

# Recruitment of Estuarine-Dependent Nekton Through a New Tidal Inlet: the Opening of Packery Channel in Corpus Christi, TX, USA

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**Abstract** The US Army Corps of Engineers recently dredged and permanently reopened Packery Channel, historically a natural tidal inlet, to allow water exchange between the Gulf of Mexico and the Laguna Madre, TX, USA. The main objective of this study was to characterize estuarine-dependent recruitment and community structure in seagrass habitats adjacent to Packery Channel pre- and post-channel opening. We sampled fish and crustacean abundance using an epibenthic sled in *Halodule wrightii* seagrass meadows in both control and impact locations over 2 years, 1 year before the opening of Packery Channel (October 2004–May 2005) and 1 year after (July 2005–April 2006). Using the before–after control–impact design, we found significantly fewer nekton post-channel opening. However, we found significantly higher mean densities of newly settled estuarine-dependent species (*Sciaenops ocellatus*, *Micropogonias undulatus*, *Lagodon rhomboides*, *Callinectes sapidus*, and penaeid shrimp) post-opening. Multivariate analyses showed significant community assemblage changes post-opening with increased contribution of estuarine-dependent species post-opening. Our results show that estuarine-dependent nekton are using Packery Channel as a means of ingress into areas of the upper Laguna Madre’s seagrass meadows that were previously

inaccessible, which may lead to higher fisheries productivity for some of these economically and ecologically important fishery species.

**Keywords** Tidal inlet · Packery Channel · Nekton recruitment · Nursery habitat · Estuarine-dependent nekton

## Introduction

Many nekton occurring in coastal waters share a common life history strategy characterized by near-shore spawning with larvae migrating through tidal inlets into shallow estuarine “nursery” grounds (Weinstein 1979; Baltz et al. 1993; Kneib 1993; Minello 1999; Heck et al. 2003). Therefore, access to high quality habitat in estuarine areas via tidal inlets is critical for reproduction, growth, survival, and sustainability of these populations. Access to nursery habitats has both ecological and economic implications because as much as 75% of commercially or recreationally important species in the Gulf of Mexico are estuarine-dependent (Chambers 1991).

In an effort to restore flow between the Gulf of Mexico and the upper Laguna Madre, TX, USA, the United States Army Corps of Engineers (USACE) completed a project in 2005, named North Padre Island Storm Damage Reduction and Environmental Restoration Project that permanently reopened the Packery Channel, a historic tidal inlet. The tidal inlet was periodically open until the 1930s but has since remained closed due to natural sedimentation until the completion of the USACE project. The new inlet is approximately 4-m deep and 37-m wide and extends 5.6 km from the seaward end of the jetties to the Gulf Intercoastal Waterway (GIWW; United States Army Corps of Engineers 2003). Impacts of the new inlet to the

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upper Laguna Madre were mathematically modeled to extend north into Corpus Christi Bay and south towards Baffin Bay (United States Army Corps of Engineers 2003). The USACE (2003) predicted that hypersaline conditions in the upper Laguna Madre negative estuarine complex would be periodically reduced due to the new connection to the Gulf of Mexico; however, overall changes in hydrodynamics were expected to be minimal to the system.

For estuarine-dependent nekton, Packery Channel creates a direct link between the Gulf of Mexico and nearby habitats (e.g., primarily seagrass meadows) in the upper Laguna Madre. The new channel is 35 km from the nearest tidal inlet (Aransas Pass), and a new means of ingress into the estuarine system may result in higher fisheries productivity since these adjacent nursery habitats were previously inaccessible to nekton recruiting from other inlets (Bushon 2006). The upper Laguna Madre is a highly productive hypersaline estuary because of its shallowness (average depth 75 cm) with extensive seagrass meadows (Quammen and Onuf 1993). Submerged aquatic vegetation supports high nekton abundance and richness because it has high food availability, provides sediment stability, refuge from predation, and habitat complexity (Orth et al. 1984; Quammen and Onuf 1993; Kneib and Wagner 1994). Therefore, the upper Laguna Madre could potentially sustain higher densities of newly recruiting fisheries species, support rapid growth rates, and ultimately increase survival of juveniles that may subsequently contribute to adult populations (Minello 1999; Beck et al. 2001; Heck et al. 2003).

A new tidal inlet may influence the nekton community structure of the upper Laguna Madre. Changes in physical (distance from tidal inlets, salinity, water depth, etc.) and biotic factors (food abundance, predation, competition, and life history traits) have been shown to impact nekton abundance and community assemblages (Hoff and Ibara 1977; Weinstein et al. 1980; Rozas and Hackney 1984; Kneib 1993; Levin et al. 1997). The opening of Packery Channel may cause both physical and biological changes. In particular, variations in seasonal migrations of estuarine-dependent species through the new tidal inlet have the potential to influence community structure.

Few studies have related estuarine species composition and abundance to the open or closed period of tidal inlets along the Texas coast. Reid (1957) published the only Texas study assessing the impact of dredging and reopening a tidal inlet on estuarine organisms by examining the impacts of opening Rollover Pass in Galveston Bay, Texas from 1954–1956. Reid (1957) suggested that stenohaline marine forms were immigrating into the estuary after opening of the inlet due to higher salinity levels. Simmons and Hoese (1959) studied Cedar Bayou Pass in Mesquite

Bay, TX, USA during periods when the inlet was open and when it naturally closed due to sedimentation. They determined that when open, it was important to the migration and development of young *Sciaenops ocellatus*, *Paralichthys lethostigma*, and penaeid shrimp. More recently, several studies have been conducted in Southern Australia on intermittently open–closed tidal inlets and their impact to nekton densities and assemblages. Most of these studies have shown that after opening a previously closed inlet, there are increased densities of estuarine-dependent species (Griffiths and West 1999; Griffiths 2001; Jones and West 2005) and nekton community changes, which may be attributed to the increase of tidal flow and a closer distance to the ocean (Young and Potter 2003). However, Jones and West (2005) caution that permanently opening an inlet may only have short-term improvements to recreational and commercial fisheries. No current research exists along the Gulf of Mexico coast assessing the impact of opening a tidal inlet in terms of fishery productivity and estuarine community assemblages.

The opening of Packery Channel presents a unique opportunity to examine the impacts of a new tidal inlet on juvenile fish and crustacean density and community structure in the adjacent estuarine seagrass habitats. The purpose of this study was to characterize seasonal nekton use and community structure in seagrass habitats adjacent to Packery Channel prior to opening of the new inlet and examine changes post-opening.

## Methods

### Study Location

The Laguna Madre is a bar-built coastal lagoon and one of the largest hypersaline systems in the world (Javor 1989). It extends approximately 200 km south from Corpus Christi Bay to the Mexico border (McKee 2008) and is separated into two subunits (the upper Laguna Madre and lower Laguna Madre) by the Land Cut south of Baffin Bay (Tunnell et al. 2002). Salinities in the upper Laguna Madre are typically 40 ppt, but historically salinities have reached >100 ppt (Quammen and Onuf 1993). *Halodule wrightii* is the predominant habitat type due to its ability to tolerate high salinities (Britton and Morton 1989).

### Delineation of Sites and Sampling

We selected sampling locations near Packery Channel using a before–after control–impact (BACI) design. Hydrodynamic modeling by Brown and Militello (1997) suggested that water level and velocity changes would be seen in areas at least 3 km from the opening of Packery Channel.

We selected four sampling locations near Packery Channel within the “impact” area. We also chose three areas greater than 7 km from Packery Channel as “control” locations (Fig. 1). The control locations extended north into upper Laguna Madre along the GIWW into Corpus Christi Bay, south into the Laguna Madre, and northwest near the Humble Channel. All sampling areas were located in *H. wrightii* seagrass meadows and were chosen to give substantial spatial coverage within and outside the impact area.

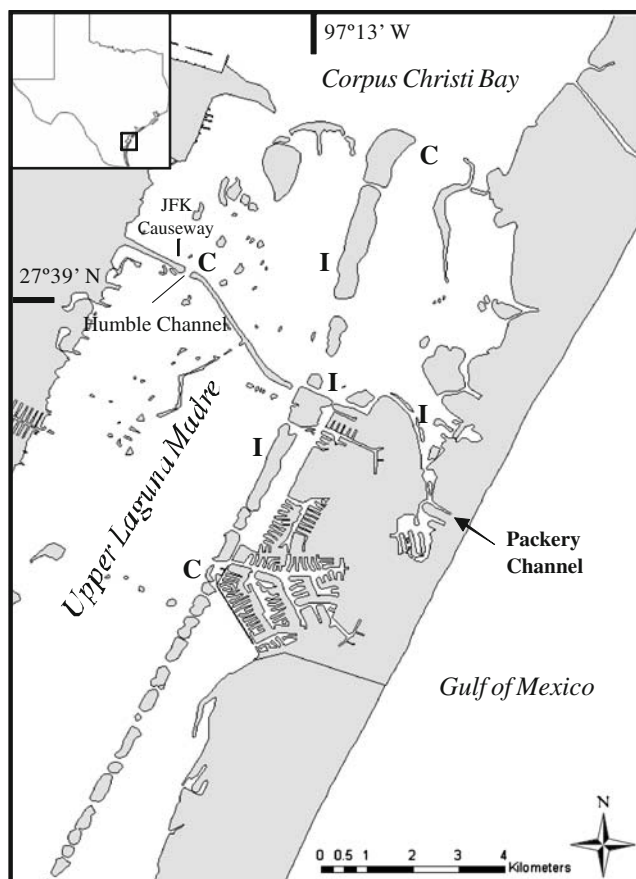
Nekton abundance was sampled twice each season for 2 years: 1-year pre-opening of Packery Channel and 1 year after. We took six replicate samples with an epibenthic sled at each location, for a total of 84 samples each season (48 impact locations and 36 control locations). The only exception was during summer when we collected 42 total samples (24 impact locations and 18 control locations) both pre- and post-opening because Packery Channel was prematurely opened due to wave action from a hurricane in the Gulf of Mexico midway through the summer sampling season. The epibenthic sled consists of a metal

frame with an opening of 0.6 m (length) by 0.75 m (height) with a 1-mm mesh conical plankton net. The sled was pulled ~17 m through seagrass meadows, covering 10 m<sup>2</sup> of bottom. This device has been shown as an effective and efficient gear for sampling nekton in seagrass meadows by numerous investigators (for example, see Stunz et al. 2002). The sampling dates for both pre- and post-opening follow respectively: fall (October 2004–November 2004; October 2005–November 2005), winter (February 2005; February 2006), spring (March 2005–April 2005; March 2006–April 2006), and summer (May 2005; July 2005). The samples were rough-sorted in the field removing large algae, detritus, and seagrass and preserved in 10% formalin. In the laboratory, nekton were sorted, identified to lowest possible taxon, measured, and preserved in 70% ethanol. If more than 20 individuals were caught for each species or group, the largest and smallest and 20 other random individuals were measured. *Farfantepenaeus aztecus*, *Farfantepenaeus duorarum*, and *Litopenaeus setiferus* were all grouped into “penaeid shrimp” because most of these three species were indistinguishable at our most common length range (10–18 mm TL; Rozas and Minello 1998). At each site, water temperature (°C) and dissolved oxygen (ppm) were measured using a YSI DO 200. Salinity (ppt) was measured using a refractometer and water depth (cm) was recorded during each sampling period.

#### Statistical Analysis

Data were analyzed with analysis of variance (ANOVA) using SAS 9.1 in a BACI design to identify nekton density changes due to an environmental change (Stewart-Oaten and Murdoch 1986), such as opening Packery Channel. We used a partially-nested hierarchical ANOVA model with BA and CI as fixed main effects and locations as random effects. Sampling dates were nested within the BA treatment, and sampling locations were nested within the CI treatment (Keough and Mapstone 1997). We used the RANDOM statement in the general linear model procedure, which calculates the expected mean squares and correct F-values for mixed models with fixed and random effects (Montagna and Ritter 2006). The distribution of the residuals were analyzed using the UNIVARIATE procedure and data were transformed ( $\log_{10}(x+1)$ ,  $\ln(x+1)$ , or fourth root) to ensure homogeneity of variance and normality of the residuals.

We tested for differences in pre- and post-opening density and abundance of economically important estuarine-dependent species during their peak recruitment period in the impact locations only. These species were: *S. ocellatus*, *Lagodon rhomboides*, *Micropogonias undulatus*, *Callinectes sapidus*, and penaeid shrimp (*F. aztecus*, *F. duorarum*, and *L. setiferus*). We restricted size class to newly settled individuals during peak recruitment season



**Fig. 1** Control and impact locations in the upper Laguna Madre and Corpus Christi Bay, TX, USA near the Packery Channel. C control locations and I impact locations

for density estimation. *Sciaenops ocellatus* mean densities (restricted to  $\leq 10$  mm SL) and sizes were calculated from fall samples only (Holt et al. 1983). *Lagodon rhomboides* mean densities (restricted to  $\leq 15$  mm SL; Levin et al. 1997; Patillo et al. 1997) and sizes, as well as *M. undulatus* mean densities (restricted to  $\leq 13$  mm SL; Petrik et al. 1999; Poling and Fuiman 1999; Ditty et al. 2005) and sizes were calculated from winter samples. *Callinectes sapidus* mean densities (restricted to  $\leq 5$  mm CW) and sizes were calculated by combining fall, winter, and spring samples (Pile et al. 1996; Blackmon and Eggleston 2001). Penaeid shrimp mean densities (restricted to post larval individuals  $\leq 25$  mm TL) and sizes were calculated by combining all seasons (Zein-Eldin and Renaud 1986; Patillo et al. 1997). Student's *t*-tests ( $\alpha=0.05$ ) were used to compare species mean densities and mean sizes pre- versus post-opening during their peak recruitment. Total catch was converted to density (organisms/m<sup>2</sup>) and then log ( $x+1$ ) transformed to minimize heteroscedasticity.

Relative abundance (RA%) was calculated seasonally for all fishes and crustaceans collected in impact locations. An overall RA (%) was also calculated for each species of fish and crustacean by combining both pre- and post-opening seasonally. The change in relative abundance (RA% change) was then calculated for each species and group of nekton seasonally.

We used a multivariate analysis (PRIMER v.6; Clarke and Gorley 2006) to test for significant differences in community assemblages between pre- and post-opening impact locations (Dawson Shepherd et al. 1992; Greenstreet and Hall 1996; Fisher and Frank 2002). The goal of this analysis was to test for differences in community assemblages post-channel opening by using several routines from PRIMER (Ludwig and Reynolds 1988; Catalán et al. 2006). We examined the mean densities of each species collected by date (14 total) for pre- and post-opening. Data were fourth root transformed prior to analysis to reduce the differential effects of dominant species and differentiate between pre- and post-opening with having many or few rare species (Clarke and Green 1988). Bray–Curtis resemblance matrices were constructed for both pre- and post-opening and were then compared using the RELATE routine, with the null hypothesis that there is no relationship between the two similarity matrices (Clarke and Gorley 2006). The RELATE routine performs a rank correlation and compares the results to randomly permuted samples. Community assemblage between pre- and post-opening was further explored using nonmetric multidimensional scaling (MDS) based on Bray–Curtis similarity with Bray–Curtis cluster groups superimposed for interpretation (Clarke and Warwick 2001). We also used two-way crossed SIMPER (Clarke and Warwick 2001) to determine overall species composition pre- and post-opening across all season groups because species composition changes seasonally.

## Results

### Physical Parameters

Water depth ranged from 21 cm (spring pre-opening) to 38 cm (fall post-opening), with some seasonal differences pre- and post-opening. Dissolved oxygen was consistent throughout the study period ranging between 6.71 and 8.37 mg l<sup>-1</sup>. Both salinity and temperature were higher post-opening over all seasons, both peaking during the summer (33.4°C and 40 ppt, respectively; Table 1). We did not measure flow nor changes to habitat types, but during post-opening sampling, large differences were observed in water movement and physical alterations to habitat (i.e., extensive seagrass loss on exposed sandbars) most likely a result of an increase in tidal fluctuation.

### Nekton Density

We collected a total of 5,986 individual fishes representing at least 25 species from 17 families and 126,510 individual crustaceans representing seven taxa during pre-opening sampling of Packery Channel between October 2004 and May 2005. Post-opening of Packery Channel we collected a total of 5,972 individual fishes representing at least 28 species with 20 families, and 46,511 individual crustaceans representing seven species between July 2005 and April 2006. For some taxa, juveniles were only identified to family. Samples were examined seasonally in the impact locations because we found seasonal differences in nekton composition and density in the impact locations adjacent to Packery Channel, and mean density, size, total catch, and relative abundance (RA%) were calculated for each species or family (Table 2). During fall pre-opening, *Lucania parva*, *Syngnathus* sp., and *Cyprinodon variegatus* were the most abundant fishes (30.5%, 24.4%, and 23.2%, respectively). However, *Gobiosoma boleosoma*, *Syngnathus* sp., and *L. parva* were more abundant (33.6%, 22.9%, and 17.6%, respectively) fall post-opening. In the winter, *L. parva* and *L. rhomboides* were the most abundant fishes (33.3% and 28.0%, respectively) pre-opening; post-opening *L. rhomboides*, *M. undulatus*, and *G. boleosoma* were most abundant (32.0%, 19.3%, and 13.1%, respectively). In the spring *L. rhomboides*, *L. parva*, and *Gobiosoma robustum* were the most abundant fishes (37.4%, 25.4%, and 17.3%, respectively) pre-opening; post-opening *L. rhomboides* and *G. boleosoma* were the most abundant (31.8% and 29.6%, respectively). *Lagodon rhomboides* and *G. robustum* were the most abundant fishes summer pre-opening (42.7% and 24.5%, respectively). Post-opening, *L. rhomboides* and *G. robustum* were also abundant (22.4% and 18.2%, respectively) as well as *G. boleosoma* and *Eucinostomus argenteus* (21.2% and 16.4%, respectively). *Palaemonetes*

**Table 1** Mean physical parameters (with standard errors, SE) for control and impact locations both pre-opening, October 2004–July 2005, and post-opening, July 2005–April 2006. The mean was

calculated from measurements taken at each sampling location twice each season. – No measurement was taken due to instrument malfunction

Parameter	Pre				Post			
	Control		Impact		Control		Impact	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
<b>Fall</b>								
Dissolved oxygen (mg/L)	8.37	0.2	7.30	0.1	7.70	0.6	7.41	0.3
Water temperature (°C)	24.8	1.6	20.6	1.8	26.4	0.4	27.1	0.3
Salinity (‰)	33	0.6	34	0.6	40	0.9	39	1.0
<b>Winter</b>								
Dissolved oxygen (mg/L)	8.24	0.3	8.14	0.2	7.96	0.3	7.86	0.2
Water temperature (°C)	14.0	1.2	13.9	0.8	15.5	0.4	16.0	0.2
Salinity (‰)	29	0.3	29	0.4	37	0.6	38	0.2
<b>Spring</b>								
Dissolved oxygen (mg/L)	7.34	0.5	6.87	0.5	7.25	0.2	7.39	0.2
Water temperature (°C)	21.3	0.7	21.8	0.7	23.4	0.2	24.6	0.2
Salinity (‰)	27	0.3	27	0.2	40	1.4	39	1.7
<b>Summer</b>								
Dissolved oxygen (mg/L)	–	–	–	–	6.71	0.7	6.78	0.8
Water temperature (°C)	–	–	–	–	33.2	0.7	33.4	0.4
Salinity (‰)	–	–	–	–	40	1.9	40	0.5

spp. were the most abundant crustaceans over all seasons both pre- and post-opening.

We examined the overall differences in nekton with the opening of Packery Channel and found significantly fewer nekton post-opening in impact locations (mean=15.88 m<sup>-2</sup> ± 1.37 SE) than pre-opening impact sites (mean=59.12 m<sup>-2</sup> ± SE=5.69; BA × CI interaction  $F_{1,567}=50.81$ ;  $p<0.001$ ; Table 3, Fig. 2). Crustaceans dominated nekton total catch pre- and post-opening (95% and 89%, respectively). *Palaemonetes* sp. dominated the crustacean abundance both pre- and post-opening (83% and 52%, respectively). Because of this numerically dominant species, we separated nekton into three broad taxonomic categories, fish, crustaceans, and *Palaemonetes* sp. to determine density changes post-opening. Although there were higher mean densities of fish post-opening in impact locations (mean=2.40 m<sup>-2</sup>±0.26 SE) versus pre-opening (mean=1.95 m<sup>-2</sup>±0.12 SE), there was no significant difference (BA × CI interaction  $F_{1,567}=1.29$ ;  $p=0.2564$ ; Table 3, Fig. 2). However, there were significantly fewer crustaceans and *Palaemonetes* sp. (BA × CI interaction  $F_{1,567}=60.00$ ;  $p<0.001$ ;  $F_{1,567}=59.63$ ,  $p<0.001$ , respectively) in impact locations post-opening (mean=13.48 m<sup>-2</sup>±1.23 SE; mean=7.71 m<sup>-2</sup>±1.04 SE, respectively) versus pre-opening (mean=57.17 m<sup>-2</sup>±5.64 SE; mean=51.48 m<sup>-2</sup>±5.58 SE, respectively; Table 3, Fig. 2).

In general, we found higher densities of estuarine-dependent species in impact locations with the opening of Packery Channel. Several estuarine-dependent species that had recently settled into the seagrass meadows from their

planktonic phase had significantly higher mean densities post-opening. Specifically, we found significantly higher densities of newly settled *S. ocellatus* ( $p<0.01$ ;  $t=-3.55$ ;  $df=94$ ), *L. rhomboides* ( $p=0.005$ ;  $t=-2.85$ ;  $df=94$ ), *M. undulatus* ( $p<0.001$ ;  $t=-3.90$ ;  $df=94$ ), *C. sapidus* ( $p<0.001$ ;  $t=-5.01$ ;  $df=286$ ), and penaeid shrimp ( $p<0.001$ ;  $t=-4.83$ ;  $df=334$ ) in the impact locations (Table 4, Fig. 3a). Of the identifiable penaeid shrimp, *F. aztecus* were the predominant species.

In addition to the increase in newly settled individuals to the impact locations with the opening of Packery channel, we also observed distinct size differences for all size classes of estuarine-dependent species, with the general pattern of significantly larger individuals pre- versus post-opening. All of the estuarine-dependent species analyzed were significantly smaller post-opening in impact locations: *S. ocellatus* ( $p<0.001$ ;  $t=6.71$ ;  $df=26$ ), *L. rhomboides* ( $p<0.001$ ;  $t=15.49$ ;  $df=497$ ), *M. undulatus* ( $p<0.001$ ;  $t=5.62$ ;  $df=247$ ), *C. sapidus* ( $p<0.001$ ;  $t=14.90$ ;  $df=1053$ ), and penaeid shrimp ( $p<0.001$ ;  $t=10.23$ ;  $df=6201$ ; Table 4, Fig. 3b).

#### Community Assemblage

Our community analysis revealed differences in overall community structure as well as seasonally pre- versus post-opening. We found no correlation in pre- and post-opening abundance matrices using the RELATE routine ( $R=0.213$ ,  $p=0.123$ ). Differences in pre- and post-opening samples were also seen from the cluster analysis and MDS

**Table 2** Mean densities, number  $m^{-2}$  (SE) and mean size, mm, of all nekton collected from impact locations (see Fig. 1) are shown seasonally for both pre- and post-opening. All impact locations were combined for overall mean densities and sizes by season. Each mean density is calculated from a total of 48 samples taken each season, with the exception of summer when only 24 samples were collected each pre- and post-opening sampling. Mean sizes (standard length for fish, total length for shrimp, and carapace width for crabs) were calculated from number of species measured each season pre- and post-opening. The total number of organisms collected (total catch) is given seasonally for pre-opening, post-opening, and overall (pre- and post-opening combined) for all groups and species. The relative abundance (RA) is listed seasonally for fishes and crustaceans for pre-opening, post-opening, and overall (pre- and post-opening combined). The change in relative abundance (RA% change) was also calculated for each species and group of nekton seasonally. The post-opening RA (%) was subtracted from the pre-opening RA (%) to calculate the change. A negative value shows a decline in relative abundance, and a positive number indicated an increase in relative abundance. – No measurement was taken

Species	Pre						Post						Overall total catch	Overall RA (%)	RA% change		
	Mean density (#/m <sup>2</sup> )	SE	Mean size (mm)	SE	Total catch	RA (%)	Mean density (#/m <sup>2</sup> )	SE	Mean size (mm)	SE	Total catch	RA (%)					
<b>Fall</b>																	
Total Fishes	1.875	(0.183)	26.80	(0.00)	898	1.863	(0.222)	0.0	(0.000)	894	0.0	(0.00)	0	0.0	1792	0.1	-0.1
<i>Cynoscion nebulosus</i>	0.002	(0.002)	18.65	(0.101)	208	0.015	(0.009)	17.0	(0.009)	7	0.8	(1.64)	7	0.8	215	12.0	-22.4
<i>Cyprinodon variegatus</i>	0.433	(0.000)	0.00	(0.000)	0	0.0	(0.000)	23.2	(0.007)	10	1.1	(3.90)	10	1.1	10	0.6	1.1
<i>Eucinostomus argenteus</i>	0.048	(0.017)	28.29	(2.12)	23	1.208	(0.200)	18.7	(0.200)	580	64.9	(0.26)	580	64.9	603	33.6	62.3
<i>Gobionellus boleosoma</i>	0.260	(0.055)	15.87	(0.47)	125	13.9	(0.015)	16.5	(0.015)	19	2.1	(1.03)	19	2.1	144	8.0	-11.8
Unidentified Gobiidae	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	29.3	(0.002)	1	0.1	(0.00)	1	0.1	1	0.1	0.1
<i>Hippocampus zosterae</i>	0.006	(0.004)	22.67	(1.96)	3	0.3	(0.003)	17.1	(0.003)	2	0.2	(2.65)	2	0.2	5	0.3	-0.1
<i>Lagodon rhomboides</i>	0.008	(0.004)	66.48	(4.00)	4	0.4	(0.007)	63.6	(0.007)	10	1.1	(3.24)	10	1.1	14	0.8	0.7
<i>Labotes surinamensis</i>	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	48.3	(0.002)	1	0.1	(0.00)	1	0.1	1	0.1	0.1
<i>Lucania parva</i>	0.571	(0.133)	19.24	(0.38)	274	30.5	(0.028)	18.8	(0.028)	41	4.6	(0.56)	41	4.6	315	17.6	-25.9
<i>Lufjanius griseus</i>	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	71.7	(0.003)	2	0.2	(30.55)	2	0.2	2	0.1	0.2
<i>Menidia beryllina</i>	0.060	(0.038)	23.06	(1.45)	29	3.2	(0.000)	0.0	(0.000)	0	0.0	(0.00)	0	0.0	29	1.6	-3.2
<i>Opsanus beta</i>	0.002	(0.002)	73.80	(0.00)	1	0.1	(0.000)	0.0	(0.000)	0	0.0	(0.00)	0	0.0	1	0.1	-0.1
<i>Scartella cristata</i>	0.021	(0.007)	23.02	(3.26)	10	1.1	(0.038)	8.8	(0.010)	18	2.0	(0.51)	18	2.0	28	1.6	0.9
<i>Sciaenops ocellatus</i>	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	14.9	(0.009)	10	1.1	(1.06)	10	1.1	10	0.6	1.1
<i>Symphurus plagiusa</i>	0.456	(0.062)	44.32	(1.35)	219	24.4	(0.057)	49.6	(0.057)	191	21.4	(1.67)	191	21.4	410	22.9	-3.0
<i>Syngnathus</i> spp.	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	79.6	(0.002)	1	0.1	(0.00)	1	0.1	1	0.1	0.1
<i>Synodus foetens</i>	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	10.4	(0.002)	1	0.1	(0.00)	1	0.1	1	0.1	0.1
Unidentified fish	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.000)	19.5	(3.091)	9973	0.0	(0.00)	1	0.0	30129	0.0	0.0
<b>Crustaceans</b>																	
Total Crustaceans	41.992	(3.944)	17.60	(2.83)	20156	20.777	(3.091)	19.5	(0.002)	73	0.7	(0.84)	73	0.7	258	0.9	-0.2
<i>Alpheus heterochaelis</i>	0.015	(0.005)	14.56	(0.52)	185	0.9	(0.045)	9.1	(0.045)	0	0.0	(0.00)	0	0.0	1	0.0	0.0
<i>Callinectes sapidus</i>	0.002	(0.002)	19.00	(0.00)	1	0.0	(0.000)	0.0	(0.000)	0	0.0	(0.00)	0	0.0	1	0.0	0.0
<i>Libinia</i> spp.	38.604	(3.718)	14.99	(0.15)	18530	15.871	(2.671)	12.7	(2.671)	7618	76.4	(0.12)	7618	76.4	26148	86.8	-15.5
<i>Palaemonetes</i> spp.	1.473	(0.205)	24.84	(0.73)	707	3.5	(0.242)	27.7	(0.242)	1063	10.7	(0.37)	1063	10.7	1770	5.9	7.2
Penaeid spp.	1.365	(0.601)	24.57	(0.41)	655	3.2	(0.612)	20.9	(0.612)	1169	11.7	(0.29)	1169	11.7	1824	6.1	8.5
<i>Tozeuma carolinense</i>	0.148	(0.056)	9.29	(0.49)	71	0.4	(0.019)	8.3	(0.019)	49	0.5	(0.59)	49	0.5	120	0.4	0.1
Xanthidae																	
<b>Winter</b>																	
Total Fishes	1.838	(0.229)	0.00	(0.000)	881	3.348	(0.792)	22.4	(0.013)	8	0.5	(0.89)	8	0.5	2488	0.3	0.5
<i>Admia xenica</i>	0.010	(0.004)	20.12	(4.52)	5	0.6	(0.020)	15.5	(0.020)	33	2.1	(1.22)	33	2.1	38	1.5	1.5
<i>Citharichthys spilopterus</i>	0.160	(0.034)	24.71	(0.62)	77	8.7	(0.053)	25.1	(0.053)	87	5.4	(0.48)	87	5.4	164	6.6	-3.3
<i>Cyprinodon variegatus</i>	0.002	(0.002)	38.20	(0.00)	1	0.1	(0.000)	0.0	(0.000)	0	0.0	(0.00)	0	0.0	1	0.0	-0.1
<i>Fundulus grandis</i>	0.000	(0.000)	0.00	(0.000)	0	0.0	(0.023)	26.7	(0.023)	16	1.0	(1.57)	16	1.0	16	0.6	1.0
<i>fundulus similis</i>																	

<i>Gobionellus boleosoma</i>	0.075	(0.017)	17.23	(0.96)	36	4.1	0.606	(0.100)	19.4	(0.35)	291	18.1	327	13.1	14.0
<i>Gobiosoma robustum</i>	0.273	(0.066)	15.56	(0.32)	131	14.9	0.004	(0.003)	15.8	(1.25)	2	0.1	133	5.3	-14.8
Unidentified Gobiidae	0.008	(0.008)	9.48	(0.21)	4	0.5	0.110	(0.045)	9.5	(0.09)	53	3.3	57	2.3	2.8
<i>Hippocampus zosterae</i>	0.013	(0.005)	21.57	(0.78)	6	0.7	0.000	(0.000)	0.0	(0.00)	0	0.0	6	0.2	-0.7
<i>Lagodon rhomboides</i>	0.515	(0.100)	16.10	(0.25)	247	28.0	1.146	(0.313)	12.1	(0.16)	550	34.2	797	32.0	6.2
<i>Lucania parva</i>	0.610	(0.143)	18.83	(0.24)	293	33.3	0.002	(0.002)	17.6	(0.00)	1	0.1	294	11.8	-33.2
<i>Menidia beryllina</i>	0.013	(0.011)	19.22	(0.56)	6	0.7	0.002	(0.002)	29.7	(0.00)	1	0.1	7	0.3	-0.6
<i>Micropogonias undulatus</i>	0.021	(0.008)	16.35	(0.57)	10	1.1	0.981	(0.296)	12.2	(0.16)	471	29.3	481	19.3	28.2
<i>Mugil cephalus</i>	0.002	(0.002)	23.30	(0.00)	1	0.1	0.106	(0.081)	23.2	(0.31)	51	3.2	52	2.1	3.1
<i>Paralichthys lethostigma</i>	0.006	(0.004)	11.80	(2.41)	3	0.3	0.013	(0.006)	9.6	(0.44)	6	0.4	9	0.4	0.1
<i>Sciaenops ocellatus</i>	0.002	(0.002)	68.80	(0.00)	1	0.1	0.000	(0.000)	0.0	(0.00)	0	0.0	1	0.0	-0.1
<i>Symphurus plagiusa</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.006	(0.004)	34.8	(4.55)	3	0.2	3	0.1	0.2
<i>Syngnathus</i> spp.	0.125	(0.030)	69.50	(1.83)	60	6.8	0.069	(0.028)	56.7	(2.48)	33	2.1	93	3.7	-4.7
<i>Synodus foetens</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.002	(0.002)	11.5	(0.00)	1	0.1	1	0.0	0.1
Crustaceans	71.950	(9.472)	9.673	(2.070)	34535	9.673	9.673	(2.070)	0.0	(0.00)	4643	0.0	39178	0.0	0.0
<i>Alpheus heterochaelis</i>	0.002	(0.002)	17.80	(0.00)	1	0.0	0.000	(0.000)	0.0	(0.00)	0	0.0	1	0.0	0.0
<i>Callinectes sapidus</i>	0.250	(0.042)	14.76	(0.87)	120	0.3	0.619	(0.090)	9.0	(0.37)	297	6.4	417	1.1	6.0
<i>Palaemonetes</i> spp.	69.242	(9.330)	14.30	(0.14)	33236	96.2	3.679	(1.493)	14.6	(0.19)	1766	38.0	35002	89.3	-58.2
Penaeid spp.	0.669	(0.098)	19.76	(0.70)	321	0.9	5.067	(0.888)	16.1	(0.23)	2432	52.4	2753	7.0	51.5
<i>Toxema carolinense</i>	1.508	(0.341)	28.14	(0.20)	724	2.1	0.188	(0.106)	27.2	(0.48)	90	1.9	814	2.1	-0.2
Unidentified crab	0.002	(0.002)	6.30	(0.00)	1	0.0	0.000	(0.000)	0.0	(0.00)	0	0.0	1	0.0	0.0
Xanthidae	0.275	(0.047)	5.52	(0.31)	132	0.4	0.121	(0.034)	4.8	(0.34)	58	1.2	190	0.5	0.8
Spring															
Fishes															
Total Fishes	2.325	(0.254)	0.00	(0.00)	1116	2.046	2.046	(0.353)	11.5	(0.35)	982	0.4	2098	0.2	0.4
<i>Anchoa mitchilli</i>	0.000	(0.000)	22.08	(3.10)	5	0.4	0.033	(0.010)	19.1	(2.48)	16	1.6	21	1.0	1.2
<i>Citharichthys spilopterus</i>	0.127	(0.055)	27.09	(0.81)	61	5.5	0.000	(0.000)	0.0	(0.00)	0	0.0	61	2.9	-5.5
<i>Cyprinodon variegatus</i>	0.002	(0.002)	67.10	(0.00)	1	0.1	0.000	(0.000)	0.0	(0.00)	0	0.0	1	0.0	-0.1
<i>Fundulus grandis</i>	0.152	(0.032)	20.83	(0.94)	73	6.5	1.140	(0.241)	19.4	(0.37)	547	55.7	620	29.6	49.2
<i>Gobionellus boleosoma</i>	0.402	(0.060)	19.61	(0.35)	193	17.3	0.006	(0.005)	18.3	(1.13)	3	0.3	196	9.3	-17.0
<i>Gobiosoma robustum</i>	0.008	(0.008)	10.05	(0.49)	4	0.4	0.173	(0.071)	10.0	(0.06)	83	8.5	87	4.1	8.1
Unidentified Gobiidae	0.008	(0.005)	25.25	(1.06)	4	0.4	0.000	(0.000)	0.0	(0.00)	0	0.0	4	0.2	-0.4
<i>Hippocampus zosterae</i>	0.002	(0.002)	—	—	1	0.1	0.000	(0.000)	—	—	0	0.0	1	0.0	-0.1
<i>Hyporhamphus unifasciatus</i>	0.869	(0.135)	19.11	(0.48)	417	37.4	0.523	(0.125)	18.0	(0.49)	251	25.6	668	31.8	-11.8
<i>Lagodon rhomboides</i>	0.004	(0.004)	40.75	(0.35)	2	0.2	0.046	(0.015)	31.2	(1.38)	22	2.2	24	1.1	2.0
<i>Letostomus xanthurus</i>	0.592	(0.178)	20.44	(0.28)	284	25.4	0.002	(0.002)	18.8	(0.00)	1	0.1	285	13.6	-25.3
<i>Lucania parva</i>	0.015	(0.011)	19.67	(4.45)	7	0.6	0.004	(0.004)	12.1	(0.45)	2	0.2	9	0.4	-0.4
<i>Menidia beryllina</i>	0.004	(0.003)	38.15	(1.85)	2	0.2	0.000	(0.000)	0.0	(0.00)	0	0.0	2	0.1	-0.2
<i>Microgobius gulosus</i>	0.008	(0.004)	23.05	(1.00)	4	0.4	0.042	(0.012)	15.5	(2.37)	20	2.0	24	1.1	1.6
<i>Micropogonias undulatus</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.002	(0.002)	25.2	(0.00)	1	0.1	1	0.0	0.1
<i>Mugil cephalus</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.004	(0.003)	172.3	(9.70)	2	0.2	2	0.1	0.2
<i>Ophichthus gomesi</i>	0.004	(0.003)	67.35	(5.35)	2	0.2	0.000	(0.000)	0.0	(0.00)	0	0.0	2	0.1	0.2
<i>Opsanus beta</i>	0.002	(0.002)	13.60	(0.00)	1	0.1	0.000	(0.000)	0.0	(0.00)	0	0.0	1	0.0	-0.1
<i>Orthopristis chrysoptera</i>	0.002	(0.002)	25.70	(0.00)	1	0.1	0.002	(0.002)	8.8	(0.00)	1	0.1	2	0.1	0.0
<i>Paralichthys lethostigma</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.002	(0.002)	48.6	(0.00)	1	0.1	1	0.0	0.1
<i>Prionotus tribulus</i>	0.000	(0.000)	0.00	(0.00)	0	0.0	0.006	(0.004)	47.4	(1.54)	3	0.3	3	0.1	0.3
<i>Symphurus plagiusa</i>	0.110	(0.019)	59.02	(3.96)	53	4.7	0.048	(0.012)	59.6	(4.80)	23	2.3	76	3.6	-2.4
<i>Syngnathus</i> spp.	0.002	(0.002)	72.40	(0.00)	1	0.1	0.004	(0.003)	62.4	(24.90)	2	0.2	3	0.1	0.1
<i>Synodus foetens</i>															
Crustaceans	65.850	(16.069)	10.096	(1.356)	31608	10.096	10.096	(1.356)	48.6	(36454)	4846	0.2	36454	0.5	0.8

Table 2 (continued)

Species	Pre						Post						Overall total catch	Overall RA (%)	RA% change	
	Mean density (#/m <sup>2</sup> )	SE	Mean size (mm)	Total catch	RA (%)	Mean density (#/m <sup>2</sup> )	SE	Mean size (mm)	Total catch	RA (%)	SE	Total catch				RA (%)
<i>Alpheus heterochaelis</i>	0.010	(0.005)	22.62	5	0.0	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	5	0.0	0.0
<i>Callinectes sapidus</i>	0.546	(0.067)	16.16	262	0.8	0.521	(0.206)	12.0	250	5.2	(0.44)	250	5.2	512	1.4	4.4
<i>Palaeomonetes spp</i>	57.888	(15.896)	15.32	27786	87.9	1.965	(0.793)	17.4	943	19.5	(0.27)	943	19.5	28729	78.8	-68.4
Peneaeid spp.	5.417	(0.737)	21.44	2600	8.2	7.388	(0.734)	20.8	3546	73.2	(0.30)	3546	73.2	6146	16.9	65.0
<i>Tozeuma carolinense</i>	1.179	(0.288)	30.86	566	1.8	0.088	(0.036)	27.0	42	0.9	(1.02)	42	0.9	608	1.7	-0.9
Xanthidae spp	0.810	(0.144)	5.55	389	1.2	0.135	(0.044)	5.8	65	1.3	(0.35)	65	1.3	454	1.2	0.1
Summer																
Fishes																
Total Fishes	1.563	(0.225)		375	2.263	(0.390)			543					918		
<i>Anchoa mitchilli</i>	0.008	(0.008)	17.80	2	0.5	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	2	0.2	-0.5
<i>Cynoscion nebulosus</i>	0.000	(0.000)	0.00	0	0.0	0.004	(0.004)	10.1	1	0.2	(0.00)	1	0.2	1	0.1	0.2
<i>Eucinostomus argenteus</i>	0.000	(0.000)	0.00	0	0.0	0.629	(0.187)	9.8	151	27.8	(0.13)	151	27.8	151	16.4	27.8
<i>Gobionellus boleosoma</i>	0.046	(0.019)	24.42	11	2.9	0.767	(0.190)	9.1	184	33.9	(0.15)	184	33.9	195	21.2	31.0
<i>Gobiosoma robustum</i>	0.383	(0.078)	22.74	92	24.5	0.313	(0.061)	21.9	75	13.8	(0.56)	75	13.8	167	18.2	-10.7
Unidentified Gobidae	0.000	(0.000)	0.00	0	0.0	0.021	(0.021)	8.8	5	0.9	(0.26)	5	0.9	5	0.5	0.9
<i>Hippocampus zosterae</i>	0.004	(0.004)	24.80	1	0.3	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	1	0.1	-0.3
<i>Lagodon rhomboides</i>	0.667	(0.120)	26.10	160	42.7	0.192	(0.042)	39.9	46	8.5	(1.22)	46	8.5	206	22.4	-34.2
<i>Leiostomus xanthurus</i>	0.025	(0.011)	39.55	6	1.6	0.004	(0.004)	50.3	1	0.2	(0.00)	1	0.2	7	0.8	-1.4
<i>Lucania parva</i>	0.196	(0.093)	19.58	47	12.5	0.017	(0.008)	27.3	4	0.7	(1.42)	4	0.7	51	5.6	-11.8
<i>Lutjanus griseus</i>	0.000	(0.000)	0.00	0	0.0	0.013	(0.007)	15.5	3	0.6	(0.81)	3	0.6	3	0.3	0.6
<i>Lutjanus spp.</i>	0.008	(0.006)	22.90	2	0.5	0.004	(0.004)	24.7	1	0.2	(0.00)	1	0.2	3	0.3	-0.3
<i>Menidia beryllina</i>	0.000	(0.000)	0.00	0	0.0	0.004	(0.004)	16.7	1	0.2	(0.00)	1	0.2	1	0.1	0.2
<i>Microgobius gulosus</i>	0.013	(0.007)	44.93	3	0.8	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	3	0.3	-0.8
<i>Opsanus beta</i>	0.004	(0.004)	15.60	1	0.3	0.004	(0.004)	95.2	1	0.2	(0.00)	1	0.2	2	0.2	-0.1
<i>Orthopristis chrysoptera</i>	0.054	(0.021)	19.96	13	3.5	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	13	1.4	-3.5
<i>Paralichthys lethostigma</i>	0.004	(0.004)	102.00	1	0.3	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	1	0.1	-0.3
<i>Syngnathus spp.</i>	0.142	(0.034)	44.09	34	9.1	0.283	(0.079)	61.1	68	12.5	(2.44)	68	12.5	102	11.1	3.4
<i>Synodus foetens</i>	0.008	(0.006)	69.10	2	0.5	0.000	(0.000)	0.0	0	0.0	(0.00)	0	0.0	2	0.2	-0.5
Unidentified fish	0.000	(0.000)	0.00	0	0.0	0.008	(0.008)	-	2	0.4	-	2	0.4	2	0.2	0.4
Crustaceans																
Total Crustaceans	40.588	(8.417)		9741	13.271	(2.360)			3185			3185		12926		
<i>Alpheus heterochaelis</i>	0.004	(0.004)	0.00	1	0.0	0.004	(0.004)	15.3	1	0.0	(0.00)	1	0.0	2	0.0	0.0
<i>Callinectes sapidus</i>	0.046	(0.015)	16.18	11	0.1	0.079	(0.026)	7.5	19	0.6	(1.80)	19	0.6	30	0.2	0.5
<i>Palaeomonetes spp.</i>	28.896	(8.474)	15.17	6935	71.2	10.904	(2.003)	19.0	2617	82.2	(0.22)	2617	82.2	9552	73.9	11.0
Peneaeid spp.	3.888	(0.253)	33.75	933	9.6	1.254	(0.306)	21.6	301	9.5	(1.12)	301	9.5	1234	9.5	-0.1
<i>Tozeuma carolinense</i>	7.392	(1.541)	23.13	1774	18.2	0.950	(0.518)	26.6	228	7.2	(0.72)	228	7.2	2002	15.5	-11.0
Xanthidae	0.363	(0.085)	4.96	87	0.9	0.079	(0.040)	8.7	19	0.6	(0.92)	19	0.6	106	0.8	-0.3



**Table 3** Analysis of Variance nested model (overall, fish, crustacean, and grass shrimp) with date as a nested factor within the before and after treatment and sampling locations as a nested factor within the control and impact treatment

Source	df	Sum of squares	Mean square	F value	P value
<b>Overall</b>					
BA	1	16.963	16.963	135.650	<0.001
Date (BA)	12	16.504	1.375	11.000	<0.001
CI	1	0.856	0.856	6.850	0.0090
Location (CI)	5	9.001	1.800	14.400	<0.001
BA × CI	1	6.353	6.353	50.810	<0.001
Error	567	70.900	0.125		
<b>Fish</b>					
BA	1	0.858	0.858	3.240	0.0722
Date (BA)	12	23.863	1.987	7.510	<0.001
CI	1	1.782	1.782	6.730	0.0097
Location (CI)	5	37.627	7.525	28.440	<0.001
BA × CI	1	0.342	0.342	1.290	0.2564
Error	567	150.030	0.265		
<b>Crustaceans</b>					
BA	1	103.712	103.712	152.910	<0.001
Date (BA)	12	90.292	7.524	11.090	<0.001
CI	1	4.205	4.205	6.200	0.0131
Location (CI)	5	45.250	9.050	13.340	<0.001
BA × CI	1	40.697	40.697	60.000	<0.001
Error	567	384.571	0.678		
<b>Grass shrimp</b>					
BA	1	82.318	82.318	271.190	<0.001
Date (BA)	12	73.699	6.142	20.230	<0.001
CI	1	1.338	1.338	4.410	0.0362
Location (CI)	5	2.070	0.414	21.130	<0.001
BA × CI	1	18.099	18.099	9.630	<0.001
Error	567	172.106	0.304		

ordination. The Bray–Curtis cluster analysis along with the SIMPROF test revealed three significant clusters at the 72% similarity level ( $p=0.001$ ), with a pre-opening group and two post-opening groups (Fig. 4a). The MDS ordination indicates the same clear separation between the pre- and post-opening samples (Fig. 4b).

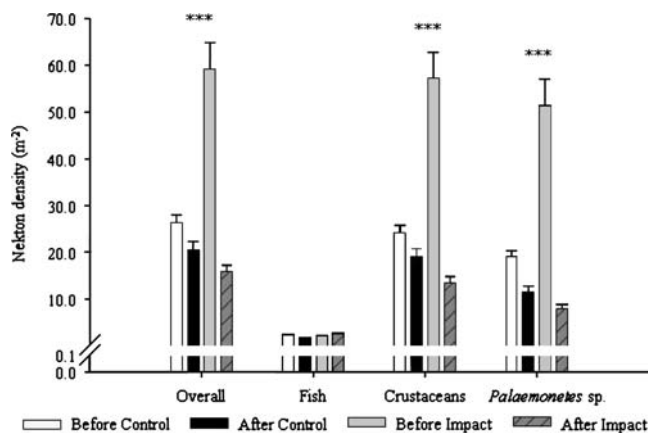
We used a two-way crossed SIMPER analysis to determine which species were contributing to the pre- and post-opening community differences. Estuarine-resident species (*Palaemonetes* sp., *L. parva*, and *Gobiidae* sp.) had the greatest contribution to the percent dissimilarity between the pre- and post-opening samples in impact locations (Table 5). However, several estuarine-dependent species also contributed to the dissimilarity of pre- and post-opening samples including penaeid shrimp, *M. undulatus*, and *C. sapidus*. *Palaemonetes* sp. had the greatest contribution to the within group similarity; however, several estuarine-dependent species had an increased percent similarity contribution to post-opening samples including penaeid shrimp, *C. sapidus*, *L. rhomboides*, and *S. ocellatus*.

**Discussion**

This study was designed to assess the impact of opening a tidal inlet by determining density patterns and community structure for estuarine-dependent and estuarine-resident species. We found strong evidence that opening new tidal inlets may have wide-ranging impacts on nekton recruitment at both the individual species and community levels. Overall, we observed striking differences in density patterns and lengths for many species as well as changes to the community structure. These data show that the opening of tidal inlets, particularly tidal inlets at great distances from other inlets, may increase fisheries productivity for some ecologically and economically important species that would not normally have access to seagrass habitats.

**Nekton Density and Abundance**

We observed numerous differences in nekton density and abundance for a variety of species, and these were most likely due to the opening of Packery Channel. Overall, there were fewer nekton present post-opening, which appears to be caused by the decline of *Palaemonetes* sp. in seagrass habitats directly adjacent to the new inlet. *Palaemonetes* sp. are an important part of estuarine communities and are found throughout estuaries along the Gulf coast (Morgan 1980). Once Packery Channel was opened and flowing, the impact locations adjacent to Packery Channel changed from backwater lagoons with little tidal fluctuation to locations with increased tidal energy and current. With larger tidal fluctuations and flow post-opening, there were long periods of seagrass exposure, and we observed but did not quantify a decrease (and loss in one area) in seagrass cover in locations nearest the inlet. *Palaemonetes* sp. select for seagrass cover to forage for

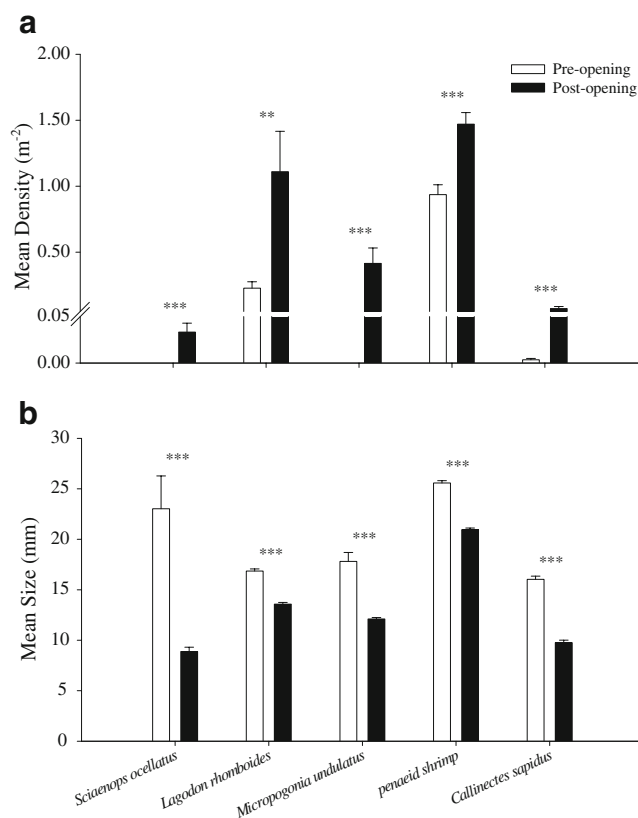


**Fig. 2** Overall mean density ( $m^{-2}$ ) of nekton, fish, crustaceans, and *Palaemonetes* sp. in control and impact locations over all seasons pre- and post-opening. Before–after–control–impact ANOVA model was used test each group; \*\*\* $p<0.001$

**Table 4** Mean densities (number  $m^{-2}$ ) and mean size, mm, of selected fish and crustaceans (SE) for both pre- and post-opening are summarized below. The mean densities of the species selected were

Species	Pre			Post			P value
	Mean	SE	Number	Mean	SE	Number	
<b>Density</b>							
<i>Sciaenops ocellatus</i>	0.000	(0.00)	48	0.033	(0.01)	48	0.001*
<i>Lagodon rhomboides</i>	0.227	(0.05)	48	1.110	(0.31)	48	0.010*
<i>Micropogonias undulatus</i>	0.000	(0.00)	48	0.415	(0.12)	48	0.001*
<i>Callinectes sapidus</i>	0.003	(0.00)	144	0.073	(0.02)	144	0.001*
Penaeid shrimp	2.715	(0.27)	168	4.370	(0.38)	168	0.001*
<b>Size</b>							
<i>Sciaenops ocellatus</i>	23.02	(3.26)	10	8.80	(0.51)	18	0.001*
<i>Lagodon rhomboides</i>	16.10	(0.25)	247	12.10	(0.16)	550	0.001*
<i>Micropogonias undulatus</i>	16.35	(0.57)	10	12.17	(0.16)	471	0.001*
<i>Callinectes sapidus</i>	15.37	(0.34)	208	9.94	(0.28)	94	0.001*
Penaeid shrimp	24.56	(0.27)	2688	21.21	(0.20)	3515	0.001*

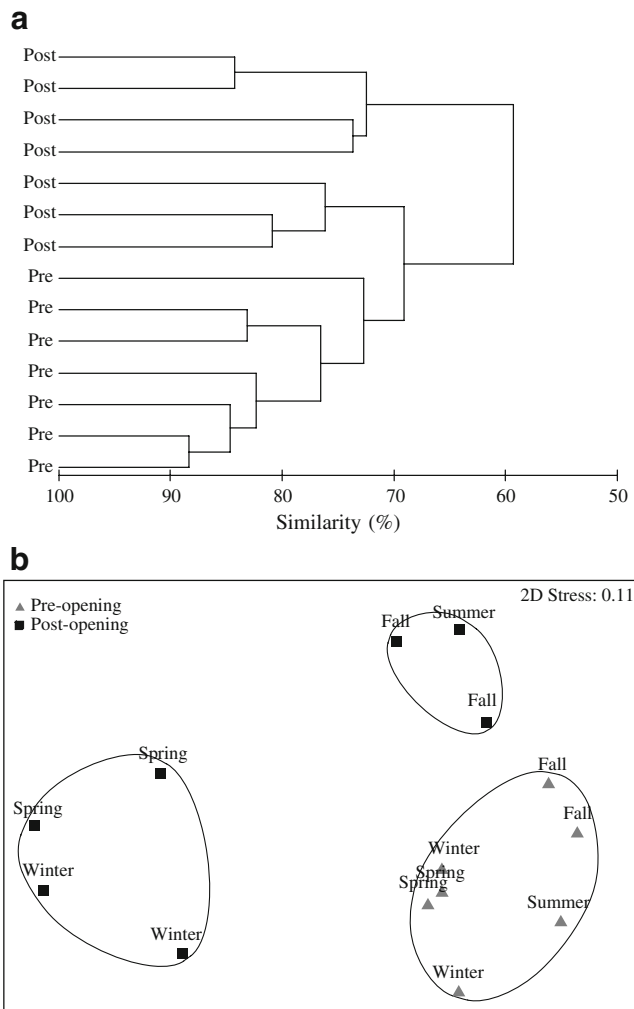
calculated during their recruitment seasons. Results of the comparison between pre- and post-opening using a Student's *t* test (*p* value) for each species are also listed. \*Value was significant



**Fig. 3** Mean densities (**a**) and size (**b**) of selected fishes and crustaceans pre- and post-opening for impact locations during their peak recruitment season. Mean densities were calculated using newly recruited individuals (*Sciaenops ocellatus*  $\leq 10$  mm SL, *Lagodon rhomboides*  $\leq 15$  mm SL, *Micropogonias undulatus*  $\leq 13$  mm SL, *Callinectes sapidus*  $\leq 5$  mm CW, penaeid shrimp  $\leq 25$  mm TL), and mean sizes were calculated from all individuals collected. Student's *t* test was performed on the selected fishes and crustaceans pre- versus post-opening; \*\* $p < 0.01$ , \*\*\* $p < 0.001$

food and to decrease predation (Morgan 1980; Orth et al. 1984). Therefore, the observed seagrass loss in the areas very near the inlet most likely caused *Palaemonetes* sp. mean densities to sharply decrease post-opening with fewer seagrass beds available for cover. The dramatic change in *Palaemonetes* sp. (an estuarine-resident species) densities post-opening with the observed loss of seagrass cover demonstrate that Packery Channel could potentially have a large impact on other estuarine-resident and estuarine-dependent species that use seagrass meadows as nursery habitat (Sheridan 2004).

We found evidence that suggests density-dependent species are recruiting to the previously inaccessible seagrass meadows of the Laguna Madre via Packery Channel. *Sciaenops ocellatus*, *L. rhomboides*, *M. undulatus*, *C. sapidus*, and penaeid shrimp all have varied seasonal recruitment patterns, but all of these species generally follow the same life history pattern where the adults spawn offshore in the Gulf of Mexico, typically near tidal inlets. Their eggs, larvae, and juveniles recruit via tidal inlets into estuarine nursery habitats where there are high productivity, survival, and growth rates of juveniles to adults (Minello 1999; Beck et al. 2001). Newly settled juveniles had very limited access to the extensive nursery habitats of the upper Laguna Madre prior to Packery Channel due to the great distance (35 km) from the nearest tidal inlet (Aransas Pass to the north). For example, Bushon (2006) examined nekton density in this area as a function of distance from Aransas Pass and found a significant decrease in nekton with increasing distance from a tidal inlet. Based upon these results, species such as *S. ocellatus* and *M. undulatus* would not have access to our study area pre-opening. We found evidence suggesting that



**Fig. 4** Bray–Curtis cluster analysis (a) and MDS ordination with Bray–Curtis cluster analysis superimposed using 72% similarity (b) of nekton density from pre- and post-opening samples from only impact locations over all seasons. Densities were averaged among locations by date for a total of 14 samples

estuarine-dependent species are recruiting to the Laguna Madre via Packery Channel. For example, before Packery Channel was open there were very low densities of *M. undulatus* present, but in the winter post-opening, they were one of the most abundant species collected. These data show that Packery Channel may result in higher fisheries productivity since the nursery habitats of the upper Laguna Madre are now accessible to numerous estuarine-dependent species. Because seagrass meadows typically sustain high densities of newly recruiting fisheries species and support rapid growth rates, access to these habitats of the upper Laguna Madre may ultimately increase the survival of juveniles that could contribute to adult populations (Rozas and Minello 1998; Minello 1999; Beck et al. 2001).

Penaeid shrimp also showed similar recruitment patterns to the upper Laguna Madre via Packery Channel. Because

our data suggest that penaeid shrimp were able to disperse into the upper Laguna Madre via other tidal inlets, we examined the increase of post larval shrimp (<25 mm) in impact locations post-channel opening. We found a significant increase of post larval penaeid shrimp in adjacent habitats post-opening suggesting they are recruiting to the upper Laguna Madre via Packery Channel. Therefore, Packery Channel may also increase penaeid shrimp productivity with increased access to the upper Laguna Madre; however, the increase may be difficult to detect since shrimp were able to recruit to these areas in large numbers even before Packery Channel was open.

Similar to penaeid shrimp, we observed increased densities of newly settled *C. sapidus* post-opening. *Callinectes sapidus* have a very complex life cycle with their peak recruitment into estuaries occurring in fall and spring but can recruit year round (Patillo et al. 1997; Etherington and Eggleston 2000). Etherington and Eggleston (2003) showed that *C. sapidus* have both primary post-larval dispersal and secondary juvenile dispersal determined by wind events, suggesting they are able to disperse great distances within estuaries that have appropriate wind regimes. *Callinectes sapidus* primary dispersal concentrates pre-settlement juveniles in habitats very near tidal inlets. The secondary dispersal distributes juvenile *C. sapidus* throughout the bay. Therefore, post-opening, we measured the densities of *C. sapidus* during their primary dispersal when they settle from their planktonic phase and before they have a second dispersal at larger sizes (Etherington and Eggleston 2000; Etherington and Eggleston 2003). Our data show that *C. sapidus* did recruit to the habitats of the upper Laguna Madre via Packery Channel. However, they were also able to easily recruit to these habitats before Packery Channel was open because we found high densities of larger *C. sapidus* pre-opening. Packery Channel may have little impact to the overall productivity of *C. sapidus* and similar species with wide dispersal patterns in the upper Laguna Madre, with other physical and biological interactions playing a greater role in determining their overall recruitment success.

Larval settlement and dispersal within estuaries is due to the interaction of many physical and biological processes (Brown et al. 2005). We found that some species of fish and especially crustaceans were able to disperse approximately 35 km from Aransas Pass to habitats in the upper Laguna Madre because we found high abundances before Packery Channel was open. Our data are consistent with typical particle circulation patterns in Corpus Christi Bay (Brown et al. 2005). Brown et al. (2005) created a circulation and physical transport model of the Corpus Christi Bay/Redfish Bay/Aransas Bay complex to determine settlement patterns of *S. ocellatus* that recruit via Aransas Pass. Their model found that particles (larvae) accumulate along the southern boundary of Corpus Christi Bay and the upper Laguna

**Table 5** Two-way crossed SIMPER summaries (pre- and post-opening across all seasons) from impact locations showing species that contributed  $\geq 1\%$  to the within group average similarity or between group dissimilarities. Data were fourth root transformed and mean

Species	Pre-opening		Post-opening		Pre- and post-opening % Dissimilarity
	Mean density per tow	% Similarity	Mean density per tow	% Similarity	
<i>Palaemonetes</i> sp.	51.48	22.83	7.70	15.19	14.75
Penaeid shrimp	2.71	9.06	4.37	16.03	4.28
<i>Lucania parva</i>	0.53	7.47	0.03	2.12	7.44
<i>Tozeuma carolinense</i>	2.21	7.41	0.91	7.71	6.63
<i>Callinectes sapidus</i>	0.34	6.87	0.38	8.99	1.63
Xanthidae	0.40	6.57	0.11	5.67	2.77
<i>Gobiosoma robustum</i>	0.32	6.20	0.06	–	5.91
<i>Syngnathus</i> sp.	0.22	5.89	0.19	5.65	1.59
<i>Lagodon rhomboides</i>	0.49	5.65	0.51	7.56	1.29
<i>Cyprinodon variegatus</i>	0.21	5.54	0.06	–	5.52
<i>Gobionellus boleosoma</i>	0.09	4.77	0.95	10.29	5.52
<i>Menidia beryllina</i>	0.03	2.38	0.00	–	3.81
<i>Micropogonias undulatus</i>	0.01	–	0.29	4.19	2.64
<i>Citharichthys spilopterus</i>	0.01	–	0.03	3.45	1.05
<i>Symphurus plagiusa</i>	0.00	–	0.01	2.02	3.12
<i>Sciaenops ocellatus</i>	0.01	–	0.01	1.73	–

densities were calculated from impact locations over all seasons for both pre- and post-opening ( $n=168$ ). – Species that contributed  $<1\%$  to the average similarity or dissimilarity

Madre, which is near Packery Channel. This may explain how juvenile penaeid shrimp and *C. sapidus* were able to disperse to habitats adjacent to Packery Channel before the inlet was open. Because crustaceans appear to be able to disperse to these habitats from Aransas Pass, it is more difficult to determine how much of the density increase can be attributed to the opening of Packery Channel.

Examining the mean size of fish and crustaceans pre-versus post-opening provides additional support that estuarine-dependent species are using Packery Channel to access the habitats of the upper Laguna Madre. The species that were able to reach areas near Packery Channel before the inlet was open were most likely growing while they were dispersing. Thus, significantly larger individuals of many estuarine-dependent species were collected pre-opening. All of the estuarine-dependent species examined for this study were significantly smaller post-opening. Juvenile *S. ocellatus* settle into seagrass meadows between 6–8 mm SL (Holt et al. 1983; Rooker and Holt 1997) and were rarely in this size range pre-opening. However, the mean size of *S. ocellatus* post-opening in the upper Laguna Madre was approximately 9 mm SL suggesting that *S. ocellatus* were recruiting to these habitats via Packery Channel. *Lagodon rhomboides*, *M. undulatus*, penaeid shrimp, and *C. sapidus* were also significantly smaller post-opening, and we collected these species at lengths of first settlement post-opening. These data suggest these estuarine-dependent fishes and crustaceans are using Packery Channel as a means of recruitment to the nursery grounds of the upper Laguna Madre. This may increase

fishery productivity for some of these economically and ecologically important fishery species.

#### Community Structure

We observed changes to community structure with the opening of Packery Channel when examining each sampling date. The overall community change appears to have corresponded with the opening of Packery Channel with the arrival of estuarine-dependent species, providing evidence that these immigrating species are using Packery Channel as a means of ingress to the upper Laguna Madre. Although post-opening estuarine-resident species had the most variation in species abundance, our data shows that increases in estuarine-dependent species contributed to the overall change in community assemblage.

Seasonal migrations of small, juvenile estuarine-dependent species have an impact on the communities of the upper Laguna Madre because some species historically have not occurred in these seagrass habitats. There was an increase in estuarine-dependent species richness post-opening; therefore, these species potentially influenced the seasonal community structure. *Sciaenops ocellatus* and *M. undulatus* did not contribute to the within group similarity pre-opening but contributed to the similarity of the community assemblage post-opening. Other estuarine-dependent species that were present pre-opening contributed more to the similarity of the post-opening group, such as penaeid shrimp, *C. sapidus*, and *L. rhomboides*. Interpretation of the MDS ordination also shows evidence of

increased recruitment of several species post-opening. Pre-opening, all the samples are grouped, whereas post-opening, there are two groups with distinct separation of fall and summer samples from spring and winter. The separation is most likely from the varied recruitment patterns of estuarine-dependent species with changes in species assemblages throughout the year. In a similar study, Akin et al. (2003) concluded seasonal occurrence of estuarine-dependent species is an important factor influencing community assemblages. These data suggest that the increase in estuarine-dependent species may have impacted the community structure in seagrass habitats of the upper Laguna Madre.

Many studies have shown that community structure change can be attributed to environmental variation (Blaber and Blaber 1980, Loneragan et al. 1987; Moser and Gerry 1989; Garcia et al. 2001; Akin et al. 2003). Although it was not the focus of our study, we observed increases in salinity and temperature post-opening. The USACE (2003) predicted that hypersaline conditions in the upper Laguna Madre would be reduced due to the new connection to the Gulf of Mexico. Although not quantified, we observed that the annual precipitation was notably lower post-opening, which most likely caused the increase in temperature and salinity post-opening. Such increases may have caused some of the changes in community structure as many studies have shown that salinity and temperature have a strong influence on community assemblages (Hoff and Ibara 1977; Weinstein et al. 1980; Loneragan et al. 1986; Akin et al. 2003).

The opening of Packery Channel has caused changes to nekton densities and overall community structure in seagrass habitats of the Laguna Madre. Overall, this study provides evidence that this new tidal inlet provides a means of ingress to the productive nursery habitats of the upper Laguna Madre that were previously inaccessible for many estuarine-dependent species, such as *S. ocellatus*, penaeid shrimp, and *C. sapidus*. This study examined density patterns and community changes, but it is also critical to document changes to the functionality of the newly available estuarine nursery habitats. Future studies should examine changes in growth and mortality rates, fine- and large-scale movement patterns, and subsequent movement to adult populations for nekton accessing and using these areas as their nursery grounds.

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