm 29.8\%\) and *Halodule* \((\bar{x} \pm SD: 1.9\% \pm 25.7\%)\) were significantly different \((t\text{-test}, t = -4.22, df = 124.2, p < 0.05)\). The differences in cover of monospecific beds with either *Thalassia* \((\bar{x} \pm SD: -19.6\% \pm 29.3\%)\) or *Halodule* \((\bar{x} \pm SD: 2.2\% \pm 29.1\%)\) were significantly different \((t\text{-test}, t = -3.37, df = 67.3, p < 0.05)\). Differences in *Thalassia* \((\bar{x} \pm SD: -15.9\% \pm 30.6\%)\) and *Halodule* \((\bar{x} \pm SD: 1.3\% \pm 18.8\%)\) cover in mixed beds were also significantly different \((\text{Paired } t\text{-test}, t = -2.16, df = 30.0, p < 0.05)\). *Thalassia* lost significantly more
blade length than Halodule in both mixed and monospecific beds (t-test, mixed beds: \( t = -4.98, \text{df} = 7.0 \); monospecific beds: \( t = -5.34, \text{df} = 31.9; p < 0.05 \)).

In the Coastal Bend, monospecific and mixed beds experienced different maximum winds (Kruskall-Wallis rank sum test, \( X^2(2) = 42.39, \text{df} = 2.0, p < 0.05 \)). Winds were significantly lower (\( \bar{x} \pm \text{SD}: 169.0 \pm 34.1 \text{ km h}^{-1} \)) at stations with Halodule compared to Thalassia (\( \bar{x} \pm \text{SD}: 211.0 \pm 9.1 \text{ km h}^{-1} \)) and mixed (\( \bar{x} \pm \text{SD}: 209.0 \pm 9.7 \text{ km h}^{-1} \)) assemblages, but winds were not different between Thalassia and mixed beds (Bonferroni-corrected \( \alpha = 0.05 \)). The chance occurrence of Thalassia beds in areas with the highest wind velocities may have contributed to the differential response by species. Regardless, the change in cover (\( \Delta C \)) shows a greater loss of Thalassia (\( \bar{x} \pm \text{SD}; \ C_{\text{pre}}: 29.2\% \pm 38.1\%; \ C_{\text{post}}: 19.6\% \pm 28.9\% \)) relative to Halodule (\( \bar{x} \pm \text{SD}; \ C_{\text{pre}}: 35.6\% \pm 39.0\%; \ C_{\text{post}}: 37.0\% \pm 37.7\%; \text{Fig. 4A} \)). The negative effects of a hurricane on a climax species compared to other systems are notable and the largest reported for the Gulf of Mexico and Caribbean (Fig. 4).

Post-Harvey pore-water ammonium concentrations (\( \bar{x} \pm \text{SD}: 128.0 \pm 56.0 \mu\text{mol L}^{-1} \)) differed from pre-storm measurements (\( \bar{x} \pm \text{SD}: 72.3 \pm 38.9 \mu\text{mol L}^{-1} \); Wilcoxon rank sum test \( W = 204, p < 0.05 \); Levene’s test for homogeneity of variance \( F_{1,73} = 6.69, p < 0.05 \)). There was no difference in the mean and variance of sediment organic carbon between pre- and post-Harvey measurements (pre-Harvey: 3.5\% \pm 0.9\%; post-Harvey: 4.4\% \pm 2.1\% ; Wilcoxon rank sum test \( W = 112, p > 0.05 \)). We found significant post-Harvey differences among sediment fractions for shell (decreased) and percent clay (increased; t-test, \( \alpha = 0.05 \)).

**Discussion**

Our results stand in contrast to a large proportion of post-hurricane assessments in the Gulf of Mexico and Caribbean.
that documented no change to seagrass communities (Tilmant et al. 1994; Steward et al. 2006; Anton et al. 2009) or only substantial declines in the abundance of pioneer species (Fourqurean and Rutten 2004; van Tussenbroek et al. 2008). Hurricane Harvey damaged seagrass habitats along the Coastal Bend as reflected by decreases in cover and blade length directly related to wind intensity. The most notable difference between our observations and previous studies is that a Category 4 hurricane measurably affected the abundance of a late successional species despite their higher reported resistance to disturbances as noted in earlier studies (Fourqurean and Rutten 2004; Cruz-Palacios and van Tussenbroek 2005; van Tussenbroek et al. 2008).

Shifts in sediment physicochemical properties, coupled with our field observations noting erosion and burial, point to the transport of sediments during the hurricane. Enhanced microbial activity following Harvey may be responsible for the difference between pre- and post-storm ammonium concentrations. Post-storm ammonium was higher and displayed greater variability, which could indicate increased microbial remineralization of organic carbon (e.g., dead roots/rhizomes) in disturbed seagrass meadows (Macreadie et al. 2015). Although we did not detect a significant difference in sediment coarseness, there was a shift in the fraction of particles > 63 μm as sand increased from 42% to 58% and shell decreased from 45% to 24%. Since our pre-Harvey sediment samples were acquired in 2011/2012, the increase in silt/clay and organic carbon likely reflect “muddification.” Seagrasses trap sediments and accrete organic matter, and over time, sediments become rich in organic content and can shift from coarse to fine grains (Katwijk et al. 2010).

Typically, sediments along the northern part of the Gulf of Mexico are finer than their carbonate-rich counterpart, which could make it easier to dislodge seagrasses. Interestingly, sediments within the Coastal Bend were sandier (~82–93% shell/sand, 7–17% silt/clay) than tropical areas like Florida Bay (~36% shell/sand, 64% silt/clay) (Jensen et al. 2009). Since the sediment fractions of our study area were comparable to compositions in the Caribbean (~90% shell/sand, 10% silt/clay; Cruz-Palacios and van Tussenbroek 2005), additional factors other than grain size may be at play in the removal of seagrasses during Harvey.

*Thalassia* exhibits significant morphological plasticity across the Caribbean and the Gulf of Mexico, with leaf width displaying the most significant variability in morphological traits (McDonald et al. 2016). An earlier study (May-Ku

![Fig. 3](image-url). The changes in cover of (A) *T. testudinum*, and (B) *H. wrightii* in mixed beds located in the Coastal Bend, Texas following the passage of a Category 4 hurricane. One permanent station exists within each of the 126 hexagon sampling cells (500-m edge). Changes in seagrass cover (ΔC) caused by the hurricane were quantified as follows: ΔC = [(C_{post} - C_{pre})/C_{pre}] × 100%. Colored hexagons reflect changes in percent cover where both seagrass species, *T. testudinum* and *H. wrightii*, co-occur. Shaded hexagons represent stations with monospecific beds of either *T. testudinum* or *H. wrightii*. Cool colors represent an increase in cover, but the difference between pre- and post-Harvey measurements were within the minimal detectable range of a Braun-Blanquet cover abundance scale (25%; with the majority of these differences less than 10%).
et al. 2010) also noted that Thalassia blade widths were significantly greater in exposed vs. sheltered locations. Such traits are consistent with reports that seagrasses with long/wide blades have higher leaf breaking forces (Puijalon et al. 2011; de los Santos et al. 2016). The relatively narrow blade widths of Thalassia in our study (5.7 mm) compared to other regions (8 mm; McDonald et al. 2016), which is nearly half the 10.7 mm reported by May-Ku et al. (2010), may have contributed to the unexpected damage suffered by Thalassia in Texas.

The differential effects of Harvey on Thalassia and Halodule was also notable and may be related to the disjunct distribution of pure stands of both species as well as the protective barrier to shear forces provided by Thalassia in mixed stands. In comparison to Thalassia, Halodule often grows in sheltered locations or under the protection of larger species that are more resistant to wave exposure (de los Santos et al. 2016). In our system, it is not uncommon for Halodule to colonize shoals while Thalassia grows along the outer and deeper edges of the bed, so it is possible that Thalassia may have buffered the effects of Harvey in mixed beds.

The low damage to Halodule populations may also be related to the rapid regrowth potential of this species. We noted that Thalassia shoots exhibited horizontal cuts across the tissue (Fig. 4C), presumably severed at the sediment surface. These cuts were not apparent on the much narrower Halodule shoots, which may have responded very rapidly (peak growth rates range from 4–7 mm d\(^{-1}\) in early fall; Dunton 1994) to higher nutrient loads from freshwater run-off following Harvey. In contrast, reported growth rates for Thalassia in the Gulf of Mexico are considerably lower at 1–3 mm d\(^{-1}\) in the Coastal Bend of Texas (Czerny and Dunton 1995) and 2–4 mm d\(^{-1}\) in Florida (Zieman 1975). Slower growth rates are life history traits typically associated with climax species like Thalassia relative to “weedy” pioneer species such as Halodule.

Here, we report substantial declines in the abundance of a climax species that is widely distributed throughout the Gulf of Mexico and Caribbean (Fig. 4). We acknowledge the temporal limitations of our study but fortunately, our samples from the Coastal Bend were collected 3–31 d before the storm and likely reflect damage wrought by Harvey. The fragmented and decayed belowground tissues in well-established seagrass beds...
successional paradigm predicts that the poor recolonization abilities of *Thalassia* results in a significantly slower recovery than either *Halodule* or *Syringodium*. Therefore, the loss of *Thalassia* may create space for the colonization of these opportunistic species. Consequently, this disturbance provides an opportunity to document changes in species abundances and compositions across spatial and temporal scales. Long-term monitoring efforts should capture the duration and extent of the recovery of seagrass beds impacted by a major hurricane and lead to better predictions of the effects of future large-scale disturbances.

### References

Anton, A., J. Cebrian, C. M. Duarte, K. L. Heck, and J. Goff. 2009. Low impact of Hurricane Katrina on seagrass community structure and functioning in the northern Gulf of Mexico. Bull. Mar. Sci. 85: 45–49.

Blake, E. S., and D. A. Zelinsky. 2018, *National Hurricane Center tropical cyclone report: Hurricane Harvey*. NOAA National Weather Service National Hurricane Center.

Byron, D., and K. L. Heck. 2006. Hurricane effects on seagrasses along Alabama’s Gulf Coast. Estuaries Coast. 29: 939–942. doi:10.1007/BF02798654

Cruz-Palacios, V., and B. I. van Tussenbroek. 2005. Simulation of hurricane-like disturbances on a Caribbean seagrass bed. J. Exp. Mar. Biol. Ecol. 324: 44–60. doi:10.1016/j.jembe.2005.04.002

Czerny, A. B., and K. H. Dunton. 1995. The effects of in situ light reduction on the growth of two subtropical seagrasses, *Thalassia testudinum* and *Halodule wrightii*. Estuaries 18: 418–427. doi:10.2307/1352324

Dawes, C. J., J. Andorfer, C. Rose, C. Uranowski, and N. Ehringer. 1997. Regrowth of the seagrass *Thalassia testudinum* into propeller scars. Aquat. Bot. 59: 139–155. doi:10.1016/S0304-3770(97)00021-1

de los Santos, C. B., and others. 2016. A comprehensive analysis of mechanical and morphological traits in temperate and tropical seagrass species. Mar. Ecol. Prog. Ser. 551: 81–94. doi:10.3354/meps11717

Di Carlo, G., and W. J. Kenworthy. 2008. Evaluation of aboveground and belowground biomass recovery in physically disturbed seagrass beds. Oecologia 158: 285–298. doi:10.1007/s00442-008-1120-0

Dunton, K. H. 1994. Seasonal growth and biomass of the subtropical seagrass *Halodule wrightii* in relation to continuous measurements of underwater irradiance. Mar. Biol. 120: 479–489. doi:10.1007/BF00680223

Dunton, K. H., W. Pulich, and T. Mutchler. 2011, *A seagrass monitoring program for Texas coastal waters: Multiscale integration of landscape features with plant and water quality indicators*. Coastal Bend Bays & Estuaries Program.

Folk, R. L. 1961, *Petrology of sedimentary rocks*, 1st Edition. Hemphills Press.

Fourquarean, J. W., and L. M. Rutten. 2004. The impact of Hurricane Georges on soft-bottom, back reef communities:
Site- and species-specific effects in South Florida seagrass beds. Bull. Mar. Sci. 75: 239–257.

Jensen, H. S., O. I. Nielsen, M. S. Koch, and I. de Vicente. 2009. Phosphorus release with carbonate dissolution coupled to sulfide oxidation in Florida Bay seagrass sediments. Limnol. Oceanogr. 54: 1753–1764. doi:10.4319/lo.2009.54.5.1753

Katwijk, M. M., A. R. Bos, D. C. R. Hermus, and W. Suykerbuyk. 2010. Sediment modification by seagrass beds: Mudification and sandification induced by plant cover and environmental conditions. Estuar. Coast. Shelf Sci. 89: 175–181. doi:10.1016/j.ecss.2010.06.008

Kilminster, K., and others. 2015. Unravelling complexity in seagrass systems for management: Australia as a microcosm. Sci. Total Environ. 534: 97–109. doi:10.1016/j.scitotenv.2015.04.061

Macedo, F. P., J. A. Lane, C. W. Skirrow, B. G. Jones, and J. R. Seymour. 2015. Losses and recovery of organic carbon from a seagrass ecosystem following disturbance. Proc. Biol. Sci. 282: 20151537. doi:10.1098/rspb.2015.1537

May-Ku, M. A., P. -L. Ardisson, and U. Ordóñez-López. 2010. Morphological variation of Thalassia testudinum in two shallow coastal environments from the southeastern Gulf of Mexico. Bot. Mar. 53: 449–455. doi:10.1515/BOT.2010.049

McDonald, A. M., P. Pradoc, K. L. Heck Jr., J. W. Fourqurean, T. A. Frankovich, K. H. Dunton, and J. Cebrian. 2016. Seagrass growth, reproductive, and morphological plasticity across environmental gradients over a large spatial scale. Aquat. Bot. 134: 87–96. doi:10.1016/j.aquabot.2016.07.007

McLeod, E., and others. 2011. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. 9: 552–560. doi:10.1890/110004

Milbrandt, E. C., J. M. Greenawalt-Boswell, P. D. Sokoloff, and S. A. Bortone. 2006. Impact and response of Southwest Florida mangroves to the 2004 hurricane season. Estuaries Coast. 29: 979–984. doi:10.1007/BF02798659

Neckles, H. A., B. S. Kopp, B. J. Peterson, and P. S. Pooler. 2012. Integrating scales of seagrass monitoring to meet conservation needs. Estuaries Coast. 35: 23–46. doi:10.1007/s12237-011-9410-x

Parrel, H. W., and others. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States’ largest lagoonal estuary, Pamlico sound, NC. Proc. Natl. Acad. Sci. USA 98: 5655–5660. doi:10.1073/pnas.101097398

Paterno, R., D. M. Tremain, D. H. Adams, A. P. Sebastian, J. T. Sauer, and J. Dutka-Gianelli. 2006. The disruption and recovery of fish communities in the Indian River Lagoon, Florida, following two hurricanes in 2004. Estuaries Coast. 29: 1004–1010. doi:10.1007/BF02798662

Parsons, T. R., Y. Maita, and C. M. Lalli. 1984, A manual of chemical and biological methods for seawater analysis, 1st Edition. Pergamon Press.

Patriquin, D. G. 1975. “Migration” of blowouts in seagrass beds at Barbados and Carriacou, West Indies, and its ecological and geological implications. Aquat. Bot. 1: 163–189. doi:10.1016/0304-3770(75)90021-2

Preen, A. R., W. J. Lee Long, and R. G. Coles. 1995. Flood and cyclone related loss, and partial recovery, of more than 1000 km² of seagrass in Hervey Bay, Queensland, Australia. Aquat. Bot. 52: 3–17. doi:10.1016/0304-3770(95)00491-H

Puigalon, S., T. J. Bouma, C. J. Douday, J. Groenneland, N. P. R. Anten, E. Martel, and G. Bornette. 2011. Plant resistance to mechanical stress: Evidence of an avoidance–tolerance trade-off. New Phytol. 191: 1141–1149. doi:10.1111/j.1469-8137.2011.03763.x

Smith, T. J., M. B. Robblee, H. R. Wanless, and T. W. Doyle. 1994. Mangroves, hurricanes, and lightning strikes. Bioscience 44: 256–262. doi:10.2307/1312230

Steward, J. S., R. W. Vinrstein, M. A. Lasi, L. J. Morris, J. D. Miller, L. M. Hall, and W. A. Tweedale. 2006. The impacts of the 2004 hurricanes on hydrology, water quality, and seagrass in the Central Indian River Lagoon, Florida. Estuaries Coast. 29: 954–965. doi:10.1007/BF02798656

Tilmant, J. T., and others. 1994. Hurricane Andrew’s effects on marine resources. Bioscience 44: 230–237. doi:10.2307/1312227

van Tussenbroek, B., M. Santos, J. Van Dijk, S. Alcaraz, and M. Calderón. 2008. Selective elimination of rooted plants from a tropical seagrass bed in a back-reef lagoon: A hypothesis tested by Hurricane Wilma (2005). J. Coast. Res. 24: 278–281. doi:10.2112/06-0777.1

Ziemann, J. C. 1975. Seasonal variation of turtle grass, Thalassia testudinum König, with reference to temperature and salinity. Aquat. Bot. 1: 107–123. doi:10.1016/0304-3770(75)90016-9

Acknowledgments

We thank the amazing staff at the University of Texas Marine Science Institute for providing logistical support to allow us to sample within weeks of Harvey’s landfall despite enormous damage to our institute facilities. In particular, we are indebted to F. Ernst for providing reliable vessels that helped us to conduct intensive field studies and our colleagues at Texas A&M University–Corpus Christi (B. Nicolau and P. Zimba) for providing lab facilities for sample processing. We are very grateful to L. Yeager for her support and providing helpful comments to earlier versions of this manuscript. We are deeply appreciative of continued funding support provided by the Coastal Bend Bays and Estuaries Program (R. Allen; Contract No. 1610), National Park Service (M. Segura; CESU Contract No. P16AC01794), and Texas General Land Office (R. Bond; Contract No. 18-083-000-A592), with in-kind support from the Mission-Aransas National Estuarine Research Reserve (J. Tunnell). A special thank you to M. Buchanan (National Weather Service) for providing us with meteorological data. The National Science Foundation RAPID grant OCE 1807143 provided analytical support for postcollection samples.