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The Response of Lake Pontchartrain Fish Assemblages to Hurricanes Katrina and Rita

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1   Title: Response of Lake Pontchartrain Fish Assemblages to Hurricanes Katrina and Rita
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45   Abstract: To assess possible impacts on Lake Pontchartrain fishes from the 2005 hurricanes, we
46   compared trawl, beach seine, and gillnet collections taken before (2000-2003, 2005) and after
47   (2006-2009) to determine if significant assemblage changes occurred. We also compared basic
48   environmental variables to test for hurricane-related changes. Significant post-hurricane changes
49   in fish assemblages occurred in trawl (ANOSIM, $R < 0.090$, $p < 0.05$) and beach seine
50   (ANOSIM, $R < 0.120$, $p < 0.05$) collections across all seasons. Gillnet assemblages exhibited
51   changes in only one season (ANOSIM, $R = 0.045$, $p < 0.05$). These consistently low global R
52   values (all $R < 0.120$) across all gears suggest only minor compositional changes in species.
53   When peak abundance periods were compared for individual species, Gulf menhaden
54   (*Brevoortia patronus*) declined in trawl collections after the hurricanes (Friedman's test, $\chi^2 =$
55   6.00, $p = 0.014$) but increased in gillnet collections (Friedman's test, $\chi^2 = 5.00$, $p = 0.025$).
56   Hardhead catfish (*Ariopsis felis*) increased in trawl collections, but Gulf pipefish (*Syngnathus*
57   *scovelli*), naked gobies (*Gobiosoma bosc*), and rough silverside (*Membras martinica*) all
58   declined in beach seine samples and Atlantic croakers (*M. undulatus*), Spanish mackerel
59   (*Scomberomorus maculatus*), and sand seatrout (*Cynoscion arenarius*) all declined in gillnet
60   samples. In general, salinity increased and water clarity and dissolved oxygen decreased after
61   the hurricanes. While the overall composition of Lake Pontchartrain fish assemblages remains
62   stable, the significant decline of some species and changes in certain environmental variables are
63   cause for concern. Future monitoring should determine if all elements of this estuary will
64   recover from these impacts.
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68   Keywords: fish assemblages, hurricanes, Lake Pontchartrain, Hurricane Katrina, Hurricane Rita
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82   Introduction

83   Estuarine fish assemblages typically exhibit resilience to large-scale natural disturbances

84   such as hurricanes (Greenwood et al. 2006; Stevens et al. 2006; Switzer et al. 2006). While

85   acute assemblage impacts may occur in the short-term due to hypoxic conditions (Stevens et al.

86   2006) or other immediate changes in water quality (Greening et al. 2006), for the most part

87   estuarine fish populations recover by the following season if not sooner. Unlike less mobile

88   estuarine organisms such as benthic infauna (Poirrier et al. 2008), adult fishes can actively swim

89   to avoid hazardous conditions and re-colonize affected habitats soon after disturbances

90   (Greenwood et al. 2006). More severe hurricane assemblage impacts have been observed in

91   physically restricted estuarine habitats such as coastal streams (Van Vrancken and O'Connell

92   2010) and tidal freshwater marshes (Piazza and La Peyre 2009) where extensive habitat damage

93   occurs. Fish assemblage recovery in these habitats is also slower because their hydrologically

94   isolated nature precludes rapid recolonization.

95   Although estuarine fishes in the southeastern United States have evolved resiliency to

96   hurricanes, their ability to recover may be reduced in systems where anthropogenic disturbances

97   occur alongside natural disturbances (Mallin and Corbett 2006). Short-term resiliency to

98   disturbances by estuarine fishes may hide significant long-term impacts associated with

99   artificially altered habitats. For example, in Lake Pontchartrain (a large oligohaline embayment

100   that borders New Orleans in southeastern Louisiana) we observed little to no year-to-year fish

101   assemblage change in a short term (three years) study (O'Connell et al. 2006). When we used a

102   larger data set that ranged over the last half century, though, we identified marked declines in a

103   common benthic fish species (Atlantic croaker, *Micropogonias undulatus*) and these impacts

104 were associated with extensive habitat destruction (i.e., shell dredging) in Lake Pontchartrain

105 (O'Connell et al. 2004). We recognize, though, that hurricane impacts may not actually be

106 responsible for observed fish declines, especially when data are not analyzed thoroughly. A

107 decline in species richness, total fish abundance, and abundances of select species on a coral reef

108 in St. Croix were initially assumed to be caused by Hurricane Marilyn in 1995. On further

109 analysis, though, these impacts were found to be unrelated to the storm and indicated that other

110 forces (e.g., fishing pressure) were responsible (Adams 2001). As in other estuary and marine

111 habitats, there is a need in Lake Pontchartrain to better understand the relationships between

112 anthropogenic effects and the innate resiliency of the aquatic ecosystem to natural disturbances

113 (Greening et al. 2006; Poirrier et al. 2008).

114   Hurricanes Katrina and Rita struck southeastern Louisiana in autumn 2005 causing a

115 unique combination of both natural and anthropogenic impacts for the Lake Pontchartrain

116 ecosystem. Natural impacts from both storms included large storm surges (2 - 4 m) which

117 inundated the estuary and caused extensive infauna mortality (Poirrier et al. 2008). The most

118 prominent anthropogenic impact associated with the 2005 storms was the discharge of

119 floodwaters from inundated New Orleans into Lake Pontchartrain (Hoe et al. 2006; Van Metre et

120 al. 2006). These stagnant floodwaters had remained in the flooded city for three weeks after

121 Hurricane Katrina struck and were assumed to be a highly toxic combination of biological and

122 chemical components (Farris et al. 2007). To assess possible impacts on Lake Pontchartrain fish

123 assemblage due either to natural or anthropogenic impacts associated with the 2005 hurricanes,

124 we compared monthly trawl, beach seine, and gillnet collections taken at six sites before (2000-

125 2003, 2005) and after (2006-2009) to determine if significant assemblage changes occurred. We

126 also tested for significant post-hurricane declines or increases in abundant or influential fish

127 species. To better understand whether natural or anthropogenic impacts drove assemblage

128 change, we also compared pre- and post-hurricane measurements of basic water quality

129 parameters.

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132 <center>Materials and Methods</center>

133 <center>Study location</center>

134   Lake Pontchartrain is a semi-enclosed oligohaline estuary with a surface area of 1,630

135 km^2 and a mean depth of 3.7 m (Sikora and Kjerfve 1985). It experiences low tidal ranges

136 (Swenson 1980) and receives fresh water input from Lake Maurepas to the west and numerous

137 rivers and streams along its northern shore. During periods of extremely high discharge (e.g.,

138 2008, 2011), Mississippi River water is diverted into the Lake via the Bonnet Carre Spillway

139 which is located in the southwest region of the Lake. Sources of pollution include urban runoff

140 from the Greater New Orleans Metropolitan Area (GNOMA) and agricultural runoff from rivers

141 and streams along the northern shore (Penland et al. 2002). Much of the southern shore is

142 armored and limited beds of submersed aquatic vegetation (SAV) still occur, mostly along shore

143 in the northeast region of the Lake. Until recently, there was an artificial connection between

144 Lake Pontchartrain and the Gulf of Mexico via connections with the Mississippi River Gulf

145 Outlet (MRGO). This connection allowed higher salinity water to enter the southeastern region

146 of the Lake. When New Orleans was pumped dry after the 2005 hurricanes, the storm water was

147 released into the estuary through outfall canals on the southern shore.

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Data Collection

151   For both pre- and post-hurricane sampling, fishes were collected using three gear types:

152   trawls, beach seines, and gillnets. Trawl sampling in demersal habitats involved using a 4.9 m

153   otter trawl, consisting of a 16 mm bar mesh body and a 6.3 mm bar mesh tail. Since Lake

154   Pontchartrain has an average depth of 4.27 m, the standard scope ratio of 7:1 was maintained by

155   using 30.5 m warps connected to the standard 40 cm X 76 cm wooden doors. The tow duration

156   was maintained at 10 minutes and the speed kept at a constant 1.83 m/s using a GPS receiver.

157   For shallow nearshore habitats, we used a 15.25 m X 1.83 m bag seine with 0.95 cm mesh which

158   was pulled to sample 50 m X 15.25 m of habitat at each site. In deeper pelagic habitats, we

159   fished a 250 m X 3.66 m gillnet with different mesh sizes: bar measurement was 5.08, 6.35, 7.62,

160   8.89, and 10.16 cm for five equally sized panels. Gillnets were fished using the strike method

161   which involves setting the net and circling it three times with a boat to drive fishes into the

162   panels.

163   All three gear types were fished on a monthly basis both prior to the 2005 hurricanes

164   (2000-2003, 2005) and after (2006-2009) at five sites in Lake Pontchartrain, with an extra mid-

165   lake trawl sample also included in the analyses (Fig 1). A total of 1,674 collections were made:

166   787 pre-hurricane collections (410 trawls, 224 beach seines hauls, and 153 gillnet sets) and 887

167   post-hurricane collections (455 trawls, 252 beach seines hauls, and 180 gillnet sets; Table 1).

168   Fishes were either counted, identified, and released in the field or anesthetized with sodium

169   bicarbonate (UNO-IACUC Protocol # 09-016), fixed with 10% formalin, and processed back in

170   the laboratory. For each collection, salinity, dissolved oxygen (ppm), Secchi depth (m), and

171   surface water temperature (^{o}C) were measured.

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174   Data Analyses

175   Prior to assessing possible long-term assemblage changes, we tested for short-term, acute

176   assemblage changes immediately following the hurricanes. We pooled the data by year and for

177   all gear types and performed non-metric multidimensional scaling (MDS) plots to determine if

178   2006 assemblages (those collected in the year following the hurricanes) differed from those in

179   subsequent years. In these plots, multi-dimensional relationships are represented in a two

180   dimensional graph and assemblages that are more similar in species composition appear closer

181   together. The resulting MDS plots showed no evidence that 2006 assemblages were different

182   from subsequent years for all gear types. Based on these results, we included data from 2006 in

183   all of our analyses.

184   To determine if fish assemblages changed after the 2005 hurricanes, we conducted

185   analysis of similarity (ANOSIM) to compare species composition using PRIMER v6 software

186   (Clarke and Warwick 2001). This multivariate method compares multiple assemblages and

187   establishes if statistically significant differences exist among them. Because estuarine fish

188   assemblages change seasonally (e.g., influx of marine species), we minimized this potential

189   influence by only comparing collections made in the same time period or season. We

190   determined seasons for each gear type by using agglomerative hierarchical clustering with group-

191   average linking (Kaufman and Rousseeuw 1990, Clarke and Warwick 2001) to group months

192   containing similar fish assemblages into seasonal groups (Idelberger and Greenwood 2005).

193   After determining seasons for each gear type, we compared collections taken before 2005 in a

194   given season with collections taken after 2005 in the same season, and so on. We repeated this

195   for all seasons and for all three gear types. For each analysis, seasonal collections taken at either

196   five (beach seine and gillnet) or six (trawl) sites were used such that each ANOSIM typically

197   compared from 60 to 168 pre-2005 collections with 60 to 168 post-2005 collections, with 60

198   representing the shortest calculated season (beach seine collections from April to June: 3 months

199   X 5 sites X 4 years) and 168 representing the longest calculated season (trawl collections from

200   November to May: 7 months X 6 sites X 4 years). Seasonal data were analyzed using a two-way

201   crossed ANOSIM design with site and pre/post 2005 as factors. If a collection contained no

202   fishes, it was omitted from the analysis. While these omissions sometimes generated unequal

203   sample sizes, two-way crossed ANOSIM is robust to minor amounts of missing data (Clarke and

204   Warwick 2001). To minimize the influence of rarer species, all abundance data were square root

205   transformed prior to analysis. If a significant difference was detected, we used the PRIMER

206   similarity percentages routine (SIMPER) to determine which species contributed most to the

207   observed change in species composition. We also generated MDS plots to present the

208   relationships between pre- and post-hurricanes assemblages for each season and each gear type.

209   To test for possible significant post-hurricane declines or increases in those fish species

210   that were determined to contribute to assemblage dissimilarity based on the SIMPER results or

211   those that were the top 15 most common species collected by each gear type, we used multiple

212   Friedman's tests. To account for seasonality, we limited our analyses to the 1-7 month

213   abundance peak for each individual species for each gear type. This peak was determined by

214   comparing mean monthly abundances for each species and choosing the multi-month period with

215   the highest abundances. With this non-parametric rank-based procedure, we assessed the

216   species' data using site averages as the block (that is, the average abundance of a species at one

217   site over the four year pre/post period) and pre/post 2005 as the factor.

218   We compared pre- and post-hurricane measurements of salinity, dissolved oxygen,

219   Secchi depth, and surface water temperature to determine if they possibly influenced observed

220   fish assemblage changes. We used multivariate analysis of variance (MANOVA) on these

221   variables only for seasons (determined previously by agglomerative hierarchical clustering) and

222   gear types when a significant assemblage change was measured using ANOSIM. For example,

223   for a given trawl season data were compared using measurements collected from the six sites

224   before (2000-2003, 2005) and six sites after (2006-2009) the hurricanes. For each set of seasons

225   analyzed, data were organized with individual sites as factors and multiple years as replicates. If

226   tests for homogeneity of variances could not be met (even with severe transformations), then

227   those single variables causing the lack of homogeneity were removed and a MANOVA was

228   conducted on the remaining variables. If only one variable exhibited homogeneity of variances,

229   then an ANOVA was used to compare pre/post 2005 data. Those single variables that exhibited

230   no homogeneity of variances were compared using Friedman's test (as explained above).

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233   Results

234   For trawl data, two seasons were identified by cluster analysis: November through May

235   (Season I) and June through October (Season II). Benthic fish assemblages (those collected by

236   trawls) exhibited significant post-hurricane changes in both seasons (ANOSIM, $R < 0.09$, $p <$

237   0.05). It should be noted, though, that this low global R value suggests only minor changes in

238   species composition between periods, with pre/post- assemblages exhibiting little to no

239   multivariate separation in the generated MDS ordination (Fig. 2). In both seasons, SIMPER

240   analyses revealed that bay anchovies (*Anchoa mitchilli*) and Atlantic croaker *(Micropogonias*

241 *undulatus*) were more numerous after the hurricanes, while in both seasons Gulf menhaden

242 (*Brevoortia patronus*) were less numerous in post-hurricane trawls (Table 2). For both seasons,

243 SIMPER analyses also revealed that *A. mitchilli* contributed most to the observed fish

244 assemblage changes with *M. undulatus* the being the second-most influential species (Table 2).

245   Beach seine data were more distinctly clustered into three seasonal groupings: December

246 through March (Season I), April through June (Season II), and July through November (Season

247 III). Inshore fish assemblages (those collected by beach seines) also exhibited significant post-

248 hurricane changes in all three pre-determined seasons (ANOSIM, $R < 0.12$, $p < 0.05$). Again,

249 the low global-R value suggests minor changes in species composition between periods and

250 assemblages showed little to no multivariate separation in the MDS ordination (Fig. 3).   In all

251 three seasons, *A. mitchilli* and *M. beryllina* were less numerous after the storms and these

252 species contributed the most to assemblage differences in two of the seasons. The change in

253 assemblage in the remaining season (II) was attributed mostly to a decrease in *B. patronus.*

254 While this species and *M. undulatus* decreased in two seasons, both species experienced

255 increases in the remaining season.

256   As with the trawl data, gillnet data also clustered into two less distinct seasonal groups,

257 but these consisted of samples collected from April through October (Season I) and November

258 through March (Season II). Gillnet collections yielded only one season (Season I) with

259 significant assemblage differences between the two periods, again with a markedly low global R

260 value (ANOSIM, $R = 0.045$, $p = 0.004$) and little to no multivariate separation in the generated

261 MDS ordination (Fig. 4). SIMPER analyses revealed that differences in this season's collected

262 assemblages were attributed to post-hurricane decreases in *B. patronus* along with increases in

263   gafftopsail catfish (*Bagre marinus*) and hardhead catfish (*Ariopsis felis*), and to a lesser extent

264   decreases in *M. undulatus* (Table 2).

265   When peak abundance periods were compared for individual fish species, *B. patronus*

266   declined significantly (Friedman's test, $\chi^2 = 6.00$, p = 0.014) in trawl collections after the

267   hurricanes but increased significantly (Friedman's test, $\chi^2 = 5.00$, p = 0.025) in gillnet collections

268   (Figs. 5 and 7). Trawl data also revealed a significant increase in *A. felis* after the hurricanes

269   (Friedman's test, $\chi^2 = 6.00$, p = 0.014; Fig. 5). In beach seine collections, three species exhibited

270   significant declines: naked gobies (*Gobiosoma bosc*; Friedman's test, $\chi^2 = 5.00$, p = 0.025), Gulf

271   pipefish (*Syngnathus scovelli*; Friedman's test, $\chi^2 = 5.00$, p = 0.025), and rough silverside

272   (*Membras martinica*; Friedman's test, $\chi^2 = 5.00$, p = 0.025; Fig. 6). In gillnet collections, three

273   other species exhibited significant declines: *M. undulatus* (Friedman's test, $\chi^2 = 5.00$, p = 0.025),

274   Spanish mackerel (*Scomberomorus maculatus*; Friedman's test, $\chi^2 = 4.00$, p = 0.046), and sand

275   seatrout (*Cynoscion arenarius*; Friedman's test, $\chi^2 = 4.00$, p = 0.046; Fig. 7). For all remaining

276   fish species, there were no significant differences in pre/post-hurricane abundances.

277   Trends for some species as measured by the SIMPER analyses did not always agree with

278   those from the Friedman analyses. For example, while *M. undulatus* was an important

279   contributor to assemblage changes in trawl collections, there was no significant change in its

280   abundance. Likewise, in beach seine collections none of the species that experienced significant

281   declines were important in driving pre/post- assemblage changes based on SIMPER analyses

282   (Table 2). For the gillnet data, there is an apparent discrepancy between an increase in *B.*

283   *patronus* during its peak abundance period (April-June) and its supposed decrease during Season

284   I (April-October). According to the SIMPER results, this latter decrease contributed greatly to

285   the measured assemblage difference, with *B. patronus* being the most influential fish species

286   (Table 2). Although the abundance of *B. patronus* in collections made this species highly

287   influential to assemblage compositions, the observed discrepancies suggest that pre/post values

288   were actually similar (pre-hurricane mean abundance per collection = 19.42 and post-hurricane

289   mean abundance per collection = 19.40; Table 2). Also, while changes in the abundance of *M.*

290   *undulatus* contributed somewhat to measured assemblage change in Season I (it was the fourth

291   most influential species), neither *S. maculatus* nor *C. arenarius* (both of which experienced

292   significant changes in abundance), contributed markedly to this assemblage change according to

293   SIMPER results (Table 2).

294   Salinity was significantly lower (ANOVA, $p = 0.042$) after the 2005 hurricanes as

295   measured during Season I trawl collections (Table 3) but was significantly higher for

296   measurements during Season II trawl collections (ANOVA, $p = 0.011$) and Seasons I

297   (Friedman's test, $p = 0.025$) and II (MANOVA, $p = 0.001$) beach seine collections. Dissolved

298   oxygen was significantly lower after the hurricanes for measurements taken during Seasons I and

299   II trawl collections (ANOVA, $p < 0.001$; Table 3), Seasons I (ANOVA, $p < 0.001$) and II

300   (MANOVA, $p = 0.008$) beach seine collections, and Season I gillnet collections (ANOVA, $p <$

301   0.001). Water clarity as measured by Secchi depth was significantly higher prior to the

302   hurricanes during Season I (ANOVA, $p < 0.001$) and II (Friedman's test, $p = 0.014$) trawl

303   collections and also during Season I (ANOVA, $p = 0.004$) seine collections (Table 3). All other

304   pre/post comparisons of these variables, along with pre/post comparisons of water temperature,

305   were non-significant (Table 3).

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309   Discussion

310   Our results suggest that four years after the 2005 hurricanes, Lake Pontchartrain fish

311   assemblages have mostly recovered.   Benthic assemblages (as measured by trawl sampling)

312   exhibited changes in both seasons, but these were driven by the two most common species (*A.*

313   *mitchilli* and *M. undulatus*) increasing after the storms. It is interesting to note that these same

314   two species also increased in Chesapeake Bay after Hurricane Isabel struck in 2003 (Houde et al.

315   2005). Concerns exist, however, about measured post-hurricane declines in trawl-collected *B.*

316   *patronus*, especially since numbers of this species had remained relatively stable in Lake

317   Pontchartrain over a half-century of extensive disturbances (O'Connell et al. 2004). The

318   abundance of most individual fish species remained unchanged following these disasters. The

319   resilience of these fish assemblages is similar to that observed for other estuaries that were

320   affected by hurricanes (Greenwood et al. 2006; Piazza and La Peyre 2009; Stevens et al. 2006;

321   Switzer et al. 2006). In Breton Sound, an estuary southeast of Lake Pontchartrain, the 2005

322   hurricanes caused extensive habitat damage to tidal freshwater marshes (Piazza and La Peyre

323   2009). While this destruction led to a short-term change in the composition of local species, by

324   spring 2007 the pre-hurricane nekton community had recovered despite the fact that marsh

325   habitat remained damaged (Piazza and La Peyre 2009). Similar physical habitat damage

326   occurred in Charlotte Harbor, Florida during the active 2004 hurricane season and again the local

327   estuarine fish assemblage structure remained stable (Greenwood et al. 2006; Greenwood et al.

328   2007). It should be noted, though, that continued deterioration of mangrove root structure and

329   the slow rate of mangrove colonization may yet affect fish assemblages on a long-term basis

330   (Greenwood et al. 2007). One of these 2004 hurricanes also generated hypoxic conditions in

331   Charlotte Harbor which led to local fish kills (Stevens et al. 2006). This impact was also

332   temporary in that the local fish assemblages appeared to have recovered in no more than two

333   weeks following the storm (Stevens et al. 2006). During the same hurricane season, the St. Lucie

334   estuary in southeastern Florida also experienced extensive storm-related disturbances such as

335   increased fresh water input and near hypoxic conditions (Switzer et al. 2006). Again, local

336   nekton community recovery was evident after four months (Switzer et al. 2006). In most of

337   these examples, assemblage or community recovery is attributed to the ability of adult nekton to

338   avoid adverse conditions though their mobility (Greenwood et al. 2006; Switzer et al. 2006).

339   Such mobility is not available to benthic or sedentary organisms and may lead to relatively

340   higher hurricane-related mortality for these estuarine organisms (Poirrier et al. 2008). The

341   positive effects of nekton mobility in response to disturbances may be minimized when escape

342   corridors are reduced or eliminated in highly modified estuaries.

343   In trawl collections after the 2005 hurricanes, the ecologically and economically

344   important species *B. patronus* decreased significantly during its typical period of peak abundance

345   (March through May). This filter-feeding species serves as a prey item for many other fishes and

346   supports one of the top fisheries by volume in the United States (Smith 2001; Vaughan et al.

347   2011). The extent to which *B. patronus* influences estuarine communities in the northern Gulf of

348   Mexico makes this species an indicator of the overall health and productivity of these aquatic

349   systems (Vaughan et al. 2011). Trawl sampling in Lake Pontchartrain mostly collects juvenile *B.*

350   *patronus*, not adults. During the spring (again, March through May) juvenile *B. patronus*

351   typically use upper estuaries such as Lake Pontchartrain as nurseries. Higher salinities could

352   have driven these fish to use other less saline habitats farther up the estuary such as Lake

353   Maurepas, similar to the results of other studies of Lake Pontchartrain (Cashner et al. 2001) and

354   elsewhere (Haley et al. 2010; VanderKooy 2011). But salinities were lower after 2005 during

355   Season I (November through May) trawl collections which coincided with the period of peak

356   abundance of *B. patronus* in the trawl (March through May), even though salinities were

357   typically higher in other post-hurricane comparisons (Table 3). Another explanation for the

358   decline in *B. patronus* is that significantly lower dissolved oxygen levels in both trawl seasons

359   caused these fish to avoid portions of Lake Pontchartrain. While these lower dissolved oxygen

360   levels were not hypoxic (lowest measurement = 4.60 mg/l), nearby 'dead zones' had been

361   identified farther down the estuary in Chandeleur Sound during the same period (Lopez et al.

362   2010). In avoiding hypoxic or anoxic areas, aquatic organisms (including *B. patronus*) can

363   become concentrated in normoxic water, thus making them more vulnerable to fishing effort

364   (Smith 2001; Burkholder et al. 2004; Breitburg et al. 2009). Local commercial fishing pressure

365   on *B. patronus* has actually been reduced following the 2005 hurricanes due to damage to fishery

366   infrastructure, but fishing mortality has also increased possibly due to *B. patronus* displaced

367   from offshore hypoxic zones being captured more effectively in near shore waters (Vaughan et

368   al. 2007). A similar fishery response was observed in the Albemarle–Pamlico Estuarine System

369   in North Carolina and Virginia after the active 1999 hurricane season which included three

370   named storms impacting the region (Burkholder et al. 2004). Hurricane floodwaters displaced

371   high numbers of blue crabs (*Callinectes sapidus*) causing them to "hyperaggregate" in areas

372   where they were exposed to increased commercial fishing pressure (Burkholder et al. 2004).

373   This, in turn, resulted in a 70% reduction of adult *C. sapidus* in 1999-2002 (Burkholder et al.

374   2004).

375   One benthic species, *A. felis*, increased in trawl collections after the hurricanes. This

376   species may have benefitted from the lack of commercial fishing pressure in Lake Pontchartrain

377   due to hurricane damage to boats and infrastructure (Buck 2005). Benthic fin-fishes are

378   consistently taken in large numbers as bycatch in trawling conducted by Louisiana commercial

379   shrimpers (Adkins 1993). Unlike the purse seines used in the local *B. patronus* fishery, trawls

380   not only impact benthic fishes through direct fishery mortality but also severely alter these

381   animals' habitats (Watling and Norse 1998). The reduced trawling in eastern Lake Pontchartrain

382   and nearby Lake Borgne likely reduced overall mortality for this species in the years following

383   the 2005 hurricanes. Significant changes in post-hurricane environmental variables (decreased

384   dissolved oxygen and water clarity) in trawl Season II (June through October) which coincided

385   with the peak period of abundance for *A. felis* (June through October) likely played less of a role

386   in explaining the increase in this species, unless this known scavenger was consuming other

387   organisms that may have succumbed to the detrimental local conditions caused by the hurricanes.

388   For example, *A. felis* can adjust its foraging behavior and take advantage of discarded bycatch

389   generated during shrimping season in southeastern Louisiana (Eustis 2011). As with other

390   estuaries, long term increases in such scavenger species may reflect an overall decline in trophic

391   structure and general ecosystem health.

392   Three small species, *G. bosc*, *S. scovelli*, and *M. martinica* declined after the hurricanes

393   in beach seine collections. For *G. bosc*, this change may have been associated with decreases in

394   dissolved oxygen and water clarity, while dissolved oxygen decreases during their periods of

395   abundance may have explained the decreases in the *S. scovelli* and *M. martinica*. The 2005

396   hurricanes caused extensive damage to Lake Pontchartrain's benthic community, especially the

397   ecologically dominant *Rangia cuneata* clam (Poirrier et al. 2008). Many benthic invertebrates

398   died as a result of scouring as surge waters retreated back to the Gulf of Mexico. The decline of

399   *R. cuneata* (a filter feeding organism) likely contributed to poorer water quality in nearshore

400   habitats where adults of these three species occur. Scouring may have impacted *G. bosc* as it did

401 benthic invertebrates because this species is a slow-moving, estuarine-resident goby that is

402 highly associated with benthic habitats, especially bivalve shell material (Ross and Rhode 2004).

403 Declines in *S. scovelli* and *M. martinica* may be linked to these nearshore species being

404 commonly associated with submersed aquatic vegetation (SAV). Under normal conditions, *S.*

405 *scovelli* will use SAV as refuge from predators while *M. martinica* deposits its eggs on SAV.

406 The decline of *R. cuneata* since the storms and subsequent decrease in water clarity over time

407 may have contributed to a decline in the amount of SAV available for *S. scovelli* and *M.*

408 *martinica* (i.e., plants need light). For example, October 2005 surveys discovered major

409 decreases in SAV aboveground biomass throughout Lake Pontchartrain (Poirrier et al. 2009).

410 While many SAV species can eventually recover from hurricane impacts (much like estuarine

411 nekton), the short term (3-4 years) lack of SAV after the 2005 hurricanes may have interfered

412 with the ability of *S. scovelli* to avoid predation and with the reproductive success of *M.*

413 *martinica*.

414   In gillnet collections, *B. patronus* increased after the hurricanes during its peak

415 abundance period, yet this result seemed to contradict both an assemblage-driving decrease

416 reported by the SIMPER results (Table 2) and the significant post-hurricane decline of this

417 species in trawl collections (Fig. 7). On closer examination, the SIMPER decline represents an

418 in-consequential decrease in mean abundance per collection from 19.42 to 19.40 individuals after

419 the hurricanes. The discrepancy between the gillnet and trawl results likely represents a

420 difference in response to the hurricanes by two different life stages of *B. patronus*. Adult *B.*

421 *patronus* are typically only collected in gillnets while juveniles are most numerous in trawl

422 collections. We suggest that adult *B. patronus* (age 2-4 years) fared better after the hurricanes

423 than juveniles because of their superior swimming ability that allows them to avoid hazardous

424 conditions. Not only would juvenile *B. patronus* lack this escape ability, they would also be

425 exposed to those degraded nearshore habitat conditions described in the previous paragraph.

426 Like the juveniles of most estuarine-dependent species, *B. patronus* occur in large numbers in

427 nearshore habitats which they use as refugia from predator pressure. Because of the ecological

428 and economic importance of this species, it will be necessary to monitor the recovery of *B.*

429 *patronus* juveniles in this estuary.

430   The declines in gillnet collections of *M. undulatus*, *S. maculatus* and *C. arenarius* may be

431 cause for concern, although the latter two species did not contribute to the measured pre/post-

432 assemblage change measured in April through October (gillnet Season I). In other words,

433 although the abundance of both *S. maculatus* and *C. arenarius* declined significantly, they were

434 not the drivers of overall assemblage change and, therefore, not representative of a truly

435 concerning ecological perturbation (Table 2). Unlike these two species, *M. undulatus* did

436 contribute 8.72% to the overall assemblage change measured in Season I gillnet data, with its

437 mean abundance declining from 2.54 to 0.61 individuals after the hurricanes (Table 2). The

438 abundances of the three species that contributed the most to assemblage change during gillnet

439 Season I (*B. patronus*, *Bagre marinus*, and *A. felis*) either increased or did not change markedly

440 (Table 2). However, the increase of the two catfish species (*B. marinus* and *A. felis*) and decline

441 of two drum (family Sciaenidae) species (*M. undulatus* and *C. arenarius*) may indicate the

442 beginning of system-wide environmental stress or trophic shifts. Similar changes in dominant

443 fish species in other estuaries have led to the decline of targeted and desirable fishery species,

444 that are then replaced by less desirable, lower trophic species. The alteration of the benthos by

445 the hurricanes (as described above) may have contributed to the decline of *M. undulatus* and *C.*

446 *arenarius*, both of which are associated with benthic habitats. The scouring that displaced many

447 *R. cuneata,* also likely displaced many polychaete worms, a key diet item for *M. undulatus.*

448 While *C. arenarius* feeds more on penaeid shrimp and *A. mitchilli,* this species is more benthic-

449 oriented than its sister species *C. nebulosus* and the disruption of the benthic habitat of its prey

450 may have led to its decline. Of the three species that declined in gillnet Season I, *S. maculatus* is

451 the only truly marine species (compared to the two estuarine dependent drum species). This

452 species is an uncommon late-summer visitor to the estuary, typically occurring in drier years

453 (e.g., 2000 and 2001). It is possible that their decline is more the reflection of a lack of true

454 drought years after the hurricanes rather than impacts from the storms themselves.

455   After the storms, environmental variables were typical of conditions measured

456 immediately after other hurricanes in the southeastern United States. Higher salinity, lower

457 dissolved oxygen, and increased turbidity are common outcomes of hurricane landfalls in

458 estuaries (Tabb and Jones 1962; Burkholder et al. 2004; Mallin and Corbett 2006; Stevens et al.

459 2006; Edmiston et al. 2008). A repeated theme among these studies of immediate hurricane

460 impacts on estuaries is that conditions quickly return to normal, including the composition of

461 local fish assemblages (Tabb and Jones 1962; Piazza and La Peyre, 2009; Rodgers et al. 2009).

462 The changes in fish assemblages after the 2005 hurricanes were often associated with increases

463 of influential species and in many seasons the abundances of other common species remained

464 stable (Table 2). Though there is concern for species that consistently declined over multiple

465 gear types (e.g., *B. patronus*) it appears that many of the hurricanes' impacts on local species are

466 short-lived. Even though many water quality parameters were significantly different after the

467 hurricanes, our post-hurricane period lasted four years beyond the storms, long after

468 environmental variables should typically revert back to normal. In some cases, it is possible that

469   environmental variables remained changed due to other circumstances (i.e., impacts from newly

470   constructed hurricane protection structures, closure of the Mississippi River Gulf Outlet, etc.).

471   As coastal areas in the southeastern United States become more susceptible to projected

472   increased tropical storm activity, long term data such as we present here will allow

473   documentation of any effects from both natural and anthropogenic disasters.   While most

474   estuarine nekton species appear resilient to storms, we did measure significant declines in

475   important fishery species (e.g., *B. patronus*) as well as some smaller, inshore species (e.g., *S.*

476   *scovelli*).   Whether these changes are short or long term, can only be determined with future

477   sampling. Beyond estuarine nekton, other organisms such as seagrasses can eventually recover

478   after storms (Byron and Heck 2006, Poirrier et al. 2009), whereas other taxa (e.g., benthic

479   bivalves) are more susceptible to hurricane impacts (Poirrier et al. 2008). If these organisms

480   which have important roles in estuarine ecosystems (e.g., water filtration, prey items) cannot

481   recover from hurricane damage, then we may expect to experience long-term impacts on other

482   organisms which rely on them. For example, the widespread and ecologically dominant *R.*

483   *cuneata* is an important prey item for blue crabs (*C. sapidus*) which, in turn, are important prey

484   items for estuarine finfish, including most drums; as go the prey species, so go the predator

485   species. These trophic cascades can develop in estuarine ecosystems and advance unnoticed for

486   years because nekton species are resilient and estuaries themselves are highly variable on a year-

487   to- year basis. To detect such impacts, it is necessary to continuously collect and evaluate long-

488   term data to effectively measure possible changes to an ecosystem and determine their causes.

489   These continuous data will be needed to determine long term trends in declining species or

490   species that may indicate increasing habitat perturbation. Managers of estuarine resources need

491   to beware of the apparent short-term recovery of estuarine nekton assemblages after disasters

492 which may hide long-term significant declines in species, such as those we have measured in

493 Lake Pontchartrain (O'Connell et al. 2004; O'Connell et al. 2007).

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515   Literature Cited

516

517   Adams, A. 2001. Effects of a hurricane on two assemblages of coral reef fishes: multiple-year

518   analysis reverses a false 'snapshot' interpretation. Bulletin of Marine Science 69: 341-

519   346.

520   Adkins, G. 1993. A comprehensive assessment of bycatch in the Louisiana shrimp fishery.

521   Bourg: Louisiana Department of Wildlife and Fisheries Technical Bulletin No. 42.

522   Breitburg, D.L., J.K. Craig, R.S. Fulford, K.A. Rose, W.R. Boynton, D.C. Brady, B.J. Ciotti, R.J.

523   Diaz, K.D. Friedland, J.D. Hagy III, D.R. Hart, A.H. Hines, E.D. Houde, S.E. Kolesar,

524   S.W. Nixon, J.A. Rice, D.H. Secor, T.E. Targett. 2009. Nutrient enrichment and fisheries

525   exploitation: interactive effects on estuarine living resources and their management.

526   Hydrobiologia 629: 31–47.

527   Buck, E.H. 2005. Hurricanes Katrina and Rita: fishing and aquaculture industries - damage and

528   recovery. Congressional Research Service Report, Order Code RS22241.

529   Burkholder, J., D. Eggleston, H. Glasgow, C. Brownie, R. Reed, G. Janowitz, M. Posey, G.

530   Melia, C. Kinder, R. Corbett, D. Toms, T. Alphin, N. Deamer, and J. Springer. 2004.

531   Comparative impacts of two major hurricane seasons on the Neuse River and western

532   Pamlico Sound ecosystems. Proceedings of the National Academy of Sciences of the

533   United States of America 101: 9291-9296.

534   Byron, D., and K.L. Heck. 2006. Hurricane effects on seagrasses along Alabama's gulf coast.

535   Estuaries and Coasts 29: 939–942.

536   Cashner, R.C., M.T. O'Connell, J.H. Humphries, and M.A. Poirrier. 2001. Impact of a prolonged

537   period of low rainfall on the aquatic community in the Lake Pontchartrain estuary,

538   Louisiana, USA. Abstract published for Symposium on the Role of Drought in Aquatic

539   Ecosystems Albury, NSW, Australia sponsored by the Cooperative Research Centre for

540   Freshwater Ecology and The Murray-Darling Freshwater Research Centre, Albury, NSW,

541   Australia, February, 2001.

542 Clarke, K.R., and R.M. Warwick. 2001. Change in marine communities: an approach to

543   statistical analysis and interpretation. 2nd ed. Plymouth, United Kingdom: PRIMER-E.

544 Edmiston, H.L., S.A. Fahrny, M.S. Lamb, L.K. Levi, J.M. Wanat, J.S. Avant, K. Wren, and N.C.

545   Selly. 2008. Tropical storm and hurricane impacts on a Gulf Coast estuary: Apalachicola

546   Bay, Florida. Journal of Coastal Research Special Issue 55: 38–49.

547 Eustis, S.P. 2011. Bycatch of the Lake Pontchartrain Basin inshore shrimp fishery and its effect

548   on two sea catfish species: the gafftopsail catfish (*Bagre marinus*) and the hardhead

549   catfish (*Ariopsis felis*). Master's thesis. University of New Orleans, New Orleans,

550   Louisiana.

551 Farris, G.S., G.J. Smith, M.P. Crane, C.R. Demas, L.L. Robbins, and D.L. Lavoie. 2007. Science

552   and the storms—the USGS response to the hurricanes of 2005. U.S. Geological Survey

553   Circular 1306.

554 Greening, H., P. Doering, and C. Corbett. 2006. Hurricane impacts on coastal ecosystems.

555   Estuaries and Coasts 29: 877-979.

556 Greenwood, M.F.D., C.F. Idelberger, and P.W. Stevens. 2007. Habitat associations of large-

557   bodied mangrove-shoreline fishes in a southwest Florida estuary and the effects of

558   hurricane damage. Bulletin of Marine Science 80: 805-821.Greenwood, M.F.D., P.W.

559   Stevens, and R.E. Matheson, Jr. 2006. Effects of the 2004 hurricanes on the fish

560   assemblages in two proximate southwest Florida estuaries: change in the context of

561   interannual variability. Estuaries and Coasts 29: 985-996.

562   Haley, T.H., R.K. Bolton, and C.E. Johnston. 2010. Invasion of gulf menhaden in the Alabama

563   River. Southeast Fisheries Council Proceedings 52: 13-15.

564   Hoe, A., E.A. Laws, R.P. Gambrell, H.-S. Bae, M. Tan, R.D. DeLaune, Y. Li, and H. Roberts.

565   2006. Pathogen indicator microbes and heavy metals in Lake Pontchartrain following

566   Hurricane Katrina. Environmental Science and Technology 40: 5904–5910.

567   Houde, E.D., J. Bichy, and S. Jung. 2005. Effects of Hurricane Isabel on fish populations and

568   communities in Chesapeake Bay. In *Hurricane Isabel in Perspective,* ed. K.G. Sellner.

569   Edgewater, MD: Chesapeake Research Consortium, CRC Publication 05-160.

570   Idelberger, C. and M.F.D. Greenwood. 2005. Seasonal variation in fish assemblages within the

571   estuarine portions of the Myakka and Peace Rivers, Southwest Florida. Gulf of Mexico

572   Science 2: 224–240.Lopez, J.A., A. Baker, and E. Boyd. 2010. Water quality in

573   Chandeleur Sound in 2008 and 2010. Lake Pontchartrain Basin Foundation Report.

574   http://saveourlake.org/PDF-documents/our-coast/ChandeleurSound_WaterQuality_10-

575   2010.pdf. Accessed 20 August 2012.

576   Kaufman, J.B. and P.J. Rousseeuw 1990. Finding groups in data: an introduction to cluster

577   analysis. New York: Wiley.

578   Mallin, M.A. and C.A. Corbett. 2006. How hurricane attributes determine the extent of

579   environmental effects: multiple hurricanes and different coastal systems. Estuaries and

580   Coasts 29: 1046-1061.

581 O'Connell, M.T., R.C. Cashner, and C.S. Schieble. 2004. Fish assemblage stability over fifty

582 years in the Lake Pontchartrain estuary; comparisons among habitats using canonical

583 correspondence analysis. Estuaries 27: 807-817.

584 O'Connell, M.T., R.C. Cashner, and C.S. Schieble. 2006. Fish assemblage instability and

585 hydrologic influences in Lake Pontchartrain, Louisiana (USA), a degraded oligohaline

586 estuary. In *Coastal Environment and Water Quality*, eds. Y.J. Xu. and V.P. Singh.

587 Highlands Ranch, Colorado: Water Resources Publications, LLC.

588 O'Connell, M.T., T.D. Shepherd, A.M. Uzee-O'Connell, and R.A. Myers. 2007. Long–term

589 declines in two apex predators, bull sharks (*Carcharhinus leucas*) and alligator gar

590 (*Atractosteus spatula*), in Lake Pontchartrain, an oligohaline estuary in southeastern

591 Louisiana. Estuaries and Coasts 30: 1–8.

592 Penland, S., P. McCarty, A. Beall, and D. Maygarden. 2002. Environmental overview of the

593 Lake Pontchartrain Basin. In *Environmental Atlas of the Lake Pontchartrain Basin*, eds.

594 S. Penland, A. Beall, and J. Kindinger, 2-6. New Orleans, Louisiana: Lake Pontchartrain

595 Basin Foundation. Open File Report 2. U.S. Geological Survey.

596 Piazza, B.P. and M.K. La Peyre. 2009. The effect of Hurricane Katrina on nekton communities

597 in the tidal freshwater marshes of Breton Sound Louisiana, USA. Estuarine, Coastal and

598 Shelf Science 83: 97-104.

599 Poirrier, M.A., Z.R. del Ray, and E.A. Spaulding. 2008. Acute disturbance of Lake Pontchartrain

600 benthic communities by Hurricane Katrina. Estuaries and Coasts 31: 1221-1228.

601 Poirrier, M.A., E.A. Spalding, and C.D. Franze. 2009. Lessons learned from a decade of

602 assessment and restoration studies of benthic invertebrates and submersed aquatic

603   vegetation in Lake Pontchartrain. Journal of Coastal Research: Special Issue 54: pp. 88 –

604   100.

605 Rodgers, J.C., A.W. Murrah, and W.H. Cooke. 2009. Vegetation of the Weeks Bay Reserve,

606   Alabama from NDVI data. Estuaries and Coasts 32: 496-507.

607 Ross, S.W. and F.C. Rhode. 2004. The gobioid fishes of North Carolina (Pisces: Gobioidei).

608   Bulletin of Marine Science 74: 287-323.

609 Smith, J. W. 2001. Distribution of catch in the Gulf Menhaden, *Brevoortia patronus*, purse seine

610   fishery in the northern Gulf of Mexico from logbook information: are there relationships

611   to the hypoxic zone? In *Coastal Hypoxia: Consequences for Living Resources and*

612   *Ecosystems*, *Coastal Estuarine Stud.*, vol. 58, eds. N.N. Rabalais and R.E. Turner, 311–

613   320. Washington, DC: AGU.

614 Stevens, P.W., D.A. Blewett, and J.P. Casey. 2006. Short-term effects of a low dissolved oxygen

615   event on estuarine fish assemblages following the passage of Hurricane Charley.

616   Estuaries and Coasts 29: 997-1003.

617 Swenson, E.M. 1980. General hydrography of Lake Pontchartrain, Louisiana. Environmental

618   Analysis of Lake Pontchartrain, Louisiana, its surrounding wetlands, and selected land

619   uses. New Orleans: US Army Engineer District. DACW29-77-C-0253.

620 Switzer, T.S., B.L. Winner, N.M. Dunham, J.A. Whittington, and M. Thomas. 2006. Influence of

621   sequential hurricanes on nekton communities in a southeast Florida estuary: short-term

622   effects in the context of historical variations in freshwater inflow. Estuaries and Coasts

623   29: 1011-1018.

624 Tabb. D.C. and A.C. Jones. 1962. Effect of Hurricane Donna on the aquatic fauna of north

625   Florida Bay. Transactions of the American Fisheries Society 91: 375-378.

626   VanderKooy, S. 2011. Habitat description for the Gulf Menhaden stock in the U.S. Gulf of

627   Mexico. Report submitted to the Southeast Data, Assessment, and Review (SEDAR).

628   SEDAR 27-DW07.

629   Van Metre, P.C., A.J. Horowitz, B.J. Mahler, W.T. Foreman, C.C. Fuller, M.R. Burkhardt, K.A.

630   Elrick, E.T. Furlong, S.C. Skrobialowski, J.J. Smith, J.T. Wilson, and S.D. Zaugg. 2006.

631   Effects of Hurricanes Katrina and Rita on the chemistry of bottom sediments in Lake

632   Pontchartrain, Louisiana, USA. Environmental Science and Technology 40: 6894–6902.

633   Van Vrancken, J. and M. O'Connell. 2010. Effects of Hurricane Katrina on freshwater fish

634   assemblages in a small coastal tributary of Lake Pontchartrain, Louisiana. Transactions of

635   the American Fisheries Society 139: 1723-1732.

636   Vaughan, D.S., J. J. Govoni, and K. W. Shertzer. 2011. Relationship between Gulf menhaden

637   recruitment and Mississippi River flow: model development and potential application for

638   management. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem

639   Science 3: 344-352.

640   Vaughan, D.S., Shertzer, K.W. & Smith, J.W. 2007. Gulf menhaden (*Brevoortia patronus*) in the

641   U.S. Gulf of Mexico: Fishery characteristics and biological reference points for

642   management. Fisheries Research 83: 263–275.

643   Watling, L. and E. Norse. 1998. Disturbance of the seabed by mobile fishing gear: a

644   comparison to forest clearcutting. Conservation Biology 12: 1180-1197.

645   **Fig**. **1** Sampling sites in Lake Pontchartrain for trawl, beach seine, and gillnet collections. Mid-lake site (M) was only sampled with

646   trawls.

647   **Fig. 2** MDS plots of pre (black triangles) and post (gray triangles) 2005 hurricane trawl samples collected from Lake

648   Pontchartrain during Seasons I (November-May) and II (June-October).

649   **Fig. 3** MDS plots of pre (black triangles) and post (gray triangles) 2005 hurricane seine samples collected from Lake

650   Pontchartrain during Seasons I (December-March), II (April-June), and III (July-November).

651   **Fig. 4** MDS plots of pre (black triangles) and post (gray triangles) 2005 hurricane gillnet samples collected from Lake

652   Pontchartrain during Seasons I (April-October) and II (November-March).

653   **Fig. 5** Mean number of *B. patronus* and *A. felis* collected by trawls at six Lake Pontchartrain sites before and after the 2005

654   hurricanes. Collections were made during peak seasons for both species: *B. patronus* (March-May) and *A. felis* (June-October).

655   In trawl collections taken after the 2005 hurricanes, there were significantly less *B. patronus* (Friedman's test, $\chi^2 = 6.00$, p =

656   0.014) and significantly more *A. felis* (Friedman's test, $\chi^2 = 6.00$, p = 0.014).

657   **Fig. 6** Mean number of *G. bosc*, *S. scovelli*, and *M. martinica* collected by beach seines at five Lake Pontchartrain sites before and

658   after the 2005 hurricanes. Collections were made during peak seasons for each species: *G. bosc* (February-May), *S. scovelli*

659   (April-August), and *M. martinica* (July-October). In beach seine collections taken after the 2005 hurricanes, all three species

660   declined significantly: *G. bosc* (Friedman's test, χ^2=5.00, p = 0.025), *S. scovelli* (Friedman's test, χ^2=5.00, p = 0.025), and *M.*

661   *martinica* (Friedman's test, χ^2=5.00, p = 0.025).

662   **Fig. 7** Mean number of *B. patronus*, *M. undulatus*, *S. maculatus*, and *C. arenarius* collected by gillnets at five Lake Pontchartrain sites

663   before and after the 2005 hurricanes. Collections were made during peak seasons for each species: *B. patronus* (April-June)

664   *M. undulatus* (May-September), *S. maculatus* (August-October), and *C. arenarius* (June-September). In gillnet collections

665   taken after the 2005 hurricanes, *B. patronus* increased significantly (Friedman's test, χ^2=5.00, p = 0.025) while the other three

666   species decreased significantly: *M. undulatus* (Friedman's test, χ^2=5.00, p = 0.025), *S. maculatus* (Friedman's test, χ^2=4.00, p =

667   0.046), and *C. arenarius* (Friedman's test, χ^2=4.00, p = 0.046).

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Table 1 Numbers of nekton collections made from Lake Pontchartrain both pre- (2000-2003, 2005) and post-hurricanes (2005-2009) using three gear types: trawls, beach seines, and gillnets.

	Year	Trawl	Beach Seine	Gillnet
Pre-Hurricanes				
	2000	54	30	18
	2001	125	60	41
	2002	98	59	47
	2003	44	27	17
	2004	20	11	7
	2005	69	37	23
	Total	410	224	153
Post-Hurricanes				
	2005	5	13	0
	2006	96	59	36
	2007	113	60	47
	2008	130	60	52
	2009	111	60	45
	Total	455	252	180

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Table 2 Pre/post mean abundances, contribution percentages, and cumulative percentages for those species that contributed significantly to pre/post hurricane differences in assemblages from SIMPER analyses. Results are by season and gear type from trawl (2 seasons), beach seine (3 seasons), and gillnet (1 season) collections. Note that for the sake of clarity in interpretation, we here report actual mean abundances per collection whereas typical SIMPER tables reports transformed mean abundances.

Gear-Season	Species	Pre-hurricane mean abundance per collection	Post-hurricane mean abundance per collection	Percent contribution to assemblage change	Cumulative percent contribution to assemblage change
Trawl-Season I	*Anchoa mitchilli*	154.39	262.81	55.15	55.15
(Nov.-May)	*Micropogonias undulatus*	14.65	18.26	18.10	73.25
	Brevoortia patronus	20.64	4.42	13.19	86.44
	Cynoscion arenarius	1.12	0.78	2.89	89.93
	Ictalurus furcatus	0.25	0.14	1.29	90.61
Trawl-Season II	*Anchoa mitchilli*	481.58	853.38	71.48	71.48
(Jun.-Oct.)	*Micropogonias undulatus*	11.21	12.08	10.68	82.17
	Cynoscion arenarius	0.63	2.51	4.22	86.38
	Brevoortia patronus	2.20	0.73	2.41	88.79
	Anchoa hepsetus	0.38	0.17	1.83	90.62
Seine-Season I	*Menidia beryllina*	61.12	48.60	20.00	20.00
(Dec.-Mar.)	*Anchoa mitchilli*	72.58	17.65	16.98	36.98
	Micropogonias undulatus	41.07	13.18	13.78	50.76
	Brevoortia patronus	112.67	5.05	12.92	63.68
	Mugil cephalus	7.80	1.24	5.77	69.45

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Mugil curema	23.24	2.76	4.55	74.00
Leiostomus xanthurus	33.29	4.72	3.86	77.86
Fundulus grandis	0.87	2.34	3.48	81.34
Cyprinodon variegatus	3.70	1.66	2.89	84.23
Gobiosoma bosc	2.88	0.19	2.53	86.76
Lucania parva	11.50	0.34	2.01	88.77
Fundulus similis	0.17	1.96	1.99	90.76
Seine-Season II (Apr.-Jun.) *Brevoortia patronus*	462.79	265.60	25.36	25.36
Anchoa mitchilli	92.76	22.43	11.61	36.97
Menidia beryllina	87.93	23.47	11.18	48.16
Micropogonias undulatus	18.28	37.90	8.99	57.15
Mugil cephalus	15.95	9.22	5.24	62.39
Leiostomus xanthurus	20.12	5.07	4.40	66.79
Lucania parva	58.41	0.63	3.40	70.19
Fundulus grandis	3.40	2.02	2.60	72.79
Strongylura marina	1.76	1.98	2.52	75.31
Elops saurus	1.69	1.03	2.44	77.75
Cyprinodon variegatus	11.26	0.72	2.25	80.00
Gobiosoma bosc	2.33	0.33	2.00	82.00
Lagodon rhomboides	3.24	0.45	1.89	83.89
Syngnathus scovelli	2.76	0.30	1.83	85.72
Membras martinica	2.00	0.27	1.65	87.37
Cynoscion arenarius	1.22	0.68	1.65	89.01
Fundulus similis	0.78	1.20	1.19	90.20
Seine- Season III (Jul.-Nov.) *Anchoa mitchilli*	107.88	62.26	21.88	21.88
Menidia beryllina	97.47	14.48	14.48	36.36
Mugil cephalus	4.66	2.34	5.86	42.22

	Elops saurus	1.27	4.67	4.87	47.10
	Micropogonias undulatus	4.49	1.29	4.29	51.39
	Brevoortia patronus	3.18	16.24	4.17	55.56
	Cynoscion nebulosus	2.17	1.22	3.94	59.50
	Strongylura marina	1.24	2.42	3.67	63.17
	Membras martinica	2.59	1.10	3.38	66.55
	Gobiosoma bosc	2.99	0.06	2.25	68.80
	Fundulus grandis	1.12	0.92	2.12	70.92
	Leiostomus xanthurus	0.92	0.70	2.11	73.03
	Lagodon rhomboides	0.99	1.17	2.00	75.03
	Syngnathus scovelli	4.03	0.63	1.93	76.96
	Oligoplites saurus	0.48	0.79	1.90	78.85
	Lucania parva	5.04	0.24	1.57	80.42
	Bairdiella chrysoura	0.80	1.32	1.46	81.88
	Anchoa hepsetus	1.14	0.91	1.38	83.27
	Cyprinodon variegatus	4.07	0.08	1.10	84.37
	Ariopsis felis	0.50	0.49	1.10	85.47
	Fundulus similis	0.29	0.47	1.02	86.49
	Mugil curema	0.10	0.35	1.01	87.49
	Sphoeroides parvus	0.70	0.15	0.94	88.44
	Sciaenops ocellatus	0.09	0.66	0.88	89.32
	Gobiesox strumosus	0.42	0.06	0.82	90.14
Gillnet-Season I	*Brevoortia patronus*	19.42	19.40	24.92	24.92
(Apr.-Oct.)	*Bagre marinus*	2.85	3.69	18.10	43.02
	Ariopsis felis	1.00	1.43	8.80	51.82
	Micropogonias undulatus	2.54	0.61	8.72	60.54
	Leiostomus xanthurus	2.64	0.89	6.17	66.71

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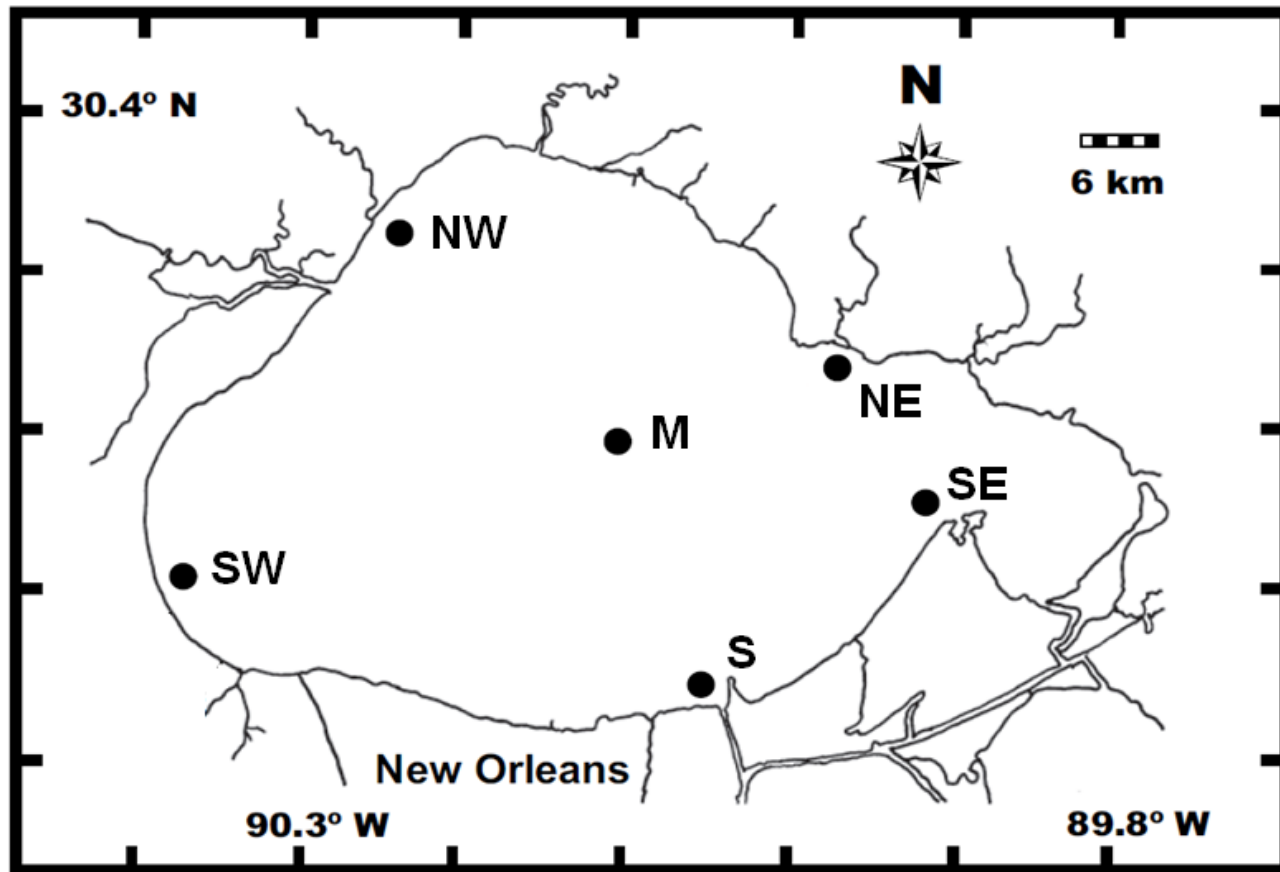|			
Alosa chrysochloris	0.67	0.51	5.45	72.16
Dorosoma cepedianum	1.12	0.97	5.30	77.46
Cynoscion nebulosus	1.22	0.45	5.23	82.69
Mugil cephalus	0.61	0.16	3.00	85.69
Elops saurus	0.15	0.17	2.65	88.34
Pogonias cromis	0.15	0.38	2.24	90.58

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706 **Table 3** Mean values and standard errors (S.E.) for environmental variables measured pre- and post-hurricanes by gear and season.
707 Significance (p) values for the factor Pre/Post hurricanes were calculated from either MANOVA/ANOVA, ANOVA, or Friedman's
708 tests. MANOVA was performed when the test of the preliminary assumption that the covariance matrices of the dependent variables
709 are the same across groups in the population was met, as indicated by the Box's test. For those combinations of environmental
710 variables that could be tested by MANOVA, this test was performed with the environmental variables as dependent factors and
711 Pre/Post (shown), Site, and Pre/Post*Site as the independent factors. For MANOVA, the Overall Pre/Post significance value indicates
712 the significance of the Pre/Post factor. If this was significant, subsequent ANOVAs were run for each variable, with the *post-hoc* error
713 rate adjusted to 0.025. If the Box's test was significant or the MANOVA could not be performed, an ANOVA was performed
714 individually for each variable, without the error rate adjustment. ANOVAs were performed for those variables that met the
715 homogeneity of variance test (Levene's). If ANOVA could not be performed (i.e., Levene's test was significant), then Friedman's test
716 (a non-parametric rank-based procedure; seasonally, with site averages as the block and Pre/Post as the factor) was performed.
717 Bolded values indicate significant results and Pre/Post trends in environmental variables are indicated.
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Environmental Variable	Gear / Season	Pre-Hurricanes	Post-Hurricanes	Overall MANOVA Pre/Post significance	Individual Pre/Post significance	Trend	Test Used
	Trawl/SI (Nov.-May)	Mean (S.E.)	Mean (S.E.)				
Temperature		18.48(0.36))	18.24 (0.83)		0.208		ANOVA
Water Clarity		1.33(0.04)	0.97(0.10)		**0.001**	**pre>post**	ANOVA
Salinity		4.92(0.15)	4.80(0.34)		**0.042**	**pre>post**	ANOVA
Dissolved O_2		8.77(0.09)	8.01(0.21)		**0.001**	**pre>post**	ANOVA
	Trawl/SII (Jun.-Oct.)						
Temperature		27.76(0.27)	28.04(0.23)		0.671		ANOVA
Water Clarity		1.55(0.05)	1.34(0.04)		**0.014**	**pre>post**	Friedman's
Salinity		5.61(0.20)	5.89(0.18)		**0.011**	**pre<post**	ANOVA
Dissolved O_2		7.04(0.09)	6.57(0.07)		**0.001**	**pre>post**	ANOVA
	Seine/SI (Dec.-Mar.)						
Temperature		13.76(0.38)	13.92(0.62)		0.655		Friedman's
Water Clarity		0.82(0.05)	0.60(0.07)		**0.004**	**pre>post**	ANOVA

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Salinity		4.39(0.25)	4.57(0.42)		**0.025**	**pre<post**	Friedman's
Dissolved O_2		9.45(0.16)	8.36(0.26)		**0.001**	**pre>post**	ANOVA
	Seine/SII (Apr.-Jun.)						
Temperature		26.12(0.54)	25.45(0.53)	**0.001**	0.380		MANOVA/ANOVA
Water Clarity		0.84(0.04)	0.79(0.04)	**0.001**	0.181		MANOVA/ANOVA
Salinity		3.51(0.22)	4.56(0.21)	**0.001**	**0.001**	**pre<post**	MANOVA/ANOVA
Dissolved O_2		6.89(0.17)	6.25(0.17)	**0.001**	**0.008**	**pre>post**	MANOVA/ANOVA
	Seine/SIII (Jul.-Nov.)						
Temperature		25.90(0.58)	25.68(0.54)	0.053			MANOVA
Water Clarity		0.89(0.04)	0.84(0.04)		0.655		Friedman's
Salinity		5.76(0.30)	6.05(0.28)		0.180		Friedman's
Dissolved O_2		6.62(0.15)	6.21(0.14)	0.053			MANOVA
	Gillnet/SI (Apr.-Oct.)						
Temperature		26.76(0.37)	26.47(0.33)		0.493		ANOVA
Water Clarity		1.26(0.06)	1.13(0.05)		0.180		Friedman's
Salinity		4.85(0.25)	5.34(0.23)		0.139		ANOVA
Dissolved O_2		7.10(0.12)	6.45(0.11)		**0.001**	**pre>post**	ANOVA

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● S

New Orleans

90.3° W

89.8° W

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Figure 2

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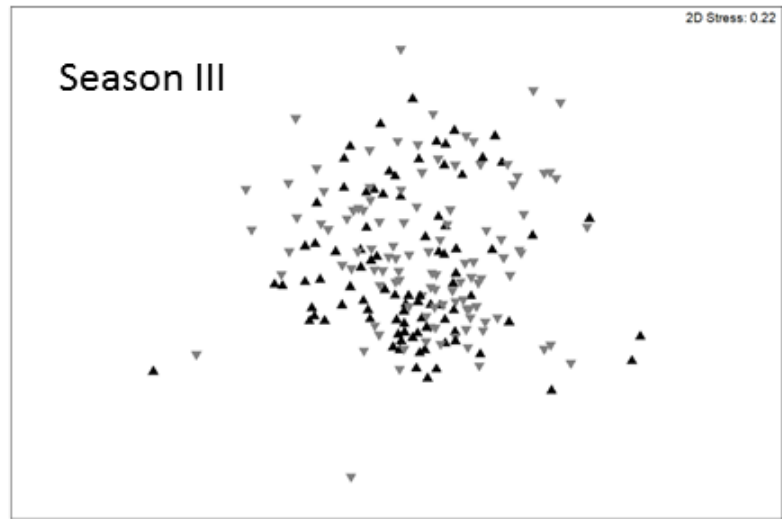Season I — 2D Stress: 0.22

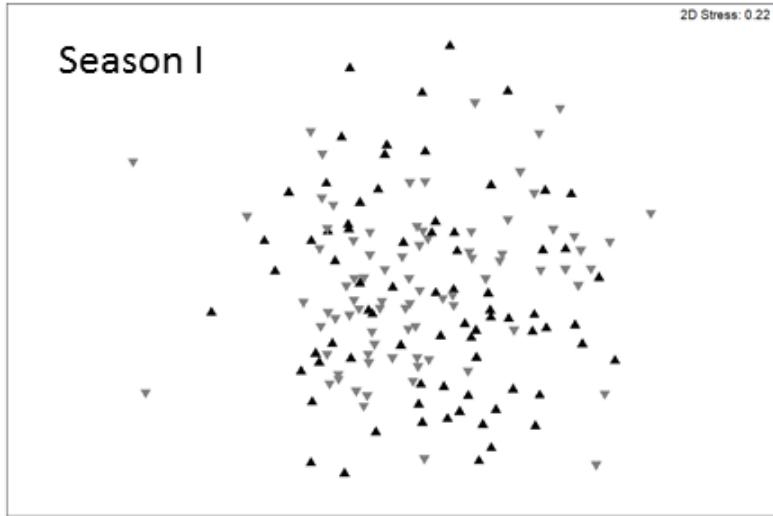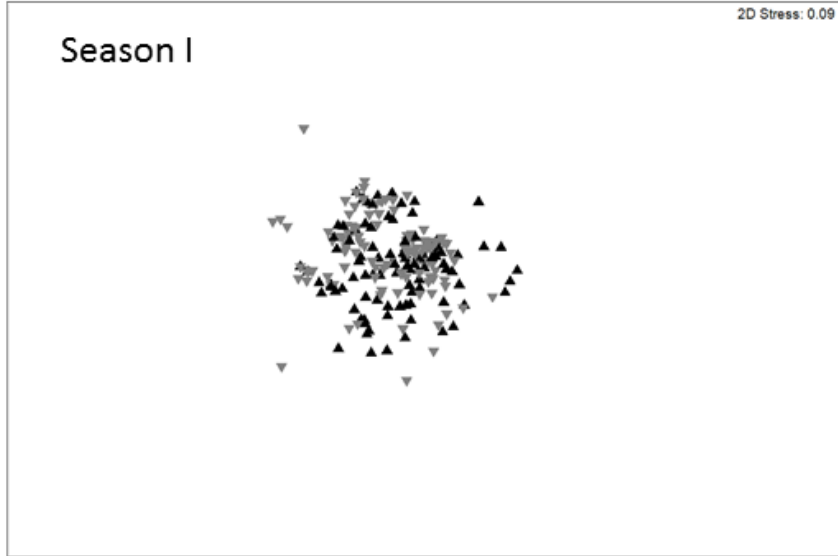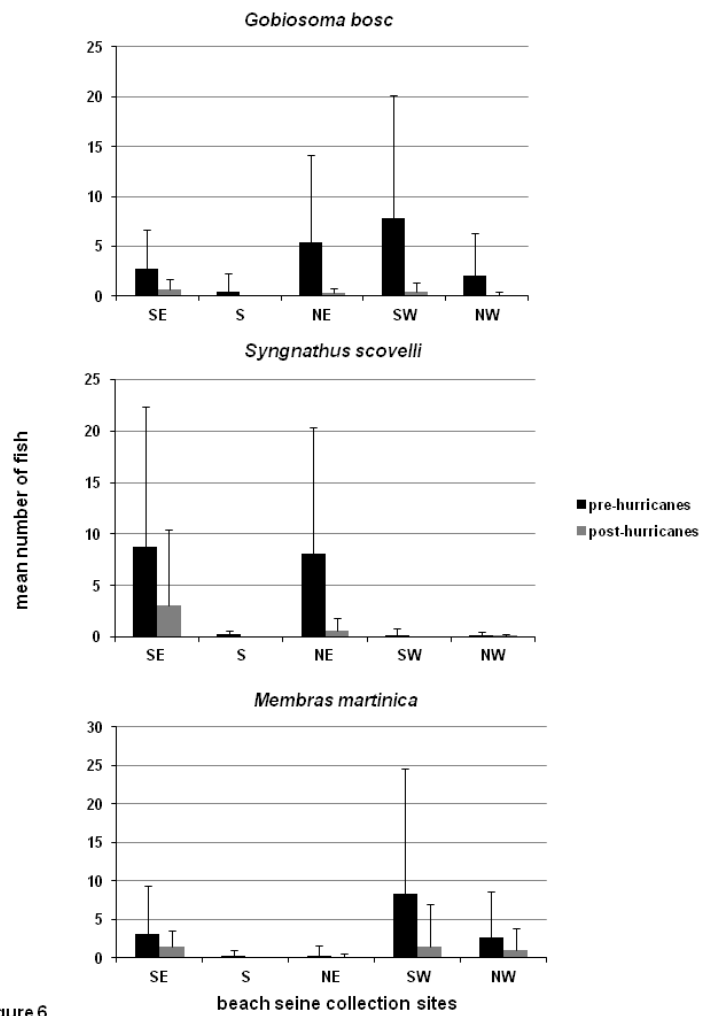Season II — 2D Stress: 0

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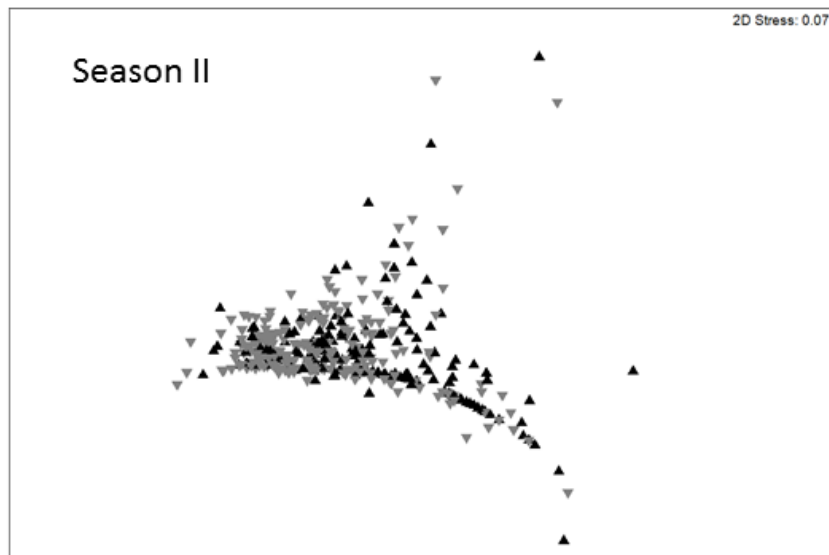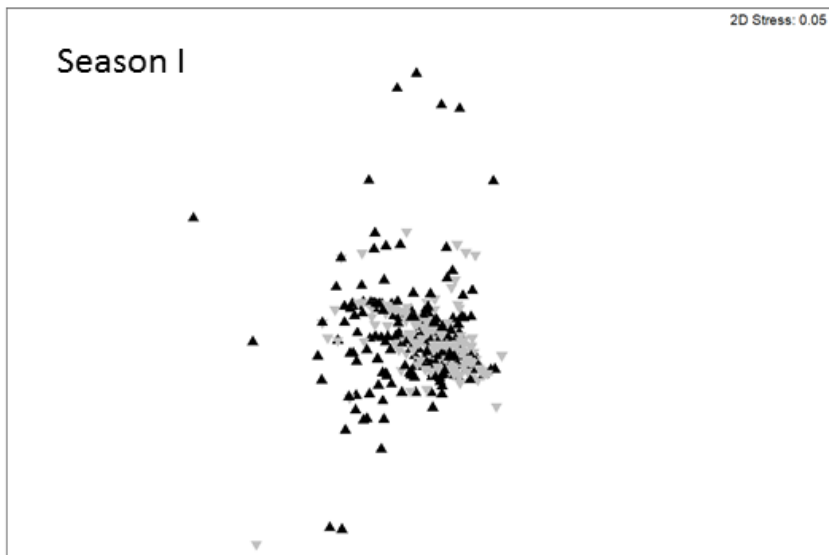
Figure 3

Figure 4

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Figure 5

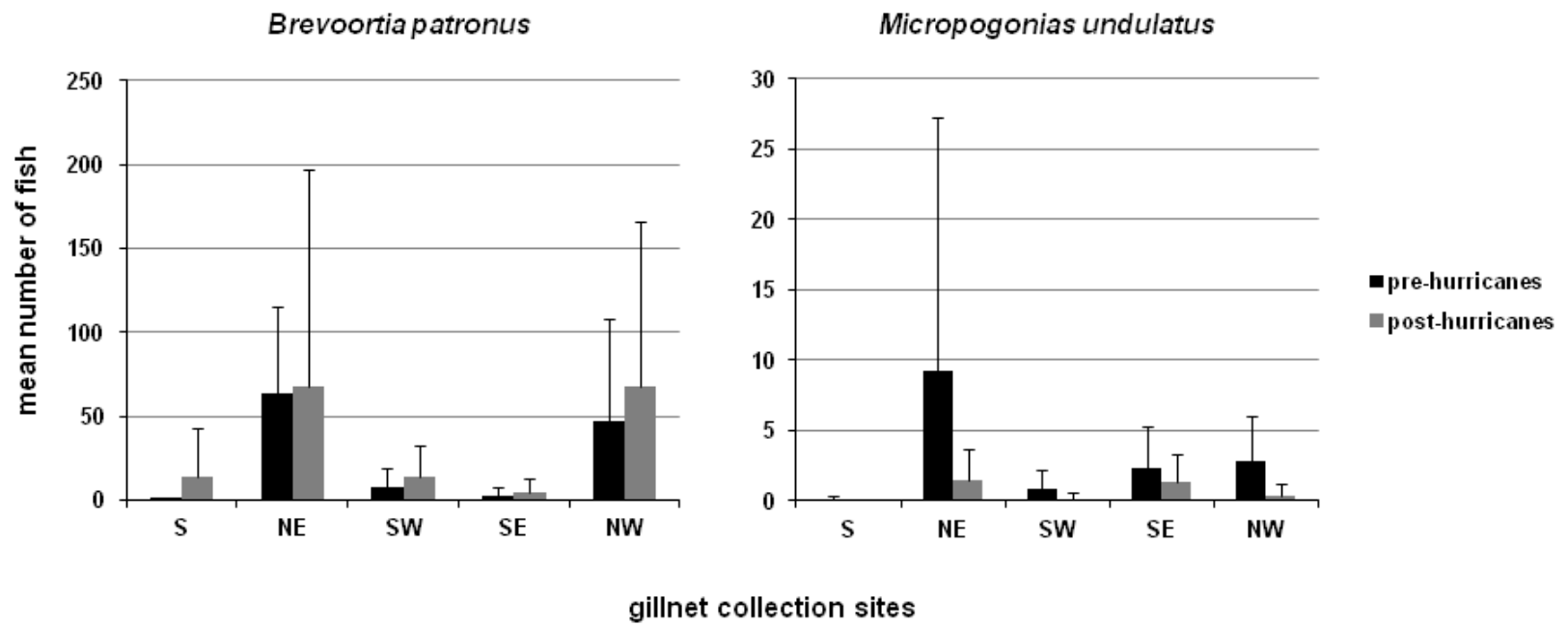744
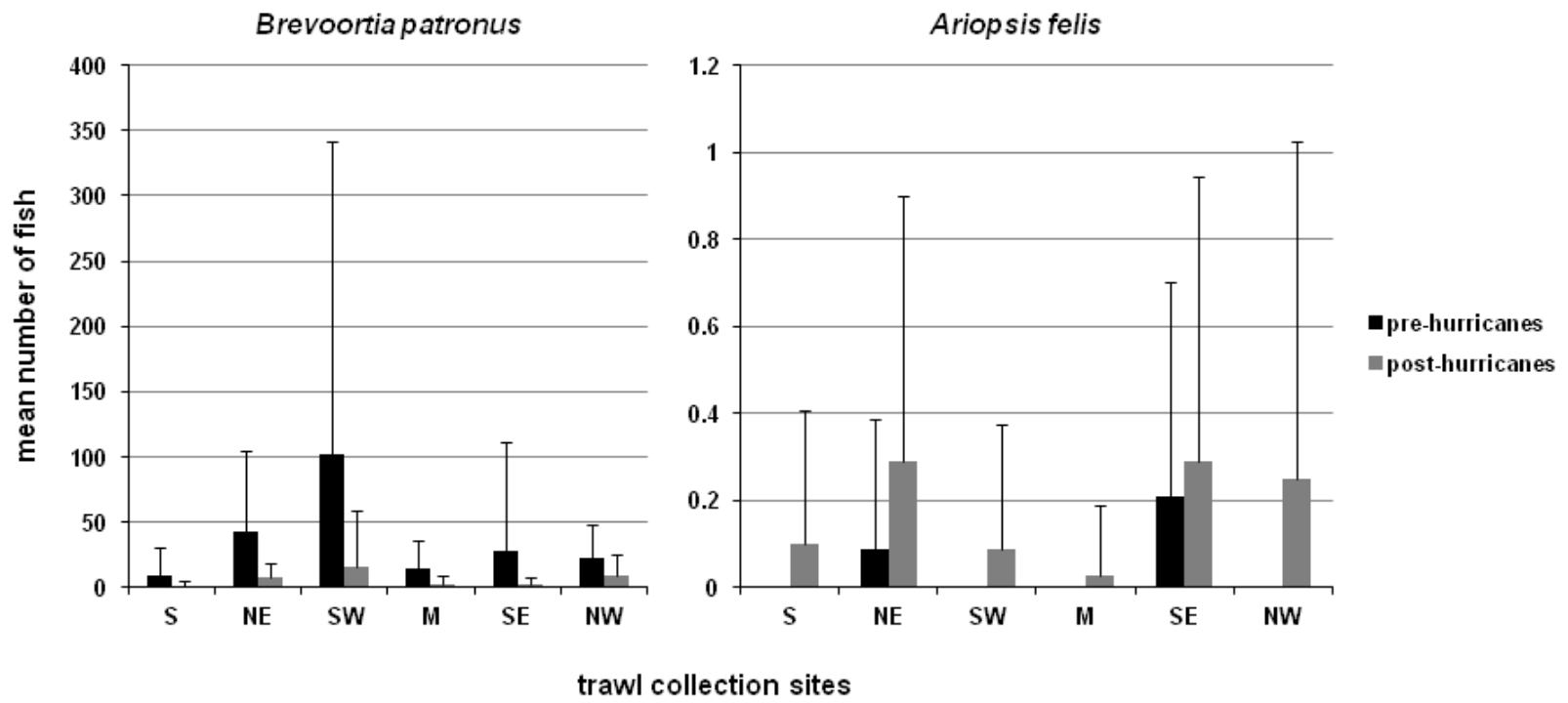
Figure 6

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Brevoortia patronus — *Micropogonias undulatus*

Figure 7 part 1

Figure 7 part 2

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