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Impact of Hurricane Harvey on Galveston Bay Saltmarsh Nekton Communities

Jenny W. Oakley[1] · George J. Guillen[1]

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Abstract
Coastal saltmarshes are a unique habitat at the interface of tidal coastal waters and freshwater inflow providing foraging and nursery habitat for a dynamic nekton community. Saltmarshes are particularly exposed to natural disturbances such as tropical storms, which can cause shifts in water chemistry and nekton community composition. Hurricane Harvey resulted in widespread flooding and record freshwater inflow into Galveston Bay in late August 2017. This study examined the influence of the hurricane on nekton community composition of two saltmarshes in Galveston Bay, TX. Nekton were monitored from February to December 2017 using minnow seines and Breder traps. Reduced abundance and increased diversity, despite the overall reduced number of taxa of the nekton community, were documented following the hurricane. Exacerbating these differences were reduced catches of the numerically dominant daggerblade grass shrimp, *Palaemonetes pugio*, following the event. For some key dominant species, a significant reduction in length was measured between pre- and post-disturbance; therefore, it is likely that new recruits, rather than the return of displaced adults, drove the community recovery. A complete recovery to a pre-disturbance state will likely require at least a full year due to seasonal recruitment patterns of many of the saltmarsh nekton species. Short-term but large-scale natural disturbances can significantly impact saltmarsh nekton communities, but because of their dynamic nature, they are generally resilient.

Keywords Flood · Marsh · Tidal wetland · Tidal creek · Fish · Disturbance

Introduction

Saltmarshes occurring in brackish waters provide habitat for both marine and freshwater migrant functional groups (Elliott et al. 2007). These productive ecosystems support a diverse nekton community with accessibility to food and refuge from predators, and serve as nursery habitat for the immature stages of many commercially and recreationally important species (Sheaves et al. 2015; Hall et al. 2016; Allen et al. 2017). Some saltmarsh specialists such as the saltmarsh topminnow *Fundulus jenkinsi* (a candidate for endangered species act consideration) have a high affinity for this habitat, indicating that it is functionally essential throughout their life cycle (Peterson et al. 2003; Guillen et al. 2015).

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✉ Jenny W. Oakley
oakley@uhcl.edu

[1] Environmental Institute of Houston, University of Houston-Clear Lake, 2700 Bay Area Blvd, Houston, TX 77058, USA

Saltmarshes are dynamic ecosystems influenced by variable amounts of both tidal saltwater exchange and freshwater inflow. Because of their transitional position in the landscape, they are particularly exposed to extreme physical disturbances that can cause significant perturbation to the biotic community (Piazza and La Peyre 2009). Storm surges and rain-induced flooding from hurricanes are examples of climatically induced extreme pulse events that can result in intense ecosystem disturbance (Yang et al. 2008). The persistence and magnitude of impacts on saltmarsh biological communities from these types of disturbances can serve as bioindicators of ecosystem resilience. The resilience of coastal ecosystems has become a subject of increasing interest as it relates to global climate change and the expected increase in the number and severity of tropical storms (Switzer et al. 2006; Webster et al. 2005; Trenberth et al. 2018).

Hurricane Harvey caused widespread flooding throughout Southeast Texas, impacting the Galveston Bay Area. Harvey has been described as an extremely rare event, exceeding other tropical cyclone rainfall totals of record in the contiguous USA (van Oldenborgh et al. 2017). The Texas Water

Development Board estimated that the total freshwater inflow to the Galveston Bay system caused by Hurricane Harvey (August 25–September 20, 2017) was 14.2 billion cubic meters, which was greater than the average annual freshwater inflow to the system based on the 65-year period from 1941 to 2015 (13.7 billion cubic meters) (Schoenbaechler 2018; Guthrie et al. 2012). The record influx of fresh water to the bay drowned saltmarshes and flushed out the salt water, bringing with it suspended sediment, debris, and pollutants. The effects of this hurricane on two saltmarsh nekton communities within Galveston Bay, TX, are described herein.

Methods

Galveston Bay is located in southeast Texas and is the largest estuary in the state and the seventh largest in the USA with the fourth most populous metropolitan area in the country within its watershed. The long-term average salinity for Galveston Bay is 15.1 psu but varies widely due to changes in freshwater inflow into the system (Pinckney et al. 2017). The drainage basin for the bay includes the metropolitan areas of Dallas/Fort Worth and Houston, TX, contributing to sizeable freshwater inputs into the estuary from the Trinity (55%) and San Jacinto (26%) rivers, respectively (Guthrie et al. 2012).

Nekton communities inhabiting two saltmarshes located on the eastern and western shoreline of Galveston Bay were studied. These sites were chosen because of the availability of previously collected pre-storm data and on-going monitoring of the nekton community. These pre-storm data were collected as part of a state-wide study on populations of *F. jenkinsi*. Site 21 is located at an unnamed tidal tributary to the southern arm of Moses Lake (TCEQ Segment 2431C) at 25th Ave N. near Texas City, Galveston County, TX (29.408970, −94.951680) (Fig. 1). Site 113 is located in an unnamed tidal tributary to Lone Oak Bayou at the FM 562 Bridge Crossing in Chambers County, TX (29.611300, −94.677060) (Fig. 1). Both sites are located on relatively small tidal creeks with small contributing watersheds. While they have direct tidal access, they are both located more than 2 km upstream from the open waters of Galveston Bay.

Prior to hurricane landfall, the sites were sampled every other month from February to August 2017. Post-disturbance, sites were sampled every other week through December 2017. Ambient water quality, including water depth (m), salinity (psu), dissolved oxygen (mg/L), and temperature (C), was measured using a YSI ProDSS sonde. Secchi depth transparency (m) was also measured during each sampling event using a Secchi tube.

Nekton sampling at each site and sampling event consisted of three 10 m hauls of a 15′×4′ minnow seine (1/8″ bar mesh) along the marsh edge. Three Breder traps were also deployed overnight (through a falling tidal cycle) facing the inundated marsh (Breder Jr. 1960). Breder traps were constructed with clear plexiglass (0.08″ thickness) using the same dimensions (12″ × 6″) as Lopez et al. (2011). Nekton were identified in the field when possible and released. When necessary, specimens were administered a lethal dose of MS-222, fixed in a 10% buffered formalin solution, and then brought back to the laboratory where they were identified to species, counted, and measured (standard length in mm, five individuals per gear type and replicate).

Fish community structure was characterized using various community metrics including total taxa abundance (N), relative abundance (%), taxa richness (S), and the Shannon-Wiener diversity index (H′) (Magurran 2004). These data were plotted to facilitate visual comparisons. Basic statistical analyses (*t* test, one-way ANOVA) were conducted on lengths of selected numerically dominant species using Sigma Plot 14.0 software with a significance level of $\alpha = 0.05$. When data distributions were non-normal, Kruskal-Wallis one-way ANOVA on ranks was used.

Multivariate statistical methods were used to compare sites and collection periods using taxa composition. Nekton assemblage data were $\log(x + 1)$ transformed. The resemblance of individual collections was compared with the Bray-Curtis similarity index using the PRIMER 7 statistical software package (Clarke and Warwick 2001). Non-metric multidimensional scaling (nMDS) plots of assemblages were also constructed in PRIMER 7 to display assemblage similarities by sample event. Pearson correlation was used to identify the influence of individual species contributions to assemblage similarities.

Results

Hurricane Harvey made landfall on August 25, 2017, in Rockport, TX, and then slowly moved over southeast Texas where record amounts of rain fell in the Galveston Bay watershed. Water levels at the two study sites peaked on August 29, 2017 (Fig. 2). Immediately following the Hurricane flood event (September 11, 2017, 17 days after landfall), salinities were very low at sites 21 (1.16 psu) and 113 (0.47 psu) (Fig. 3). Salinity at Site 21 had recovered to levels within a standard deviation (σ) of the average salinity recorded at the site from all pre-disturbance historical data approximately 64 days after the Hurricane (Fig. 3). While no historic data (pre-2017) are available to compare Site 113, nekton community structure and dominant marsh plants indicate that the average salinity at the site prior to the hurricane was likely lower but comparable to Site 21. Both sites experienced increases in water level during the disturbance with complete inundation of saltmarsh habitat; however, there was no

Fig. 1 Map of saltmarsh nekton community study sites, Galveston Bay, Texas. Site 21 (29.408970, − 94.951680) Site (29.611300, − 94.677060) ArcGIS 10.3

significant physical damage observed (from scouring) to the saltmarsh plant structure after the disturbance event at either of the two study sites.

A total of 61,741 individuals representing 44 different species were captured during the study (Table 1). Total community abundance and taxa richness declined immediately following the flood disturbance (Fig. 4a). Community diversity and evenness increased immediately following the disturbance (Fig. 4b). Decreased abundance during the post-disturbance period was primarily driven by the decrease in daggerblade grass shrimp (*Palaemonetes pugio*) (Table 1). At site 21, the fish community differences observed immediately after the disturbance were primarily driven by the increased abundance of bay anchovy, *Anchoa mitchilli*. Other species that occurred with regularity at site 21 that were not captured immediately following the disturbance were pinfish, *Lagodon rhomboides*, and gulf pipefish, *Syngnathus scovelli*. Site 113 experienced a reduction in some of the historically observed species immediately following the disturbance, including atlantic croaker, *Micropogonias undulates*, naked goby, *Gobiosoma bosc*, and striped mullet, *Mugil cephalus*.

Standard length was compared pre- versus post-disturbance for the most abundant species (*P. pugio*) and the two most abundant fish species observed at each site (inland silverside, *Menidia beryllina* and *A. mitchilli*). No significant difference in *P. pugio* and *M. berrylina* lengths was observed between sites within each disturbance time period. Consequently, all length data for each of these species were pooled for both sites to evaluate differences in lengths between pre- and post-disturbance periods. In contrast, site 21 had significantly larger *A. mitchilli* than site 113 ($p = < 0.001$) so each site's data were analyzed separately to avoid an interaction effect. Specimens of *P. pugio* were significantly larger pre-disturbance compared with post-disturbance ($p = < 0.001$). Similarly, *M. beryllina* specimen lengths were significantly larger pre versus post-disturbance ($p = 0.0437$). *A. mitchilli* lengths showed no significant difference between

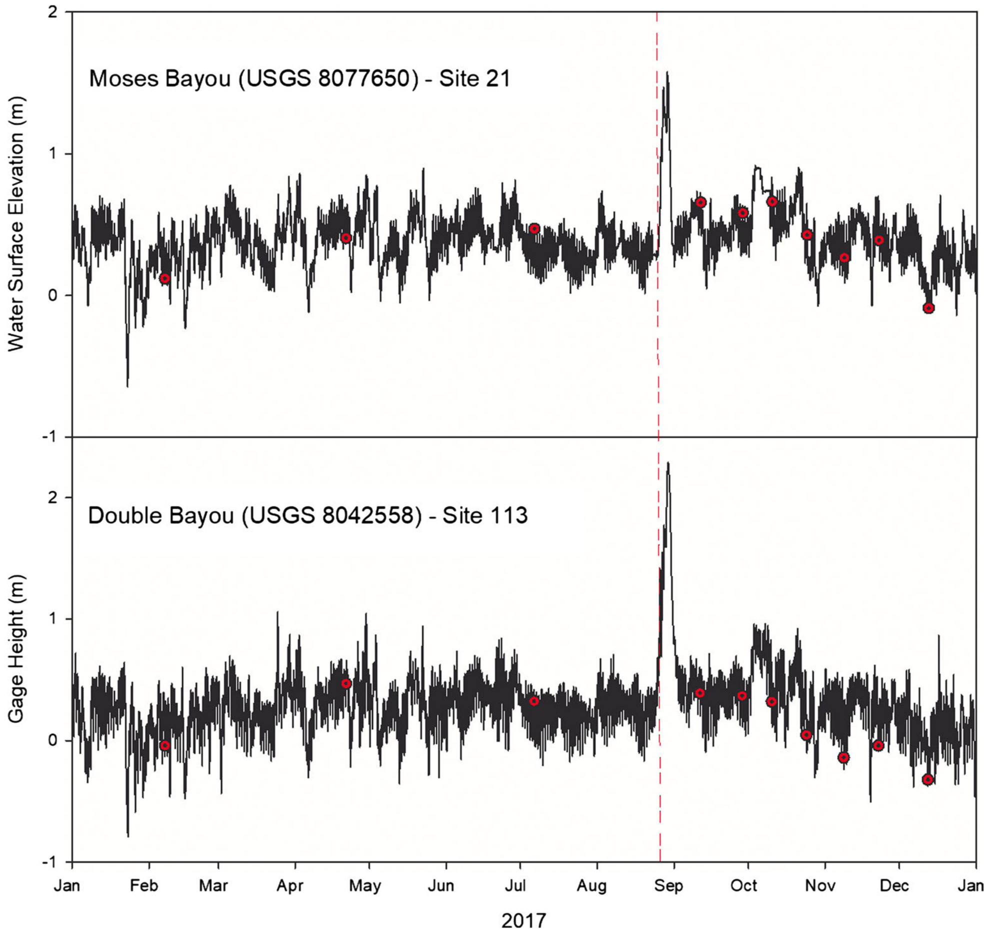

Fig. 2 USGS water level data for 2017, illustrating the flood event following Hurricane Harvey's Landfall on August 25, 2017 (red dashed line), with saltmarsh nekton community sampling events plotted as red circles SigmaPlot 14.0

pre- and post-disturbance periods for either site (site 21 $p = 0.204$, site 113 $p = 0.285$).

During the study, seasonal shifts in community structure similar to historic (2014–2015) data collected from site 21 were observed (Guillen et al. 2015). However, the seasonal shift in species composition from the post-disturbance period deviated from patterns observed prior to Hurricane Harvey which depict seasonal trends along the second ordination (MDS2) from the bottom right corner of the figure to the top left (see historic data-blue triangles, Fig. 5). The community samples collected post-disturbance (see green squares, Fig. 5) were instead dispersed on the opposite MDS1 ordination, falling out on the bottom left of the figure. Similar temporal trend was observed when comparing site 21 to site 113 indicating that this event was widespread and had a similar impact to the saltmarsh nekton communities bay-wide (Fig. 5). The species with the highest absolute correlation with the MDS1 ordination, which depicts the shift in community composition from historic conditions to post-disturbance time periods, were spot *Leostomus xanthurus* ($r = 0.876$), *M. cephalus* ($r = 0.800$), *A. mitchilli* ($r = -0.841$), and *M. beryllina* ($r = -0.742$) and are displayed as vector overlays on Fig. 5. Historic data collected by Guillen et al. (2015) did not include invertebrate species; therefore, *P. pugio* and other invertebrate species that likely also show high correlation with the MDS1 ordination for Fig. 5 are not depicted.

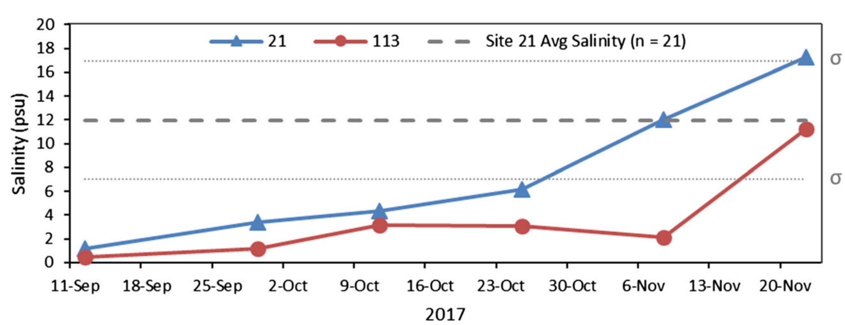

Fig. 3 Salinity (psu) recorded at each sampling event (site 21 blue triangles, site 113 red circles) and the average salinity (dashed line) from all pre-disturbance and historic sampling events at site 21 with standard deviation intervals (dotted lines marked with σ) Excel 2016

Table 1 Abundance of nekton catch per sampling event, all gear and replicates pooled. Vertical red dotted line indicates the timing of the disturbance event

Site 21	Species name	02/07/17	04/21/17	07/06/17	09/11/17	09/28/17	10/10/17	10/24/17	11/08/17	11/22/17	12/12/17	Grand total
Fish	*Menidia beryllina*	2	162	59	9	240	136	138	144	196	145	1231
	Anchoa mitchilli	12	3	9	354	68	438	74	59	26	–	1043
	Poecilia latipinna	2	–	3	–	5	5	616	272	4	17	924
	Gambusia affinis	2	–	–	–	–	–	342	224	–	49	617
	Brevoortia patronus	14	296	–	3	–	–	–	1	–	–	314
	Elops saurus	–	29	1	–	–	–	–	–	236	–	266
	Cyprinodon variegatus	–	3	1	–	2	4	173	–	1	3	187
	Sciaenops ocellatus	4	–	–	–	1	–	105	52	2	6	170
	Fundulus jenkinsi	27	–	–	–	1	–	1	7	–	109	145
	Gobiosoma bosc	75	2	–	–	–	–	56	6	–	6	145
	Lagodon rhomboides	43	34	10	–	–	–	–	–	–	40	127
	Adinia xenica	–	–	–	–	10	3	14	–	–	24	51
	Micropogonias undulatus	34	–	–	–	1	2	–	–	–	2	39
	Mugil cephalus	4	18	1	–	3	–	–	–	–	–	26
	Fundulus grandis	1	–	–	1	3	–	10	3	–	3	21
	Fundulus pulvereus	1	–	–	–	–	5	6	5	–	–	17
	Syngnathus scovelli	5	5	2	–	–	–	–	–	–	–	12
	Leostomus xanthurus	2	7	–	–	–	–	–	–	–	–	9
	Lucania parva	1	5	1	–	–	–	–	1	–	1	9
	Pogonias cromis	–	8	–	–	–	–	–	–	–	–	8
	Ctenogobius boleosoma	–	–	–	4	1	–	–	–	–	–	5
	Oligoplites saurus	–	–	–	4	–	1	–	–	–	–	5
	Cynoscion arenarius	–	–	–	–	–	4	–	–	–	–	4
	Bairdiella chysoura	–	2	1	–	–	–	–	–	–	–	3
	Eucinostomus argenteus	–	–	–	–	1	–	1	–	–	–	2
	Lepomis macrochirus	–	1	–	–	1	–	–	–	–	–	2
	Lepomis spp.	–	–	–	1	–	–	1	–	–	–	2
	Paralichthys lethostigma	1	1	–	–	–	–	–	–	–	–	2
	Syngnathus louisianae	–	–	2	–	–	–	–	–	–	–	2
	Cynoscion nebulosus	–	–	–	–	–	1	–	–	–	–	1
	Cyprinus carpio	–	–	–	–	1	–	–	–	–	–	1
	Eucinostomus melanopterus	–	–	–	–	–	1	–	–	–	–	1
	Fundulus chrysotus	1	–	–	–	–	–	–	–	–	–	1
	Ophichthus gomesii	–	–	–	1	–	–	–	–	–	–	1
Invertebrate	*Palaemonetes pugio*	4931	8007	2037	69	222	8	175	10,221	158	3244	29,072
	Litopenaeus setiferus	–	–	30	8	29	30	990	129	68	2	1286
	Farfantepenaeus aztecus	214	752	7	–	1	2	3	9	1	–	989
	Callinectes sapidus	113	16	47	42	3	–	39	16	3	4	283
	Taphromysis louisianae	–	–	–	–	–	–	–	–	1	–	1
	Site 21 total	5489	9351	2211	496	593	640	2744	11,149	696	3655	37,024

Table 1 (continued)

Site 113	Species name	02/08/17	04/19/17	07/05/17	09/11/17	09/28/17	10/10/17	10/24/17	11/08/17	11/22/17	12/12/17	Grand total
Fish	*Anchoa mitchilli*	6	32	317	–	101	57	190	557	320	–	1580
	Gambusia affinis	133	25	509	29	4	6	109	325	10	32	1182
	Poecilia latipinna	52	1	95	38	10	2	5	138	59	70	470
	Lucania parva	24	1	4	20	23	2	110	101	17	61	363
	Brevoortia patronus	339	5	–	–	–	–	–	8	–	–	352
	Micropogonias undulatus	181	14	2	–	–	–	–	–	–	–	197
	Gobiosoma bosc	142	2	2	–	1	–	–	16	–	1	164
	Dorosoma petenense	–	–	–	–	8	43	3	32	2	22	110
	Menidia beryllina	20	1	1	27	19	–	12	13	7	6	106
	Elops saurus	26	2	–	–	–	1	–	0	8	–	37
	Fundulus jenkinsi	21	–	–	–	1	–	–	3	3	6	34
	Fundulus pulvereus	–	–	25	1	–	–	2	–	1	1	30
	Cyprinodon variegatus	1	–	4	4	–	–	–	4	–	13	26
	Mugil cephalus	19	1	3	–	–	–	–	–	–	–	23
	Lepomis spp.	–	–	2	–	–	1	17	0	1	–	21
	Fundulus grandis	1	–	2	–	–	–	–	2	–	11	16
	Leostomus xanthurus	–	14	–	–	–	–	–	–	–	–	14
	Lepomis macrochirus	1	–	1	8	–	–	1	2	–	–	13
	Syngnathus scovelli	3	1	3	–	–	–	–	–	1	–	8
	Sciaenops ocellatus	–	–	–	–	–	–	–	–	4	1	5
	Fundulus chrysotus	1	–	–	1	–	–	–	1	–	–	3
	Adinia xenica	–	2	–	–	–	–	–	–	–	–	2
	Citharichthys spilopterus	–	2	–	–	–	–	–	–	–	–	2
	Dorosoma cepedianum	1	–	–	–	–	–	–	1	–	–	2
	Ctenogobius boleosoma	–	–	–	–	–	–	–	1	–	–	1
	Episosteus oculatus	–	–	–	–	1	–	–	–	–	–	1
	Lepomis gulosus	1	–	–	–	–	–	–	–	–	–	1
	Syngnathus louisianae	–	–	1	–	–	–	–	–	–	–	1
Invertebrate	*Palaemonetes pugio*	9973	424	271	31	97	40	76	4193	1669	2495	19,269
	Farfantepenaeus aztecus	–	285	–	61	43	1	–	–	18	–	408
	Callinectes sapidus	86	10	8	2	7	3	7	20	–	6	149
	Litopenaeus setiferus	–	–	17	–	16	13	12	29	40	–	127
	Site 113 total	11,031	822	1267	222	331	169	544	5446	2160	2725	24,717
	Grand total	16,520	10,173	3478	718	924	809	3288	16,595	2856	6380	61,741

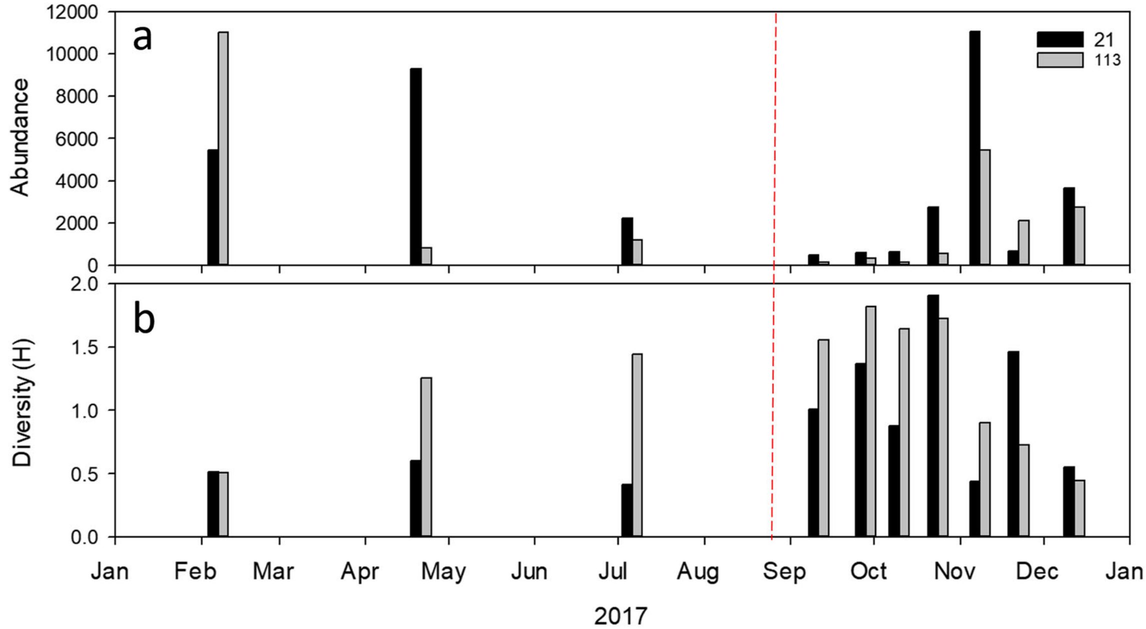

Fig. 4 (a) Abundance and (b) Shannon Weiner diversity of seine catch by sampling event at sites 21 (black bars) and 113 (gray bars). Red dashed line is landfall of Hurricane Harvey SigmaPlot 14.0

Discussion

Overall, total saltmarsh nekton abundance observed during sampling events immediately following Hurricane Harvey disturbance was lower than before, while community diversity increased following the disturbance. Much of these differences can be attributed to a reduced catch in the numerically dominant *P. pugio* following the event, leading to higher diversity and evenness, despite a reduced number of taxa (Magurran 2004). The most numerically dominant species (*P. pugio*) and the most abundant fish species (*M. berrylina*) at site 21 experienced a reduction in size following the disturbance. This indicates that re-population of the saltmarshes following the disturbance was more influenced by new recruits (juveniles) than the return of displaced adults (Reese et al. 2008).

Due to the geographic scale and duration of the event, it is highly unlikely that any saline water refugia for marine species remained near the study areas, while freshwater species were most likely displaced downstream into estuarine saltmarsh habitats. The occurrence of primarily freshwater and oligohaline species such as common carp, *Cyprinus carpio*, spotted gar, *Lepisosteus oculatus*, darter goby, *Ctenogobius boleosoma*, and threadfin shad, *Dorosoma petenense*, captured post-disturbance indicates a long-distance displacement of species from upstream or adjacent drainages into atypical habitats. Furthermore, when the marsh was inundated with deeper water, the efficiency of sampling with seines was reduced. Many habitat-associated species could retreat to the inundated marsh, which could have shifted the bias of the gear to open-water species such as *A. mitchelli* and *M. beryllina*.

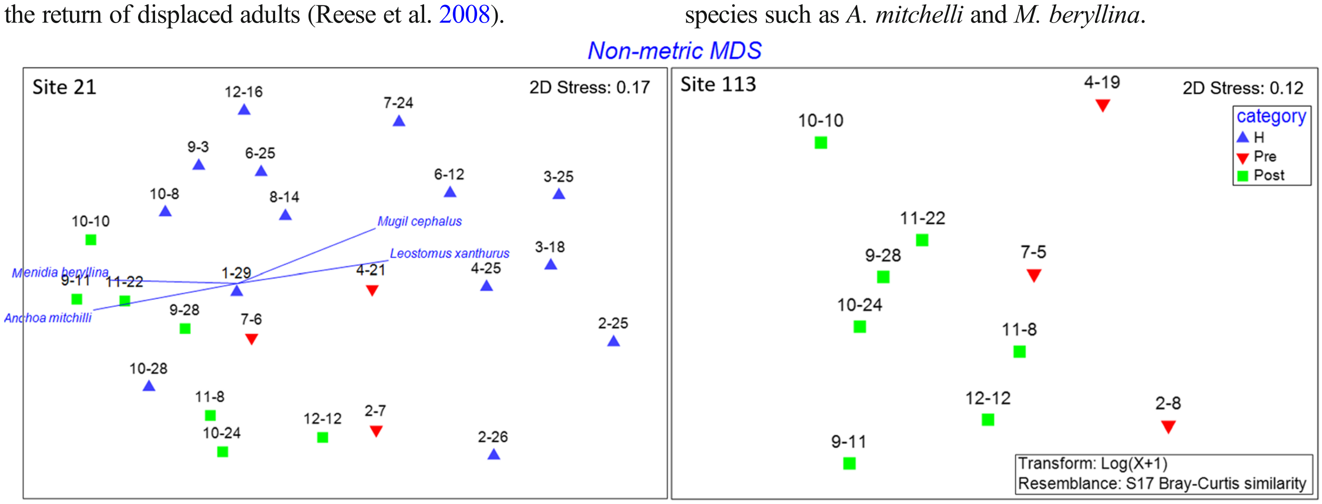

Fig. 5 nMDS plots of nekton communities by site. Events labeled by month-day sampled, historic data "H" (Guillen et al. 2015) as blue triangle, 2017 data prior to flood "Pre" (red upside-down triangles) and post-flood data "Post" (green squares). Ordinations on site 21 for 4 species with highest correlation to MDS1. Primer 7

While this study illustrated a dramatic reduction in *P. pugio* abundance immediately following an extreme freshwater flooding event, Piazza and La Peyre (2009) observed a dramatic increase in eastern grass shrimp *Palaemonetes paludosus* abundance at a tidal marsh community immediately following Hurricane Katrina, which had caused a significant tidal storm surge in their study area. Disturbance events caused by hurricanes, including tidal surge and wind damage, and overland flooding caused by excessive rain have been shown to impact saltmarsh nekton communities inversely, but in both cases, fluctuations in *Palaemonetes* spp. have been primary numeric drivers of these community changes (Piazza and La Peyre 2009). Although *P. pugio* are present in tidal saltmarshes in Galveston Bay year-round, peak abundance usually occurs in late-summer, when juvenile white shrimp *Litopenaeus setiferus* abundance is low due to seasonal spawning cycles (Kneib and Knowlton 1995). The timing of the disturbance event may have caused an exaggerated impact to the *P. pugio* population, resulting in a reduced optimal growth and spawning potential.

Natural seasonal cycles in species composition make it difficult to discern cause and effect of disturbance to saltmarsh nekton community structure (Akin et al. 2003). Temporal variation in assemblage structure is often driven by large-scale migrations and seasonal spawning patterns of many species that use the estuary as nursery habitat (Hall et al. 2016). It is possible that this extensive flood event caused high outflow velocities at tidal passes, and very low, prolonged salinities in Galveston Bay that could have disrupted larval recruitment to the Bay. Continued monitoring of estuary nekton communities is recommended to identify any long-term impacts to the 2017 year-cohorts that were associated with this flood disturbance. Longer-term surveillance may be especially important for some commercially and recreationally important species known to recruit in late-summer/early-fall such as red drum, *Sciaenops ocellatus*, blue crab, *Callinectes sapidus*, and shrimp, *Peneaid* sp. (Holt et al. 1983; Pile et al. 1996; Reese et al. 2008).

Post-disturbance sampling concluded before the nekton community structure showed signs of complete recovery and return to seasonal composition comparable to historic data. However, estuarine environments have been shown to be highly resilient to short-term, natural disturbance events (Paperno et al. 2006; Waide 1991). In similar systems that have experienced significant habitat damage following a disturbance event, the recovery period extended up to 18 months (Piazza and La Peyre 2009). Because neither of the study sites sustained significant damage to structural habitat from Hurricane Harvey, it is likely that the nekton community structure continued to recover as background levels of water quality and salinity returned and uninterrupted seasonal recruitment of immature organisms continued. A complete recovery to a pre-disturbance state will likely require at least a full year due to seasonal recruitment patterns of many of the saltmarsh nekton species. Short-term but large-scale natural disturbances can significantly impact saltmarsh nekton communities, but because of their dynamic nature, they are generally resilient.

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