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Oil and Gas Platforms on Ship Shoal, Northern Gulf of Mexico as Habitat for Reef-Associated Organisms

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OIL AND GAS PLATFORMS ON SHIP SHOAL, NORTHERN GULF OF MEXICO, AS HABITAT FOR REEF-ASSOCIATED ORGANISMS

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ABSTRACT

Nearshore Louisiana has experienced substantial changes within the last half-century, including the annual formation of the world's second largest hypoxic zone and the construction of thousands of oil and gas platforms (rigs). Ship Shoal and its rigs may provide important substrate in nearshore Louisiana because rigs act as *de facto* artificial reefs and the shoal's bottom waters were well oxygenated on 43% of days when surrounding areas were hypoxic. From July to September of 2014, fish assemblages and hydrography were compared at shoal rigs, rigs inshore of the shoal, and rigs offshore of the shoal, and stone crab populations were compared at rigs on and off the shoal. A camera array and YSI sonde were used to characterize fish assemblages and hydrography at shoal rigs, rigs inshore, and offshore of the shoal. Stone crab densities were estimated with visual counts, and their life history was characterized by removing a subsample of stone crabs for identification and measurements. Fish assemblage composition was significantly different between shoal rigs, rigs inshore, and rigs offshore of the shoal ($P<0.05$). The most notable difference between assemblages was greater contribution of demersal fishes at shoal rigs than rigs inshore and offshore of the shoal. Hypoxia was intermittent at shoal rigs and persistent at rigs inshore and offshore of the shoal. Mean hypoxia thickness (meters of hypoxic water) was significantly greater ($P<0.05$) at rigs inshore (2.6 m) and offshore of the shoal (3.1 m) than it was at shoal rigs (0.6 m). Crab densities were roughly twice as high on as they were off the shoal (mean 4.0 vs. 1.8 stone crabs/m^2; $P<0.05$), and the carapace width where 50% of females were ovigerous was 26.4 mm smaller for females off than on the shoal ($P=0.057$). Shoal rigs and rigs in surrounding waters provide important substrate for reef-associated organisms, although higher contribution of demersal fishes and densities of SCs at shoal rigs than rigs in surrounding waters suggest that shoal rigs are of higher relative

importance. These findings suggest that further mining of Ship Shoal and removal of rigs may be detrimental to reef-associated organisms in nearshore Louisiana.

CHAPTER 1: INTRODUCTION

1.1 Introduction

The Mississippi River watershed drains 41% of the contiguous United States (Turner and Rabalais 1991), and discharges into the northern Gulf of Mexico (nGOM) where it has formed vast coastal wetlands and its nutrient-rich waters drive primary and secondary productivity. These factors form the basis of Louisiana's fisheries production, which accounted for 73.8% (10.4×10^6 metric tons) of total commercial landings in the Gulf of Mexico 2004 to 2013 (National Marine Fisheries Service 2015). Notably, nutrient loading in the Mississippi River has also been linked to a growing hypoxic zone (dissolved oxygen<2.0 mg/L) in the nGOM (Rabalais et al. 2002).

The nGOM's hypoxic zone occupies an area of 15,100-18,000 km^2 during the spring and summer (Obenour et al. 2013). This zone is the second largest hypoxic zone in the world, and it primarily results from nitrogen loading in the Mississippi River. Nitrogen discharges into the nGOM's stratified shelf waters and stimulates phytoplankton blooms. These blooms senesce and eventually sink to the bottom where they decompose and drive microbial respiration, an oxygen intensive process (Rabalais et al. 2002).

The hypoxic zone occupies a large part of a region important to Louisiana's recreational and commercial fisheries (Rabalais et al. 2006), but fishery landings have mostly remained strong in the midst of this perturbation (Chesney and Baltz 2001). While some changes to community structure are evident, it is difficult to attribute these changes solely to hypoxia because other perturbations may have greater effects on community structure than hypoxia (Chesney et al. 2000) and the effects of fishing are typically first and foremost (Jackson et al. 2001). Moreover, the effects of hypoxia on nekton may be buffered because hypoxic areas in the

nGOM are intermittent and surrounded by well-oxygenated waters that may serve as hypoxia refuges (Chesney and Baltz 2001).

Ship Shoal (SS) and other sandy shoals may serve as hypoxia refuges on the Louisiana shelf because they are shallow features that often maintain normoxic bottom waters within the hypoxic zone (Gelpi et al. 2009). The shoal's high benthic microalgal production (Grippo et al. 2009) and shallow depths may help maintain oxygenated bottom waters when surrounding areas are hypoxic (Gelpi 2012). Blue crabs (*Callinectes sapidus*) and other organisms susceptible to hypoxia may find refuge on SS because of its propensity to maintain oxygenated bottom waters (Gelpi et al. 2009).

Ship Shoal has many oil and gas platforms (rigs) that aggregate reef-associated organisms. Rigs may be ecologically important structures because they act as *de facto* reefs (Stanley and Wilson 1989). Rigs provide substrate for sessile organisms such as barnacles and oysters that in turn provide structural habitat for blennies (Blenniidae), pistol shrimp (Alpheidae), stone crabs (*Mennipe spp*.), and other fouling-associated organisms (Gallaway et al. 1981). Rigs also aggregate large assemblages of reef-associated fishes (Shinn 1974; Stanley and Wilson 1989; Stanley and Wilson 1991). Since there is little naturally-occurring hard substrate in the nGOM (3% of bottom substrate from Pensacola, FL to Pass Cavallo, TX) (Parker et al. 1983), rigs may increase the settlement opportunities for juvenile, reef-associated organisms that might otherwise be lost to the system (Hernandez et al. 2003).

The use of artificial reefs (ARs) for fisheries management is contentious. Artificial reefs are established under the assumption that hard substrate is limiting for a stock and the addition of new hard substrate will result in a larger stock (Bortone et al. 1997). Further evaluation of ARs is needed because they could deplete fisheries by concentrating fishes and making them more

exploitable (Polovina 1991; Grossman et al. 2007), or they could enhance fisheries by providing a limiting substrate. These hypotheses have driven debate on whether ARs benefit or harm fisheries.

The attraction vs. production debate has been a central point of contention for managers and stakeholders of the red snapper (Lutjanus campechanus) fishery in the nGOM (Cowan et al. 2010). Shipp and Bortone (2009) argued that rigs and other ARs have transformed Alabama waters from being relatively unproductive for the red snapper fishery to being one of the most productive areas in the GOM. Although red snapper exhibit low site fidelity, ARs are sometimes net sinks for red snapper (Strelcheck et al. 2007), and red snapper do not derive much nutrition directly from rigs because they primarily feed over soft bottoms (McCawley et al. 2003). These contrasting findings suggest that rigs and other ARs could benefit fisheries in some respect and negatively affect fish production in other respects.

Because small rigs (Figure 1) in the nearshore area of the coast are rapidly being removed from the nGOM, it is important to evaluate their use by fishes and invertebrates and how environmental conditions affect the abundance and species composition at each site. Small rigs (caissons and well protectors) are rapidly being removed from the nearshore coastal zone as oil and gas exploration shifts from shallow to deep-water production (Pulsipher et al. 2001). Small rigs such as caissons and well protectors are under-represented in previous “rig” research, yet they are much more abundant in the coastal zone, especially in nearshore waters (5-25 meters) affected by the hypoxic zone. It is important to examine fish and invertebrate use of these rigs because their vertical dimension provides hard substrate in normoxic waters that may serve as refugia when bottoms are hypoxic.

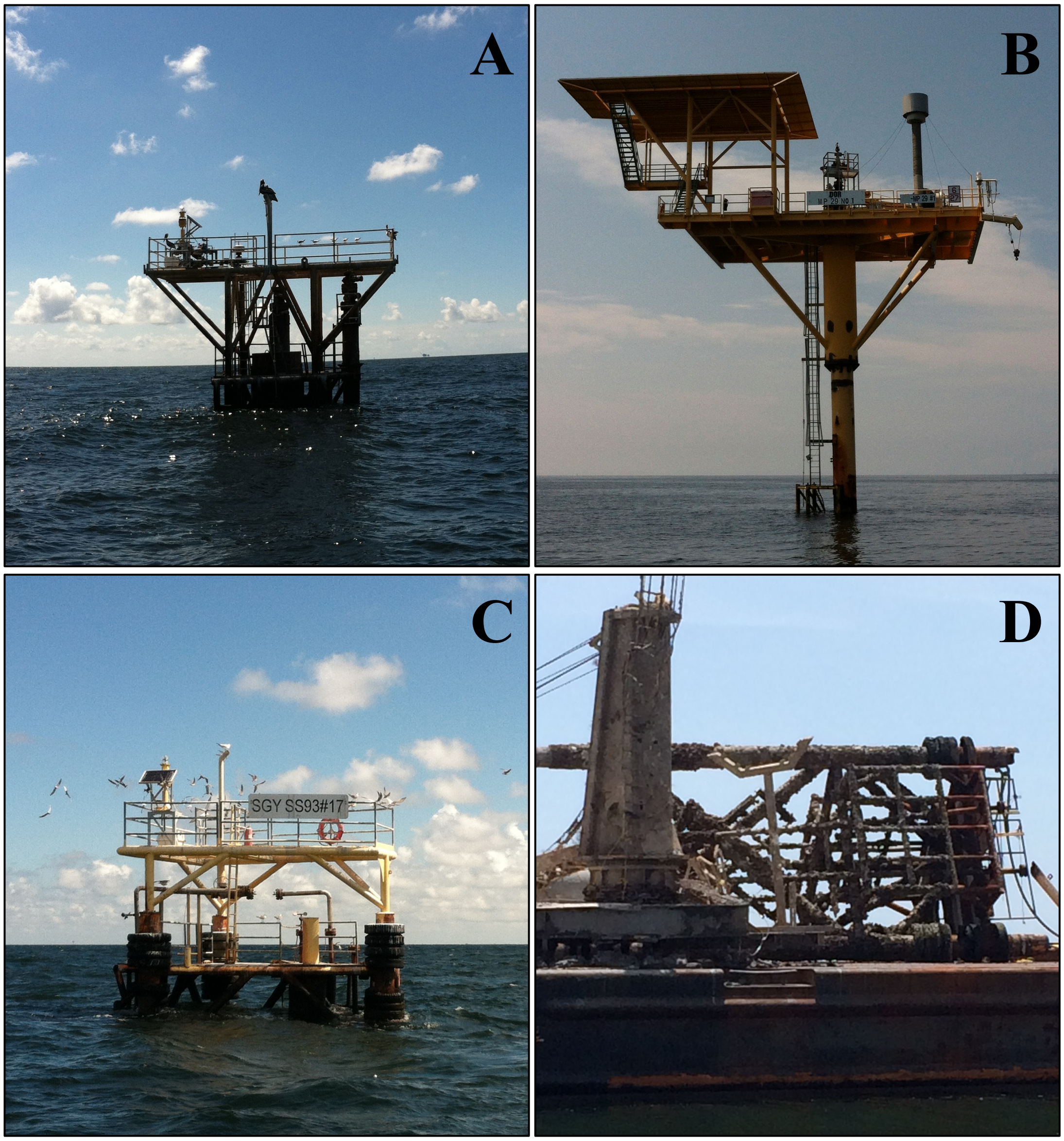

Figure 1: Small, nearshore rigs sampled in this study. Photograph A depicts a well protector, photograph B depicts a caisson, and photographs C and D depict a caisson before (C) and after (D) removal.

In this study, fish assemblages, hydrography, and stone crabs (SC) populations were compared at rigs on and around SS to determine if rigs on the shoal provide higher quality environmental conditions than rigs in surrounding hypoxic waters. Fish assemblages and hydrography were compared at SS rigs (SSR), rigs inshore of the shoal (RIS), and rigs offshore of the shoal (ROS), and SC populations were compared at rigs on and off SS. Fish assemblage and hydrographic samples off SS were categorized as RIS or ROS because preliminary work

suggested that fish assemblages and hydrography differed inshore and offshore of the shoal. Stone crab samples off SS were not divided into inshore and offshore categories because preliminary work indicated that SCs were ubiquitous in the SS region, and sample size was small. The purposes of the chapter 2 were to compare: (1) patterns of diversity between assemblages at SSR, RIS, and ROS, (2) composition of fish assemblages between SSR, RIS, and ROS, and (3) hydrography and hypoxia dynamics between SSR, RIS, and ROS. The purposes of chapter 3 were to compare SC densities and population characteristics at rigs on and off SS.

1.2 Study Area

Ship Shoal is a shallow, submarine body of medium and fine sand off the central Louisiana coast surrounded by deeper waters overlaying silty clay. Ship Shoal is a relict barrier island of the wandering Mississippi River Delta (Penland et al. 1986), located approximately 15 km offshore of the Isle Dernieres. The shoal is approximately 50 km long, ranges from 2-10 km wide (Stone et al. 2004), and water depths range from 2.7-10 m (Penland et al. 1986). From July to September of 2014, stone crabs populations, fish assemblages, and hydrography were characterized at rigs on and around SS. Sampled rigs were small (caissons and well protectors; 1-4 pilings), and 1-54 years old. Ship Shoal rigs were located in depths of 4.4 to 10.3 m, RIS were in water depths of 6.7 to 12.8 m, and ROS were in depths of 10.4 to 16.8 m.

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CHAPTER 2. COMPARISON OF FISH ASSEMBLAGES AT SMALL OIL AND GAS PLATFORMS ON AND AROUND SHIP SHOAL, NORTHERN GULF OF MEXICO

2.1. Abstract

Nearshore Louisiana is a dynamic region that is home to thousands of oil and gas platforms (rigs) and the world's second largest hypoxic zone. Ship Shoal and its rigs may be important habitat types in nearshore Louisiana because its bottom waters were well oxygenated on 43% of days when surrounding areas were hypoxic and rigs function as *de facto* artificial reefs. From July to September of 2014, a camera array and YSI sonde were used to characterize fish assemblages and hydrography at rigs in three locations on and adjacent to the shoal: Ship Shoal rigs (SSR), rigs inshore of the shoal (RIS), and rigs offshore of the shoal (ROS). A one-way PERMANOVA indicated fish assemblages were significantly different among all three sets of rigs ($P<0.05$). SIMPER analysis indicated there was 48.4% dissimilarity for the SSR vs. RIS comparison, 49.0% dissimilarity for the SSR vs. ROS, and 49.6% dissimilarity for the RIS vs. ROS. The most notable differences between assemblages were the larger contributions of demersal fishes at SSR than RIS and ROS, and more brackish-tolerant species at RIS and marine species at ROS. Mean species richness was 10.7 at SSR, 8.6 at RIS, and 9.5 at ROS, but only SSR and RIS differed significantly ($P<0.05$). Mean Shannon-Wiener Indices were 1.2 at SSR, 1.2 at ROS, and 1.3 at ROS, but differences were not significant ($P>0.05$). Hypoxia was intermittent at SSR and persistent at RIS and ROS, and mean thickness of hypoxia was significantly greater ($P<0.05$) at RIS (2.6 m) and ROS (3.1 m) than it was at SSR (0.6 m). Higher contribution of demersal fishes at SSR than RIS and ROS suggests SSR are of higher relative importance for demersal fishes. Over the course of this study, 3.3 million cubic yards of sediment were dredged from Ship Shoal and 17.5% of the studied rigs were removed. Since

many economically and ecologically important species utilize these habitat types, their depletion may have adverse fisheries consequences.

2.2. Introduction

The high productivity of the Fertile Fisheries Crescent, an area spanning from Pascagoula, MS, to Port Arthur, TX (Gunter 1968), is driven by nutrients and sediment from the Mississippi River (Gunter 1968). Louisiana's coast constitutes the bulk of this region, and from 1994 to 2013 accounted for 73.8% (10.4 x 10^6 metric tons) of total commercial fishery landings in the Gulf of Mexico (Data from NMFS Annual Commercial Landing Statistics). The primary productivity coupled with the vast coastal wetlands drive fisheries production of the region.

Over the last half-century, increasing nutrient loadings in the Mississippi River have caused the expansion of a large hypoxic zone (dissolved oxygen < 2.0 mg/L) in the northern Gulf of Mexico (nGOM) (Rabalais et al. 2002). The nGOM's hypoxic zone occupies an area of 15,100-18,000 km^2 during spring and summer (Obenour et al. 2013). This is the second largest hypoxic zone in the world, and it is fueled by nitrogen in the Mississippi River that discharges into the nGOM's stratified shelf waters and stimulates phytoplankton blooms. These blooms senesce and eventually sink to the bottom where they decompose and drive microbial respiration, an oxygen intensive process (Rabalais et al. 2002).

The hypoxic zone occupies a large part of a region important to Louisiana's recreational and commercial fisheries (Rabalais et al. 2006), but fishery landings have mostly remained strong in the midst of this perturbation (Chesney and Baltz 2001). While some changes to community structure are evident, it is difficult to attribute these changes solely to hypoxia because other perturbations may have greater effects on community structure than hypoxia (Chesney et al. 2000) and the effects of fishing are typically foremost (Jackson et al. 2001).

Moreover, the effects of hypoxia on nekton may be buffered because hypoxic areas in the nGOM are intermittent and surrounded by well-oxygenated waters that may serve as hypoxia refuges (Chesney and Baltz 2001).

Ship Shoal (SS) and other sandy shoals may serve as hypoxia refuges on the Louisiana shelf because they are shallow features that maintain normoxic bottom waters within the hypoxic zone (Gelpi et al. 2009). The shoal's high benthic microalgal production (Grippo et al. 2009) and shallow depths may help maintain oxygenated bottom waters when surrounding areas are hypoxic (Gelpi 2012). Blue crabs (*Callinectes sapidus*) and other organisms susceptible to hypoxia may find refuge on SS because of its propensity to maintain oxygenated bottom waters (Gelpi et al. 2009).

Ship Shoal has many oil and gas platforms (rigs) that attract assemblages of reef-associated fishes. Rigs are *de facto* artificial reefs for a variety of marine species (Stanley and Wilson 1989), and are ecologically important habitat types within the nGOM (Hernandez et al., 2003; Gallaway et al. 2009). Artificial reefs (ARs) can increase fishery production when they provide hard substrate where it is limited (Bull and Kendall 1994; Bortone et al. 1997; Beck 1997), but they may also enhance fisheries exploitation by concentrating fishes and making them more susceptible to fishing (Polovina 1991). The debate of over whether ARs attract or produce fishes is a major point of contention for fisheries management in the nGOM, especially for the red snapper (*Lutjanus campechanus*) fishery (Shipp and Bortone 2009; Cowan et al. 2010).

Because small rigs in the nearshore area of the coast are rapidly being removed from the nGOM, it is important to evaluate their use by fishes and invertebrates and how environmental conditions affect the abundance and species composition at each site. Small rigs (caissons and well protectors) are rapidly being removed from the nearshore coastal zone as oil and gas

exploration shifts from shallow to deep-water production (Pulsipher et al. 2001). Small rigs such as caissons and well protectors are under-represented in previous “rig” research, yet they are much more abundant in the coastal zone, especially in nearshore waters (5-25 meters) affected by the hypoxic zone. It is important to examine fish and invertebrate use of these rigs because their vertical dimension provides hard substrate in normoxic waters that may serve as refugia when bottoms are hypoxic.

The objective of this research was to compare fish assemblages and water quality at small rigs on and around SS to determine the relative importance of small rigs for reef associated fishes. The data were analyzed to compare: (1) assemblages diversity, (2) assemblage composition, and (3) hydrography at Ship Shoal rigs (SSR), rigs inshore of the shoal (RIS), and rigs offshore of the shoal (ROS).

2.2.1 Study Area

Ship Shoal is a relict barrier island of the wandering Mississippi River Delta located in the northern Gulf of Mexico off the coast of Louisiana. The shoal is a high relief body of medium and fine quartz sand that is surrounded by deeper waters that overlay silty clay (Penland et al. 1986). From July to September of 2014, fish assemblages and hydrography were sampled on and around SS (Figure 1). SSR were located in depths of 4.4 to 10.3 m, RIS were in water depths of 6.7 to 12.8 m, and ROS were in depths of 10.4 to 16.8 m. Sampled rigs were small (caissons and well protectors; 1-4 pilings) and 1-54 years old. Hydrography was dynamic throughout the study region from July to September of 2014, with a salinity range of 18.7-35.5 PSU, a temperature range off 23.3-31.7ºC, a dissolved oxygen range of 0.1-7.5 mg/L, and a Secchi range of 99-1,160 cm (Table 1).

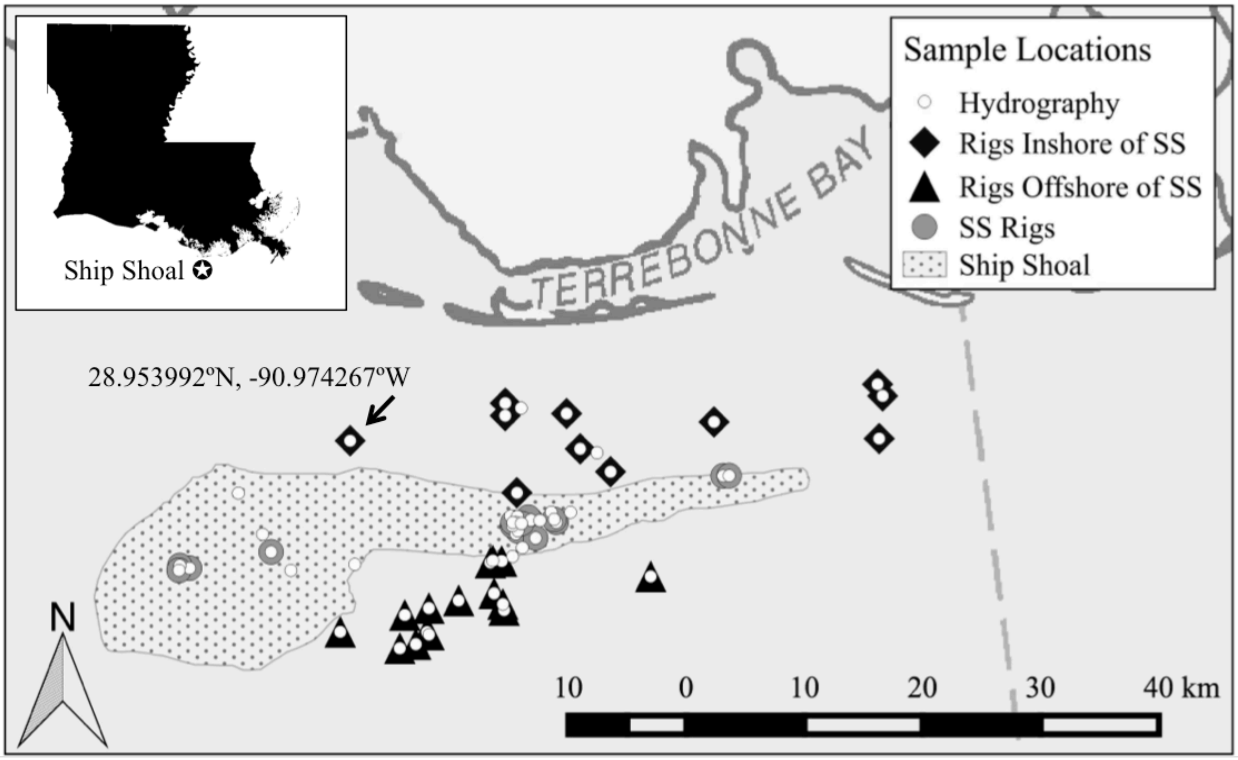


Figure 1: Sampling locations during the summers of 2014. Diamond, triangle, and solid circle markers denote individual rigs where fish assemblages were sampled once. White circle markers denote the approximate location where hydrography was sampled on one or more occasions. The dotted area is the approximate location of Ship Shoal falling within the 10 m bathymetric zone.

2.3. Methods

2.3.1. Pilot Study

From July to September of 2013, a pilot study was conducted on and around SS. The purpose of the pilot study was to fine-tune the deployment of the camera array and to build a baseline of hydrographic data. A total of 18 samples of fish assemblages and 51 hydrographic profiles were collected. Mean species richness was 6.8±1.46 at SSR, 6.5±1.67 (95% CIs) at RIS, and no fish assemblage samples were collected at ROS. Hydrography was dynamic throughout the region with salinity from 7.8 to 34.1 PSU, temperature from 26.3 to 31.4°C, dissolved oxygen from 0.2 to 10.1 mg/L, and Secchi from 45.06 to 843 cm. Additionally, SS sediments were blanketed by bottom hypoxia during 3 of 8 sampling trips. Fish assemblage data were not

used in a formal statistical analysis because sample size was small, no samples were collected at ROS, and video quality was marginal due to turbid waters. Hydrographic data from 2013 was used to help resolve hydrographic variables into factors.

Table 1: Environmental conditions (mean±2SE, range) at Ship Shoal rigs, rigs inshore of the shoal, and rigs offshore of the shoal from July to September of 2014.

	SSR Mean±2SE (range)	RIS Mean±2SE (range)	ROS Mean±2SE (range)
Surface Temperature (ºC)	30.4±0.20 (29.3-31.7)	30.9±0.48 (29.5-32.1)	30.7±0.16 (30.0-31.4)
Midwater Temperature (ºC)	29.7±0.27 (28.3-31.0)	29.7±0.45 (28.1-31.1)	28.9±0.31 (27.9-30.2)
Bottom Temperature (ºC)	28.47±0.50 (24.2-31.2)	28.0±1.15 (24.2-30.1)	26.0±0.67 (23.3-29.3)
Surface Salinity (PSU)	24.1±1.10 (18.7-30.0)	24.8±1.74 (18.8-28.5)	24.2±1.13 (20.0-29.4)
Midwater Salinity (PSU)	27.6±0.69 (22.5-31.6)	28.9±0.90 (26.7-33.5)	31.3±0.59 (28.7-33.8)
Bottom Salinity (PSU)	30.86±0.66 (25.3-35.5)	32.1±1.33 (27.8-35.2)	34.2±0.29 (32.1-35.2)
Surface D.O. (mg/L)	7.3±0.22 (6.4-8.7)	8.0±0.88 (6.4-12.2)	7.1±0.14 (6.46-7.9)
Midwater D.O. (mg/L)	6.2±0.53 (0.2-7.3)	5.7±1.04 (1.8-8.4)	5.3±0.67 (1.79-7.0)
Bottom D.O. (mg/L)	4.3±0.80 (0.1-7.3)	2.8±1.37 (0.2-7.5)	0.8±0.45 (0.1-3.7)
Secchi (cm)	441.2±73.42 (150-823)	428.2±118.16 (99-726)	587.1±128.48 (167-1160)
Depth (m)	7.7±0.36 (4.4-10.3)	9.9±0.84 (6.7-12.8)	14.0±0.84 (10.4-16.8)
Sample Size	n=38	n=14	n=23

2.3.2. Field Sampling

Fish assemblages were sampled using a triangular prism-shaped camera array, consisting of four GoPro™ Hero III cameras, two lasers, and a depth gauge (Figure 2). Three cameras faced outward, and provided a 360° view surrounding the video array. The fourth camera faced down to provide a view of the depth gauge and bottom substrate. The two outward, parallel lasers were mounted atop the array to estimate the lengths of observed fishes. Cameras were synchronized using a GoPro-Wifi Remote. The camera array was lowered and raised 3.0±0.20 m (95% CI) from the rig at a rate of 0.23±0.02 m/s (95% CI).

Figure 2: The triangular prism shaped camera array used to sample fish assemblages.

During 2013 and 2014, 126 hydrographic samples (51 during 2013, 75 during 2014) were collected using a YSI 6820 V2 Sonde and a 20 cm Secchi disk. The sonde recorded depth (m), dissolved oxygen (mg/L), salinity (PSU), and temperature (ºC) at two-second intervals. The sonde was slowly lowered at a rate of 0.04±0.0037 m/s (95% CI). The Secchi depths were measured (cm) using standard methods (Sandén and Håkansson 1996). The YSI sonde was calibrated every two weeks using the manufacturers specifications (YSI Incorporated 2012).

2.3.3. Video Estimation and Statistical Analyses of Fish Assemblages

Assumptions for all univariate and multivariate tests were evaluated, and with the exception of the one-way ANOVA of species richness, none were detected. An alpha of 0.05 was used for statistical comparisons and the measure of dispersion was one standard error unless

otherwise noted. Sample visibility was considered to be adequate for analysis when the submerged portion of the rig was visible in video footage. Since the camera array was lowered 3.0±0.20 m (95% CI) from the rig, visibility of 2.80-3.20 m was the visibility criterion. Seven samples with poor visibility were excluded from the analyses to avoid biases (Gledhill et al. 1996; Bacheler et al. 2013), leaving forty-two independent samples (15 at SSR, 11 at RIS, 16 at ROS) from rigs that met the criterion.

The maximum number of a species occurring simultaneously in a single frame (MAXNO; Ellis and De Martini 1995) was used in the statistical analyses for each species occurring more than once in the video data set (Wells and Cowan 2007; and see Bacheler et al. 2013). MAXNO provides an estimate of relative abundance and prevents counting the same fishes multiple times (Willis and Babcock 2000), and is analogous to MAX (Willis and Babcock 2000) and MIN (Wells and Cowan 2007). All fishes recorded on video were identified, and their relative abundances were estimated with the MAXNO protocol.

MAXNOs were fourth-root transformed to down-weight abundant species and used to compare the composition of fish assemblages in different locations (SSR, RIS, ROS) with a series of non-parametric and permutation procedures (PRIMER 6). A Bray-Curtis similarity matrix was calculated using MAXNOs to determine similarities among assemblages at each rig. The Bray-Curtis similarity matrix was then used to evaluate the effect of location (one-way Permutational MANOVA; Anderson 2001). A Bonferroni adjusted α of 0.017 (0.05/3) was used for *post-hoc* comparisons of all possible pairwise combinations (Day and Quinn 1991). The SIMPER (Similarity Percentages; Clarke 1993) procedure was used to determine which species contributed the most to assemblage dissimilarities.

Species richness and Shannon-Wiener indices (H') were used to compare diversity across locations. Species richness was calculated by counting the number of species present at each rig and H' was calculated as:

$$H' = - \Sigma_i \rho_i \, log(\rho_i)$$

where ρ_i is the proportion of individuals from the i^{th} species to the total number of individuals present (Shannon 1948). H' and species richness were tested to determine the effects of location (one-way factorial ANOVA, Proc Glimmix in SAS 9.4). Heteroscedasticity was detected for the test of species richness, so degrees of freedom were corrected with a Satterthwaithe adjustment and variances were estimated separately (SAS Institute 2008). A Tukey-Kramer adjustment was used in *post-hoc* comparisons of all possible pairwise combinations for H' (Day and Quinn 1991). Dunnett's T3 method was used in all possible pairwise comparisons of species richness (Dunnett 1980).

2.3.4. Analyses of Hydrographic Data

A Factor analysis (FA) was used to resolve 126 hydrographic measurements into four orthogonal variables based on a correlation matrix with a Varimax rotation (Proc Factor in SAS 9.4). Variables included in the FA were surface temperature (°C), midwater temperature (°C), bottom temperature (°C), surface salinity (PSU), midwater salinity (PSU), bottom salinity (PSU), depth (m), Secchi depth (cm), surface D.O. (mg/L), midwater D.O. (mg/L), and bottom D.O. (mg/L). Variable loadings >|0.5| were used to characterize factors. Factor scores were calculated for each sample and used to calculate centroids of the three locations in 2014: SSR, RIS, and ROS. Diameters of plotted centroid balloons equaled two standard errors and were estimated by calculating the mean standard error for the first three FA axes. Finally, hydrography of the three locations was represented graphically by plotting centroids in three-dimensional environmental

space using F1, F2, and F3. Hydrographic samples from 2013 and 2014 were used to resolve primary axes of variation, but only samples from 2014 were plotted.

Hypoxia thickness (meters of water with dissolved oxygen <2.0 mg/L) was tested to determine the effect of location during 2014 (one-way ANOVA, Proc Glimmix in SAS 9.4). Location (SSR, RIS, ROS) was a fixed effect and sampling date was included in the model as a random block effect. The model was fitted with a Poisson response distribution. A Tukey-Kramer adjustment was used in *post-hoc* comparisons of all possible pairwise combinations (Day and Quinn 1991).

2.4. Results

2.4.1. Analyses of Assemblages

Twenty-seven species representing fifteen families were observed on video (Table 2). Hook and line sampling and diver observations corroborated video observations that *Seriola dumerili* and *Seriola rivoliana* were juveniles. Age-0 *Lutjanus synagris* and Age-0 *Lutjanus campechanus* were pooled as Age-0 *Lutjanus spp.*, because it was difficult to distinguish between them on video. All other fishes were identified to the species level.

One-way Permutational MANOVA (PERMANOVA) of assemblage structure found a significant location effect (Pseudo-$F_{(2,39)}$ =4.00, P=0.001), and all three locations were significantly different (P<0.017). Assemblage composition at SSR was significantly different from RIS (Pseudo-t=1.69, P=0.009) and ROS (Pseudo-t=2.44, P=0.008), and RIS and ROS were significantly different from each other (Pseudo-t=1.69, P=0.009).

Many species contributed to the dissimilarity between assemblages across locations (Figure 3; Table 3). Mean dissimilarity was 48.4% for SSR vs. RIS, 49.0% for the SSR vs. RIS, and 49.6% for the RIS vs. ROS. *Chloroscombrus chrysurus* and *Pomatomus saltatrix* accounted

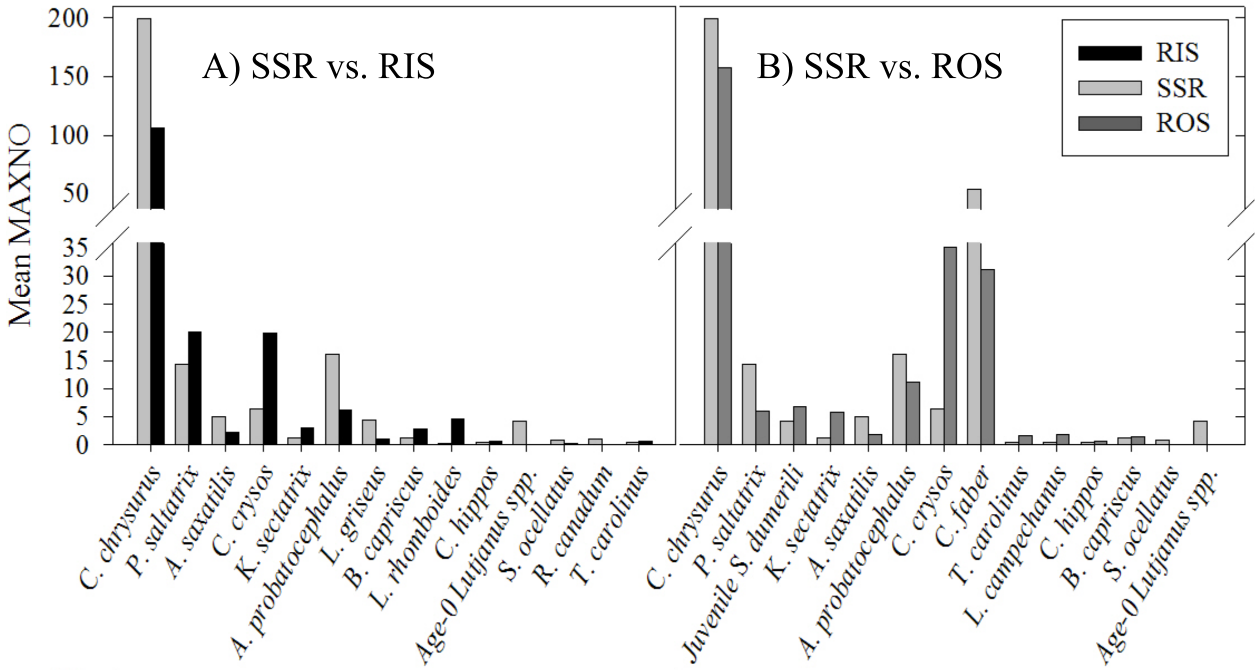
for the greatest amount of dissimilarity in all three pairwise comparisons of assemblage composition. Nevertheless *C. chrysurus* did not consistently contribute to dissimilarity between RIS and ROS because its dissimilarity/SD ratios was 1.00, and only ratios > 1 consistently contribute (Clarke and Warwick 2001).

Table 2: Species identified on video. Occurrences represent the number and percentage of samples where a species was present at Ship Shoal rigs (SSR), rigs inshore of SS (RIS), and rigs offshore of SS (ROS).

Common Name	Taxon	Demersal or Pelagic	Incidence SSR	Incidence RIS	Incidence ROS
Atlantic spadefish	*Chaetodipterus faber*	Demersal	16 (100%)	11 (100%)	15 (100%)
Blue runner	*Caranx crysos*	Pelagic	15 (94%)	9 (82%)	15 (100%)
Grey snapper	*Lutjanus griseus*	Demersal	16 (100%)	7 (64%)	14 (93%)
Sheepshead	*Archosargus probatocephalus*	Demersal	15 (94%)	10 (91%)	11 (73%)
Grey triggerfish	*Balistes capriscus*	Demersal	11 (69%)	8 (73%)	10 (67%)
Bermuda chub	*Kyphosus sectatrix*	Demersal	8 (50%)	7 (64%)	10 (67%)
Sergeant major	*Abudefduf saxatilis*	Demersal	12 (75%)	5 (45%)	6 (40%)
Atlantic bumper	*Chloroscombrus chrysurus*	Pelagic	11 (69%)	4 (36%)	6 (40%)
Bluefish	*Pomatomus saltatrix*	Pelagic	8 (50%)	7 (64%)	5 (33%)
Crevalle jack	*Caranx hippos*	Pelagic	2 (13%)	5 (55%)	8 (53%)
Florida pompano	*Trachinotus carolinus*	Demersal	5 (31%)	3 (27%)	8 (53%)
Greater amberjack	Age-0 *Seriola dumerili*	Pelagic	3 (19%)	0	10 (67%)
Red snapper	*Lutjanus campechanus*	Demersal	6 (38%)	1 (9%)	6 (40%)
Red drum	*Sciaenops ocellatus*	Demersal	9 (56%)	1 (9%)	1 (7%)
Cobia	*Rachycentron canadum*	Pelagic	7 (44%)	1 (9%)	1 (7%)
Rainbow runner	*Elagatis bipinnulata*	Pelagic	0	3 (27%)	4 (27%)
Pinfish	*Lagodon rhomboides*	Demersal	3 (19%)	4 (36%)	0
-	Age-0 *Lutjanus spp.*	Demersal	6 (38%)	1 (9%)	0
Atl. Spanish Mackerel	*Scomberomorus maculatus*	Pelagic	0	2 (18%)	5 (33%)
Ladyfish	*Elops saurus*	Pelagic	4 (25%)	1 (9%)	1 (7%)
Lookdown	*Selene vomer*	Demersal	6 (38%)	0	0
Black drum	*Pogonias cromis*	Demersal	4 (25%)	0	1 (7%)
Yellow jack	*Carangoides bartholomaei*	Pelagic	2 (13%)	0	2 (13%)
Lane snapper	*Lutjanus synagris*	Demersal	3 (19%)	1 (9%)	0
Striped mullet	*Mugil cephalus*	Pelagic	2 (13%)	2 (18%)	0
Almaco jack	Age-0 *Seriola rivoliana*	Pelagic	0	1 (9%)	3 (20%)
Southern stingray	*Dasyatis americana*	Demersal	3 (19%)	0	0
Bull shark	*Carcharhinus leucas*	Demersal	1 (6%)	0	0

Table 3: Three pair wise comparisons by location of species that accounted for a cumulative 75% of between assemblage dissimilarity (diss). MAXNOs are the means for each species ± one standard error. Diss/SD is the species' ratio of mean percent dissimilarity to its standard deviation. Mean percent dissimilarity represents the species' contribution to between location dissimilarity.

Comparison	Taxon	Mean MAXNO	Mean MAXNO	Diss / SD	Mean Diss (%)
		SSR	**RIS**		
SSR	*Chloroscombrus chrysurus*	199.31±66.23	106.09±49.35	1.21	7.27
vs.	*Pomatomus saltatrix*	14.38±5.62	20.09±12.93	1.31	3.98
RIS	*Abudefduf saxatilis*	5.00±1.73	2.18±1.07	1.27	2.79
(48.41%)	*Caranx crysos*	6.44±0.95	19.91±9.68	1.52	2.78
	Kyphosus sectatrix	1.31±0.54	3.09±1.14	1.19	2.45
	Archosargus probatocephalus	16.13±3.22	6.18±2.24	1.28	2.43
	Lutjanus griseus	4.44±1.26	1.00±0.27	1.05	2.14
	Balistes capriscus	1.19±0.26	2.91±0.97	1.16	2.07
	Lagodon rhomboides	0.25±0.14	4.55±2.83	0.81	2.02
	Caranx hippos	0.44±0.33	0.73±0.27	1.07	1.89
	Age-0 Lutjanus spp.	4.31±2.54	0.09	0.76	1.86
	Sciaenops ocellatus	0.81±0.23	0.09	1.10	1.78
	Rachycentron canadum	1.00±0.37	0.09	0.90	1.74
	Trachinotus carolinus	0.44±0.18	0.73±0.43	0.86	1.58
		SSR	**ROS**		
SSR	*Chloroscombrus chrysurus*	199.31±66.23	157.60±79.39	1.30	7.42
vs.	*Pomatomus saltatrix*	14.38±5.62	6.07±3.19	1.07	3.15
ROS	*Juvenile Seriola dumerili*	4.31±2.54	6.80±2.84	1.19	2.94
(49.02%)	*Kyphosus sectatrix*	1.31±0.54	5.87±1.90	1.24	2.73
	Abudefduf saxatilis	5.00±1.73	1.87±0.91	1.30	2.72
	Archosargus probatocephalus	16.13±3.22	11.27±2.56	1.07	2.58
	Caranx crysos	6.44±0.95	35.07±7.97	1.33	2.50
	Chaetodipterus faber	53.69±6.15	31.27±7.22	1.21	2.13
	Trachinotus carolinus	0.44±0.18	1.67±0.53	1.10	1.99
	Lutjanus campechanus	0.50±0.18	1.87±1.03	0.97	1.84
	Caranx hippos	0.44±0.33	0.73±0.21	1.07	1.78
	Balistes capriscus	1.19±0.26	1.47±0.41	1.04	1.77
	Sciaenops ocellatus	0.81±0.23	0.07	1.10	1.72
	Age-0 Lutjanus spp.	4.31±2.54	0	0.70	1.71
		RIS	**ROS**		
RIS	*Chloroscombrus chrysurus*	106.09±49.35	157.60±79.39	1.00	6.58
vs.	*Pomatomus saltatrix*	20.09±12.93	6.07±3.19	1.20	4.15
ROS	*Caranx crysos*	19.91±9.68	35.07±7.97	1.52	4.01
(49.64%)	*Juvenile Seriola dumerili*	0	6.80±2.84	1.20	3.50
	Archosargus probatocephalus	6.18±2.24	11.27±2.56	1.40	2.94
	Kyphosus sectatrix	3.09±1.14	5.87±1.90	1.21	2.90
	Abudefduf saxatilis	2.18±1.07	1.87±0.91	1.07	2.49
	Chaetodipterus faber	51.91±10.01	31.27±7.22	1.23	2.41
	Balistes capriscus	2.91±0.97	1.47±0.41	1.13	2.31
	Trachinotus carolinus	0.73±0.43	1.67±0.53	1.06	2.29
	Lutjanus griseus	1.00±0.27	3.20±0.75	1.12	2.13
	Lagodon rhomboides	4.55±2.83	0	0.69	2.01



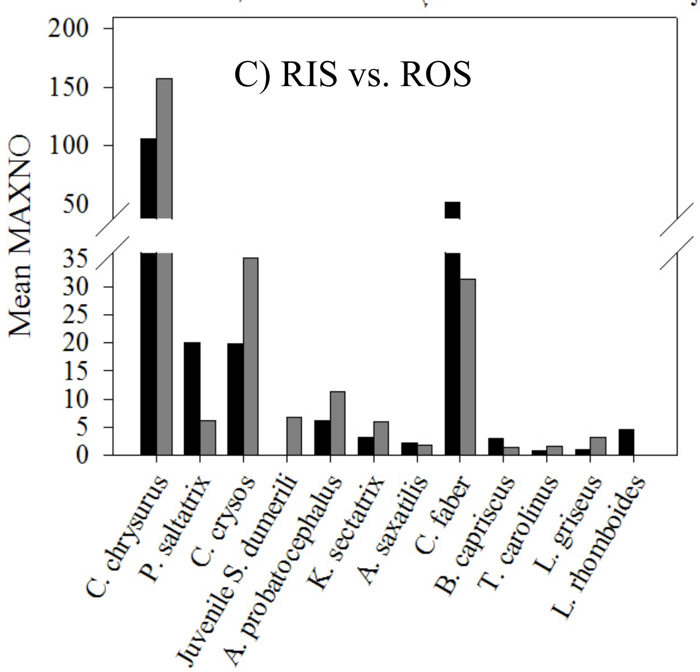


Figure 3: Mean MAXNOs of fishes by location for three pairwise comparisons: Ship Shoal rigs (SSR) vs. rigs inshore of SS (RIS) (A), SSR vs. rigs offshore of SS (ROS (B), and RIS vs. ROS (C). Mean MAXNOs are plotted in order of contribution to dissimilarity and represent fishes contributing to 75% of the dissimilarity for each respective contrast.

Species richness was significantly higher at SSR than RIS ($P<0.05$), but there were no other significant differences of species richness or H’ across locations ($P>0.05$). Mean H’ was 1.20 at SSR, 1.33 at RIS, and 1.20 at ROS, and there was no significant location effect (one-way

ANOVA $F_{(2,39)}=0.47$, $P=0.63$; Figure 4a). Mean species richness was 10.69 at SSR, 8.64 at RIS, and 9.53 at ROS, and there was a significant location effect (one-way ANOVA, $F_{(2,39)}=4.95$, $P=0.015$; Figure 4b).

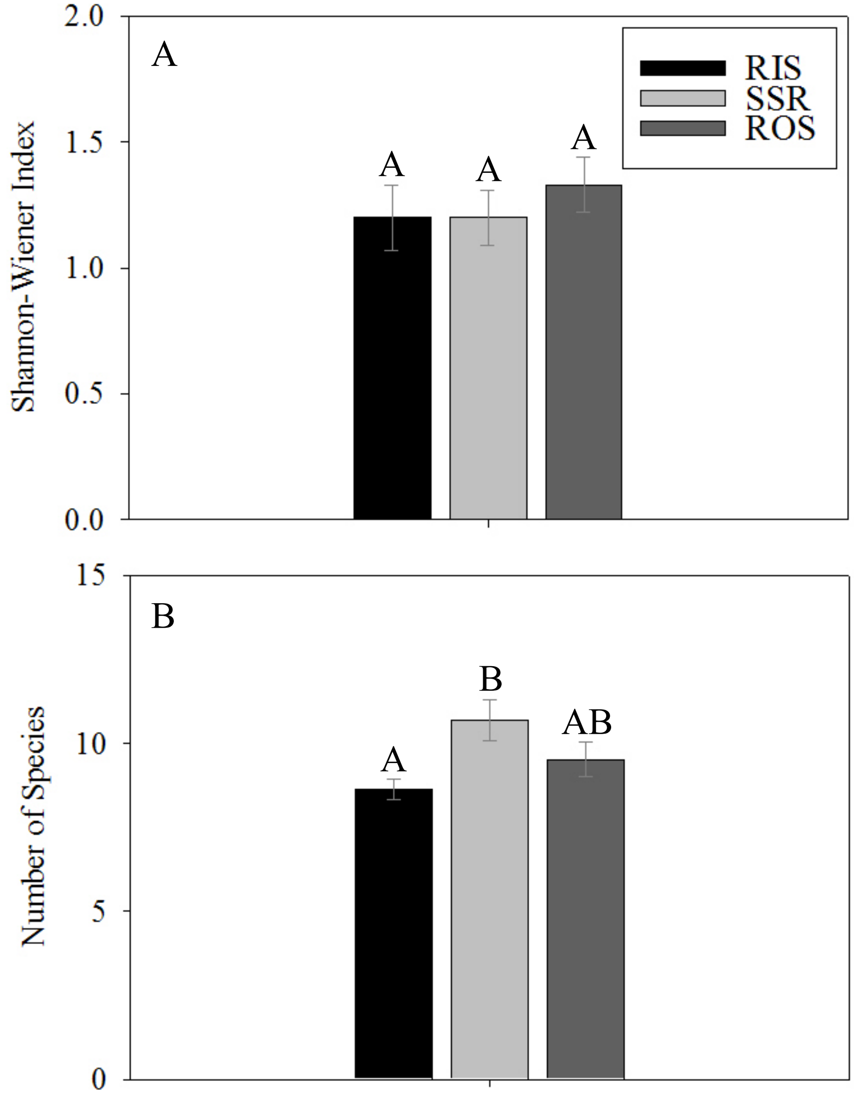


Figure 4: Shannon-Wiener Indices (A) and species richness (B) on Ship Shoal rigs (SSR), rigs inshore of SS (RIS), and rigs offshore at SS (ROS). Error bars represent one standard error, and different letters indicate significant ($P<0.05$) differences (pairwise t-test).

2.4.2. Analyses of Hydrography

The FA generated four factors that explained 81% of the total variation (Table 4). Surface temperature (positive), bottom temperature (negative), bottom salinity (positive), depth

(positive), and bottom D.O. (negative) loaded on F1. Factor 1 was interpreted as a hypoxia gradient because decreasing bottom D.O. was a major contributor to the factor, and increasing surface temperature, decreasing bottom temperature, and increasing bottom salinity are indicative of stratification, a major contributor to hypoxia (Rabalais et al. 2002). Factor 2 loaded positively for surface salinity and Secchi, and negatively for surface D.O. Factor 2 was interpreted as a river influenced gradient because fresh, highly turbid surface waters are associated with river discharge (Rabalais et al. 2001). Midwater temperature and bottom temperature loaded positively, and midwater salinity and depth loaded negatively on F3. Factor 3 was interpreted as a depth gradient because depth contributed to the factor, increasing midwater and bottom temperature are indicative of warm, shallow waters, and decreasing midwater salinity corresponds to shallower waters being fresher. Midwater D.O. loaded positively on F4.

Table 4: Principle component loadings for PCs 1-4, eigenvalues, variation explained by each principal component, and total variation explained by principal components. Principal component loadings reflect the contribution and direction of each variable to the PC. Bold loadings contribute to the principal component in their respective column and were used to interpret the principle component.

	Factor 1	Factor 2	Factor 3	Factor 4
Bottom Salinity (PSU)	**0.92**	0.10	0.15	-0.17
Bottom D.O. (mg/L)	**-0.83**	0.21	-0.02	0.23
Bottom Temperature (ºC)	**-0.70**	0.08	**0.57**	-0.03
Surface Temperature (ºC)	**0.67**	-0.13	0.26	-0.44
Depth (m)	**0.54**	0.22	**-0.57**	-0.12
Midwater Salinity (PSU)	0.35	0.44	**-0.52**	-0.47
Midwater D.O. (mg/L)	-0.34	0.06	0.10	**0.88**
Surface Salinity (PSU)	-0.29	**0.87**	-0.12	0.07
Surface D.O. (mg/L)	0.09	**-0.75**	-0.15	0.32
Secchi (cm)	0.20	**0.79**	-0.09	0.26
Midwater Temperature (ºC)	0.11	0.04	**0.94**	0.00
Eigenvalue	3.15	2.28	1.96	1.47
%Variance Explained	0.29	0.21	0.18	0.13
%Cumulative Variance Explained	0.29	0.50	0.68	0.81

The three-dimensional plot of group centroids suggested that hydrography was different among all locations because centroid 2SEs did not overlap (Figure 5). Hypoxia intensity was most severe at ROS and least severe at SSR. Hypoxia intensity at RIS was more severe than SSR and less severe than ROS. River influence generally decreased along a north-south gradient. Rigs inshore of the shoal were most strongly river influenced and ROS were influenced the least. Ship Shoal rigs were intermediate in terms of river influence but were most similar to RIS. Ship Shoal rigs were the shallowest, ROS were the deepest, and RIS were intermediate.

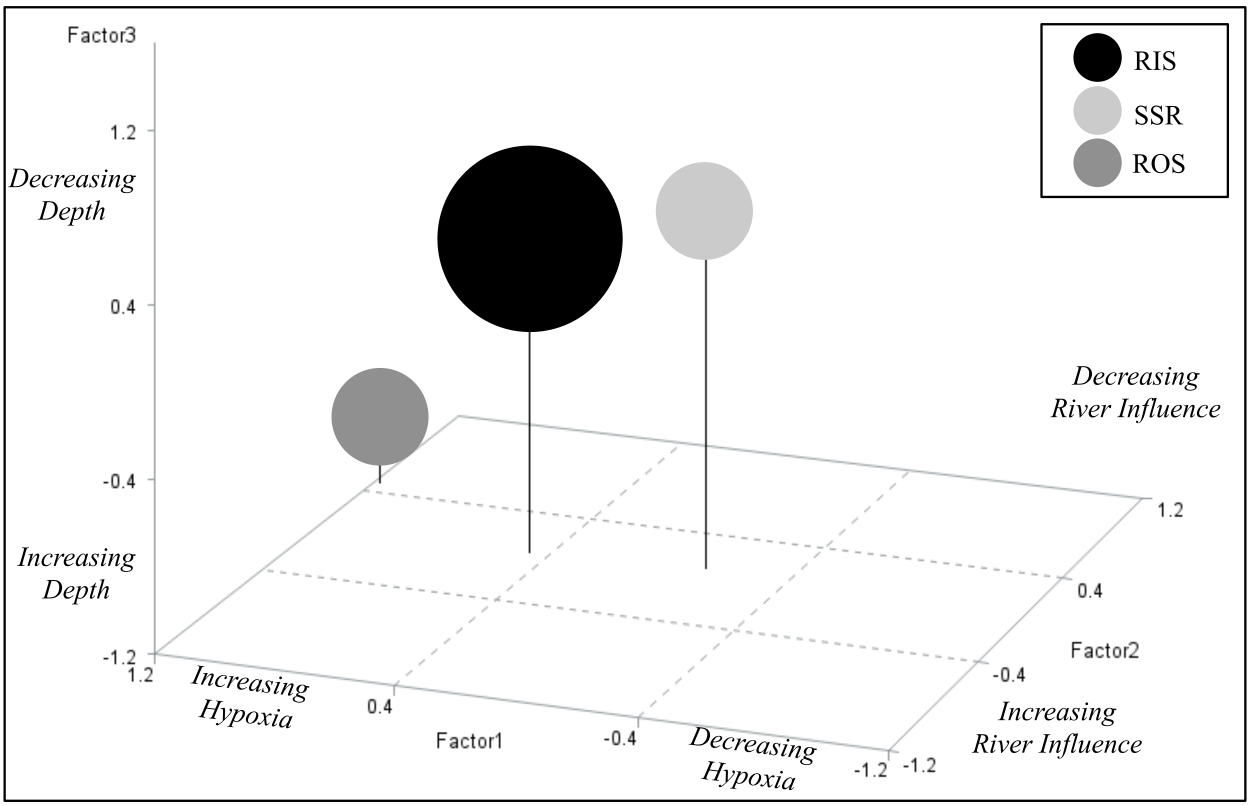


Figure 5: Figure 5: Centroids of SS rigs (SSR), rigs inshore of SS (RIS), and rigs offshore of SS (ROS). Factor 1 was interpreted as a hypoxia factor, Factor 2 as a river influence factor, and Factor 3 as a depth factor.

Hypoxia thickness differed significantly across locations (one-way ANOVA, $F_{(2,33)}=5.99$, $P=0.006$; Figure 6). Mean hypoxia thickness was 0.6 m at SSR, 2.6 m at RIS and 3.1 m at ROS. *Post-hoc* comparisons indicated hypoxia was significantly thicker at RIS than it was at SSR ($P<0.05$), thicker at ROS than it was at SSR ($P<0.05$), but not significantly different between RIS and ROS ($P>0.05$).

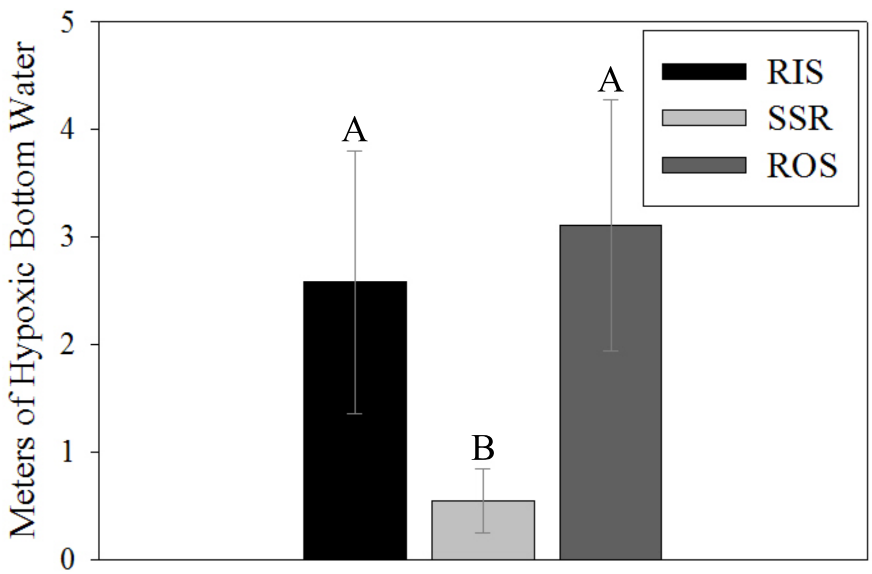


Figure 6: Thickness of hypoxia across locations: rigs inshore of the shoal, Ship Shoal rigs, and rigs offshore of the shoal. Error bars represent one standard error, and different letters indicate significant ($P<0.05$) differences (pairwise t-test).

2.5. Discussion

2.5.1. Comparison of Fish Assemblages at Rigs On and Around Ship Shoal

Ship Shoal rigs may provide better environmental conditions for demersal fishes than rigs surrounding SS. The SIMPER analysis indicated assemblage dissimilarity was driven by a variety of species, but it is noteworthy that 11 of 14 demersal species were more abundant at rigs on SS than rigs in surrounding waters (RIS and ROS). Higher abundances of demersal fishes at SSR accounted for 35.7 and 32.9% of overall dissimilarity with inshore and offshore rigs, respectively, and mean number of demersal species was 34.6 and 29.6% greater at SSR

(7.0±1.09) than RIS (5.2±1.06) and ROS (5.4±1.06) (one-way ANOVA, $P<0.05$). Furthermore, *Sciaenops ocellatus* (Figure 7) was present at nine (56%) rigs on Ship Shoal and only two rigs off SS (7%), and the following demersal species were observed three or more times on SS and no more than once off SS: *Dasyatis americana*, Age-0 *Lutjanus spp.*, *Lutjanus synagris*, *Selene vomer*, and *Pogonias cromis*. The trend of higher abundances and contributions of demersal species on than off SS suggest rigs on the shoal, or the shoal itself, are of higher relative importance for demersal fishes.

Figure 7: *Sciaenops ocellatus* swimming over a pile of barnacle rubble surrounding a Ship Shoal rig.

Higher frequencies of occurrence and abundances of demersal species on SS may be related to differences in the frequency and hypoxia thickness between SSR and RIS and ROS. From the beginning of our sampling on July 2, 2014 to the breakup of hypoxia in late August/early September of 2014, hypoxia was intermittently present on SS during approximately half of all sampling trips (4/7). Hypoxia was restricted to the deeper parts of SS during two

sampling trips and blanketed the shoal, even the shallowest parts, during two sampling trips. Meanwhile, hypoxia was persistent and relatively thicker at sites surrounding the shoal. Hypoxia reduces habitat availability and can displace demersal species (Chesney et al. 2000; Craig and Crowder 2001; Switzer et al. 2009), although intermittent hypoxia may have less severe consequences for motile demersal organisms (Pihl et al. 1991). Since hypoxia was thicker and more persistent at rigs surrounding the shoal, demersal fishes may have been able to better endure the less stressful conditions on the shoal.

Some differences in assemblage composition may be related to differences in bottom substrate (SS is dominated by sand and the surrounding area is dominated by mud), bathymetric relief provided by SS, and differences in river influence. In the Gulf of Mexico, fish assemblages vary across sand, shell, and reef habitat types (Wells and Cowan 2007), and between high-relief shoals and adjacent low-relief areas (Wells et al 2009; De Angelo et al. 2014). Fish assemblages also vary along salinity gradients (Martino and Able 2003) and general differences in hydrography (Perez-Ruzafa et al. 2007). Since SS is shallow and sandy rather than muddy, and has a different degree of river influence than the two surrounding areas, differences in fish assemblages are likely driven by all of these factors, not just hypoxia. Nevertheless, the higher abundance of demersal fishes at SSR suggests hypoxia does play a significant role in shaping fish assemblages in the study area.

There was no clear trend of diversity amongst fish assemblages at rigs on and around SS. Intense hypoxia can result in reduced species richness of macrobenthic communities (Gaston 1985; Dauer et al. 1992). Despite differences in frequency and intensity of hypoxia at SSR and rigs in surrounding water, there were no strong diversity differences between fish assemblages. The only significant difference was higher species richness at SSR than RIS, and a similar trend

was reported on and inshore of a Texas shoal (the Freeport Rocks Bathymetric High) when no hypoxia was observed (Wells et al. 2009). Since fishes congregate around sections of rig in normoxic waters when hypoxia is present (Stanley and Wilson 2004), hypoxia may have different consequences for diversity of fish assemblages around rigs than over low-relief natural bottoms.

2.5.2. Comparison of Fish Assemblages at Rigs Inshore and Offshore of Ship Shoal

Differences between RIS and ROS seemed to be associated with greater freshwater influences inshore of the shoal. All fishes observed in this study are marine species, but differences in RIS and ROS were related to higher abundances of fishes commonly found in brackish waters at RIS and fishes typical of high-salinity, offshore waters at ROS. Four species that accounted for most dissimilarity between RIS and ROS were *C. chrysurus*, *P. saltatrix*, *C. crysos*, and juvenile *Seriola dumerili*, with the later three consistently (dissimilarity/SD>1) contributing to differences. *Pomatomus saltatrix* was more abundant at RIS than ROS, and *C. crysos* and juvenile *S. dumerili* were more abundant at ROS. *Pomatomus saltatrix* is commonly found in brackish waters and is bycatch in the Gulf menhaden (*Brevoortia patronus*) fishery (Guillory and Hutton 1982), and *C. crysos* and juvenile *S. dumerili* are reef-associated species commonly found around larger rigs in high-salinity, offshore waters (Stanley and Wilson 1997). Higher abundances of fishes commonly found in brackish waters at RIS and fishes typical of higher salinity waters at ROS are consistent with salinity driven species distributions (Gunter 1961).

2.5.3. Influence of *Sargassum* on Fish Assemblages

An influx of *Sargassum spp.* was concurrent with an influx of several fish species to rigs (Figure 8). During the summer of 2014, large mats of *Sargassum* were observed throughout the

study area. *Sargassum* is a species-rich (Bortone et al. 1977), nursery habitat that may influence the recruitment of several species to nearshore areas where they do not normally occur. The fishes *Monacanthus hispidus, C. crysos, B. capriscus, Sygnathus louisiane, A. saxatilis, and Histrio histrio* typically dominate *Sargassum.* Many *Sargassum*-associated fishes were detected in this study including *C.* crysos, *B. capriscus*, *A. saxatilis*, *K. sectatrix*, *S. dumerili*, *Seriola rivoliana*, *Elagatis bipinnulata*, *Carangoides bartholomaei* and *C. hippos* (Wells and Rooker 2004). The presence of *Sargassum* during 2014 seemed to contribute to assemblage composition by carrying a number of species into the study area not observed in the 2013 pilot study, and provided the opportunity for those fishes to take up residence around the rigs.

2.5.4. Hypoxia Dynamics in the Ship Shoal Region

Hypoxia was observed overlaying SS on days proceeded by strong west winds, and tended to break up after several days of easterly or southerly winds. West winds seemed to coincide with an incursion of fresh, turbid water, and presumably facilitated the development of hypoxia on Ship Shoal. This study contrasts with previous studies that found SS's bottom waters remained normoxic while surrounding areas were hypoxic (Gelpi et al. 2009; Grippo et al. 2009). In 2013 and 2014 SS was intermittently overlaid by hypoxia, but hypoxia was thinner on SS than surrounding areas and bottom waters were often normoxic when surrounding areas were hypoxic.

2.5.5. Conclusions and Implications

Ship Shoal may be important habitat for a number of economically important species that settle to the bottom in nearshore waters during summer. Ship Shoal has been described as an important spawning ground for *Callinectes sapidus* (Gelpi et al. 2009). The shoal may also be important for a variety of demersal, reef-associated fishes of commercial and recreational

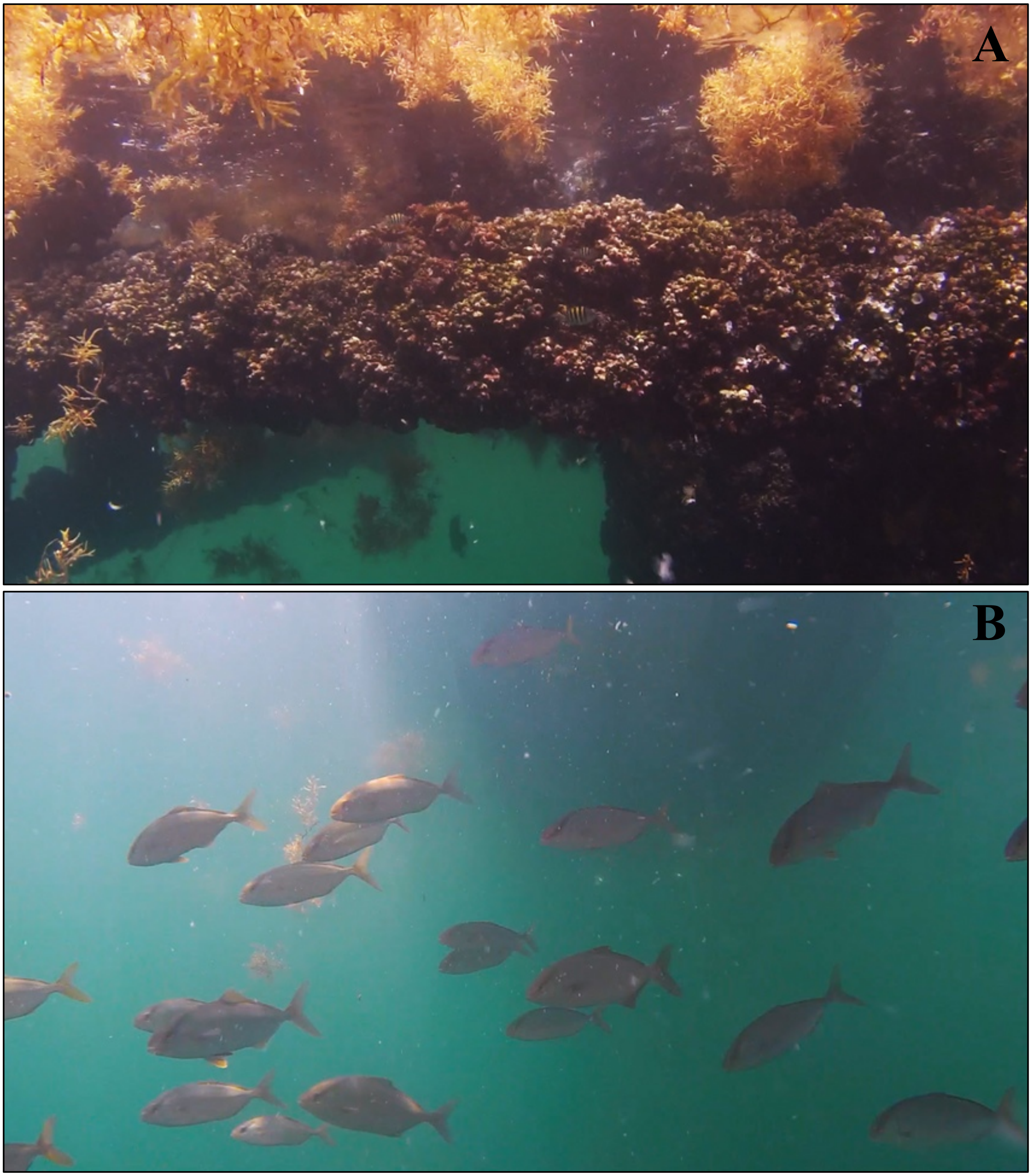


Figure 8: *Sargassum spp.* on the surface near a rig (A) and juvenile *Seriola dumerili* that were commonly observed in association with *Sargassum spp.* (B).

significance including Age-0 *Lutjanus spp.* During July of 2014, diving observations indicated a high rate of settlement of age-0 *Lutjanus spp.* at SSR and no observed settlement or aggregation at RIS or ROS. Age-0 *Lutjanus spp.* were seemingly the most numerous fishes living around rigs on Ship Shoal until early-August, when a hypoxic event corresponded with a large reduction of Age-0 *Lutjanus spp.* on Ship Shoal. Ship Shoal and its rigs may be important habitat types for recruitment of age-0 *Lutjanus spp.*, because there is less prominent hypoxia on the shoal than the surrounding areas and hypoxic waters are highly unsuitable for Age-0 *Lutjanus campechanus* (Switzer et al. 2015). Although this is speculation, rigs may also benefit Age-0 *Lutjanus spp.* by providing mounds of barnacle rubble that are similar to natural shell bottoms, a habitat type where Age-0 *Lutjanus spp.* are commonly found (Rooker et al. 2004; Mikulas and Rooker 2008; Wells et al. 2009). Nevertheless, it is difficult to speculate on the value of SSR as settlement areas for Age-0 *Lutjanus spp.* without knowing the fate of the fishes that disappeared during the early-August hypoxia.

Although a variety of reef-associated fishes are attracted to rigs, the relative importance of small rigs in shallow Louisiana waters was previously undocumented. More demersal fishes on than off SS suggests rigs on the shoal are of higher relative importance to demersal fishes than rigs in surrounding areas. Yet, RIS and ROS are important because many economically and ecologically important fishes utilize these rigs and their vertical relief may provide refugia from hypoxia. Over the course of this study, 3.3 million cubic yards of sediment were removed from Ship Shoal, and 11 of 63 of rigs sampled from 2013-2014 were removed. Managers should consider the potential ecological benefits of rigs and Louisiana's shoals when developing plans for barrier island restoration, sand dredging, and fisheries management, because depletion of these valuable habitats may have adverse fisheries consequences.

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CHAPTER 3. HABITAT USE, SIZE, AND MATURITY OF STONE CRABS (*MENIPPE SPP.*) ON SMALL OIL AND GAS PLATFORMS IN THE NORTHERN GULF OF MEXICO

3.1. Abstract

Nearshore Louisiana has experienced substantial changes within the last half-century, including the annual formation of the world's second largest hypoxic zone and the construction of thousands of oil and gas platforms (rigs). Rigs may provide key settlement sites for stone crabs in nearshore Louisiana, because they provide hard substrate in the normoxic part of the water column. Louisiana's sand shoals are important habitat types because they tend to remain oxygenated when surrounding areas are hypoxic. Patterns of habitat use by stone crabs were compared at rigs located on and off Ship Shoal. Densities were estimated with visual counts, and their life history was characterized by removing subsamples for identification, sexing and measurements. Stone crabs on and off the shoal did not differ significantly in mean carapace width (Females- 45.17 vs. 42.41 mm and Males- 28.77 vs. 32.64 mm, respectively; $P>0.05$), size-class distribution ($P>0.05$), or sex ratio ($P>0.05$). Nevertheless, stone crab densities were roughly twice as high on Ship Shoal rigs as rigs adjacent to the shoal (mean 3.96 vs. 1.80 stone crabs/m^2; $P<0.05$), and the carapace width where 50% of females were ovigerous (CW_{50}) was 26.4 mm smaller for females off than on the shoal ($P=0.057$). Stone crabs on and off the shoal had higher densities at rigs than reported for natural substrates, and their sex ratio and CW_{50} were comparable to those reported for crabs in natural substrates. Rigs on and off Ship Shoal are important habitat for stone crabs, but higher densities on the shoal suggest that shoal rigs are of higher relative importance. Further sand mining of Ship Shoal and removal of rigs may negatively affect stone crab populations in nearshore Louisiana.

3.2. Introduction

The Mississippi River watershed drains 41% of the contiguous United States (Turner and Rabalais 1991) and discharges into the northern Gulf of Mexico (nGOM) where it has formed vast coastal wetlands and its nutrient-rich waters drive primary and secondary productivity. These factors form the basis of Louisiana's valuable fisheries production, which accounted for 73.8% (10.38×10^6 metric tons) of the Gulf of Mexico's commercial landings from 1994 to 2013 (National Marine Fisheries Service 2015). Notably, nutrient loading in the Mississippi River has also been linked to a growing hypoxic zone in the nGOM (Rabalais et al. 2002).

A summertime hypoxic zone (dissolved oxygen < 2 mg/L) forms in the nGOM and is most widespread and intense from July to August (Rabalais et al. 2001). This is the second largest hypoxic zone in the world (Rabalais et al. 2002), and can occupy as much as 15,100-18,000 km^2 of Louisiana's coastal zone (Obenour et al. 2013). The hypoxic waters cause displacement of marine organisms, reduction of demersal fish habitat (Chesney et al. 2000; Craig and Crowder 2001), reduction of macrobenthic diversity and biomass, and a shift in macrobenthic community composition from domination by equilibrium species to r-strategists (Dauer et al. 1992; Pihl 1994).

The hypoxic zone falls within the most biologically productive region of the GOM (Gunter 1963); however, in spite of intensifying hypoxia, fishery landings have remained strong (Chesney and Baltz 2001). Changes in community structure are apparent, but it is difficult to attribute those changes solely to hypoxia since hypoxia is concurrent with a mosaic of other environmental changes (Chesney et al. 2000). For example, the intensification of hypoxia in the nGOM co-occurred with the augmentation of coastal hard substrates by the construction of thousands of oil and gas platforms (rigs).

Rigs may be ecologically important structures because they act as de facto artificial reefs (Stanley and Wilson 1989). Rigs provide substrate for sessile organisms such as barnacles and oysters that in turn provide habitat structure for blennies (*Blenniidae*), pistol shrimp (*Alpheidae*), stone crabs (*Mennipe spp.*), and other fouling-associated organisms (Gallaway et al. 1981). Rigs also aggregate large assemblages of reef-associated fishes (Shin 1974; Stanley and Wilson 1989; Stanley and Wilson 1991). Since there is little naturally-occurring hard substrate in the nGOM (3% of bottom substrate from Pensacola, FL to Pass Cavallo, TX) (Parker et al. 1983), rigs may increase the hard-substrate settlement opportunities for juvenile, reef-associated fishes and invertebrates that would have otherwise been lost to the system (Hernandez et al. 2003).

The use of artificial reefs (ARs) for fisheries management is contentious. ARs are established under the assumption that hard substrate is limiting for a stock and the addition of new hard substrate will result in a larger stock (Bull and Kendall 1994; Bortone et al. 1997). Further evaluation of ARs is needed because they could deplete fisheries by concentrating fishes and making them more exploitable, but those effects depend upon local fishing effort and other issues (Polovina 1991; Grossman et al. 2007). These hypotheses have driven debate on whether ARs benefit or harm fisheries.

The attraction vs. production debate has been a central point of contention for managers and stakeholders of the red snapper (*Lutjanus campechanus*) fishery in the nGOM (Cowan et al. 2010). Shipp and Bortone (2009) argue that rigs and other ARs have transformed Alabama waters from being relatively unproductive for the red snapper fishery to being one of the most productive areas in the GOM. Although red snapper exhibit low site fidelity, ARs are sometimes net sinks for red snapper (Strelcheck et al. 2007), and red snapper do not derive much nutrition directly from rigs because they primarily feed over soft bottoms (McCawley et al. 2003). These

contrasting findings suggest that rigs and other ARs could benefit fisheries in some respect and negatively affect fish production in other respects.

Because small, nearshore rigs in the nGOM are being removed, it is important to understand the role they play for the fishes and invertebrates that reside on and near them. Small rigs (caissons and well protectors) within the nearshore coastal zone are rapidly being removed because they are less expensive to remove than larger rigs, and oil and gas exploration is shifting from shallow to deep waters (Pulsipher et al. 2001). It is important to examine fish and invertebrate use of these rigs because they are abundant within the hypoxic zone and their vertical relief provides substrate in the normoxic, upper water column that may be beneficial as sources of prey and refugia.

Rigs in nearshore Louisiana may be particularly beneficial for stone crabs (SC). Stone crabs were shown to select barnacles over many other prey (Powell and Gunter 1968) and SCs are common on rigs where they prey on live barnacles and use clusters of barnacle shells for refuge (Gallaway et al. 1984). Since SCs do not swim, they normally live on or in the substrate (Bender 1971) and their population sizes are limited by availability of suitable structural habitat for refuges (Beck 1997; Shervette 2004). Relatively small changes in habitat availability could have important effects on SC populations (Beck 1997). If rigs are providing a significant amount of key substrate for SCs in the middle of the nGOM's hypoxic zone, these sites could have important benefits for nearshore stone crab populations. Consequently, it is important to understand the role small, shallow rigs play in determining SC distribution and abundance across depth, substrate, and water quality.

This study focuses on SCs living on Ship Shoal (SS) because it is an important shallow, sandy environment in the nearshore zone of the Outer Continental Shelf. Moreover, the shoal is

within a region where hypoxia is most intense, but its bottom waters are typically normoxic (Grippo et al. 2009). SCs are good candidates for study because they are a commercially important species and widely distributed throughout the GOM. Stone crab claw annual landings in the GOM averaged about 2,300 metric tons annually with a value of $23.2 million from 2004 to 2013, with Florida's west coast accounting for 99.6% of those landings (National Marine Fisheries Service 2015). There is a small, developing fishery in Louisiana (Shervette et al. 2004), with mean landings from 2004 to 2013 of about 0.8 metric tons (Figure 1).

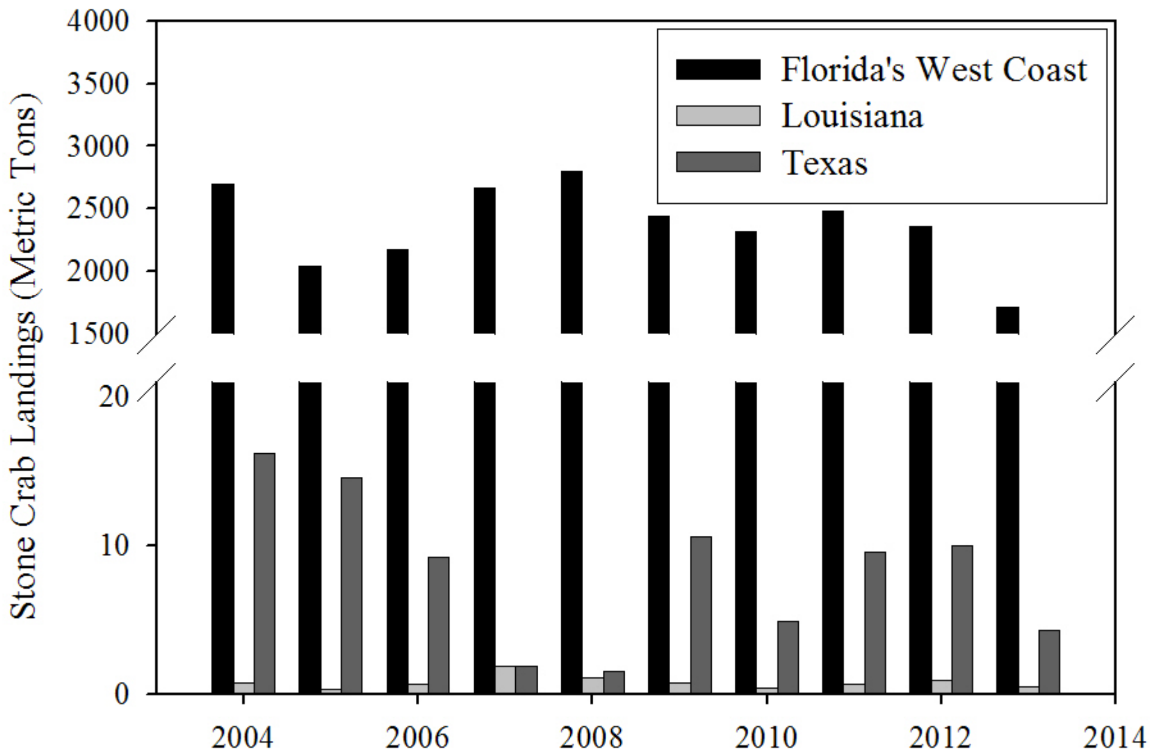

Figure 1: Stone crab landings (Metric Tons) in the northern Gulf of Mexico from 2004-2013. Landings were minimal or not reported for Alabama and Mississippi. Data source: NMFS Annual Commercial Landing Statistics.

In this study, SC populations were characterized on small rigs and compared at rigs on and off SS to determine if rigs on the shoal provide higher quality environmental conditions than rigs just off the Shoal. Sampling efforts were focused on small rigs because they dominate the assemblage of rigs in the SS area, they are rapidly being removed (Pulsipher et al. 2001), and

their simple configurations make them amenable to study. The goals of this study were to compare SC densities and population characteristics at rigs on and off SS.

3.2.1. Study Area

Ship shoal is a shallow, submarine body of medium and fine sand off the central Louisiana coast surrounded by deeper waters overlaying silty clay. It is a relict barrier island of the wandering Mississippi River Delta (Penland et al. 1986), located approximately 15 km offshore of the Isle Dernieres. The shoal is approximately 50 km long, ranges from 2-10 km wide (Stone et al. 2004), and ranges in depth from 2.7 to 10 m (Penland et al. 1986). During the summer of 2014, stone crab densities were estimated at twenty rigs, and specimens were collected for biometrics from twenty-four rigs (Figure 2). Sampled rigs were small (≤ 3 pilings),

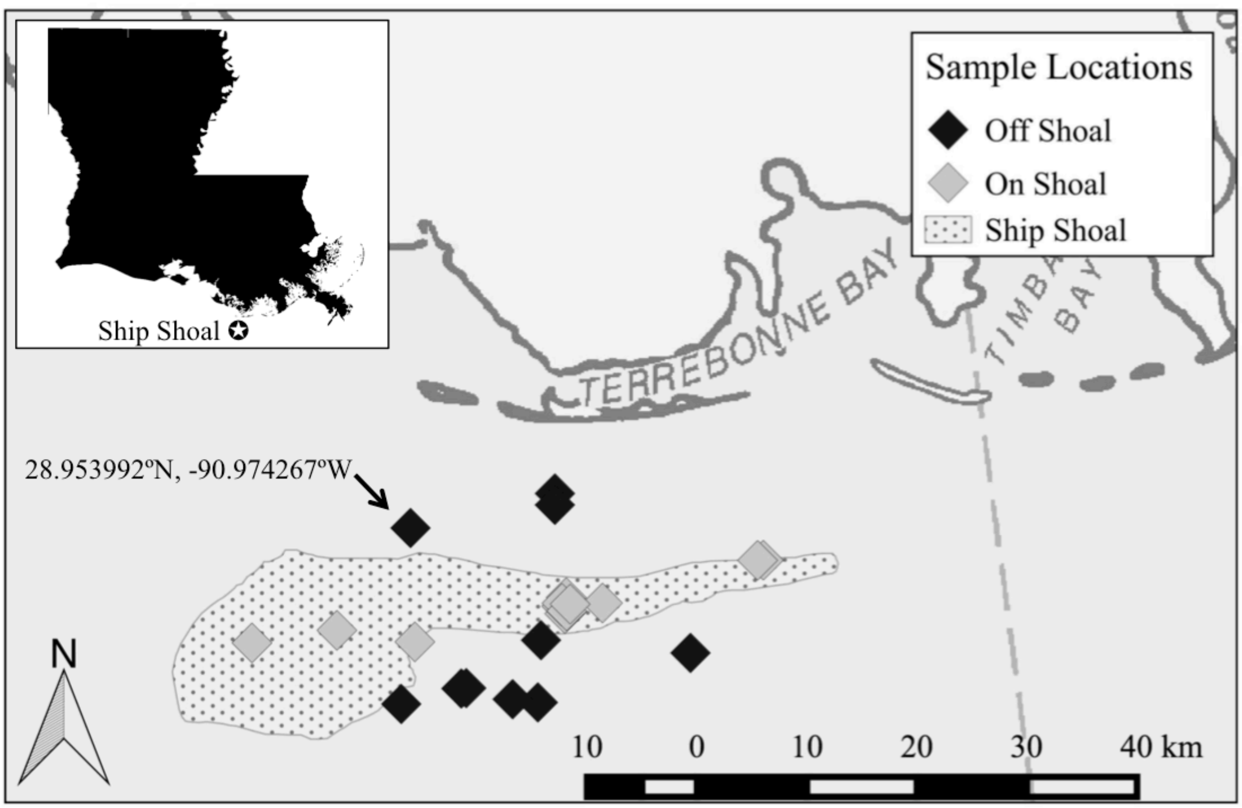

Figure 2 : Chart of rig locations where stone crabs were sampled during the summer of 2014. Grey diamonds denote rigs on Ship Shoal, and black diamonds denote rigs off Ship Shoal. The dotted area is the approximate location of Ship Shoal.

1-38 years old, and free of SCUBA diving hazards (e.g., produced water, jack-ups, crew boats). Rigs on the shoal were located in water depths of 6.7 to 10 m, and rigs off the shoal were in deeper water, 6.7 to 16.7 m. Hydrography was dynamic throughout the study region with salinity ranging from 20.1 to 35.5 PSU, temperature from 24.3 to 31.2 ºC, and dissolved oxygen from 0.1 to 8.0 mg/L (Table 1).

Table 1: Environmental conditions at rigs on and off Ship Shoal where stone crabs were collected from July to September of 2014. Values are Means ± 2SE (range). Stone crabs were collected from 14 rigs on and 10 off Ship Shoal.

	On Shoal Mean±2SE	(min-max)	Off Shoal Mean±2SE	(min-max)
Surface Temperature (ºC)	30.4±0.37	(29.3-31.7)	30.8±0.26	(30.0-31.3)
Midwater Temperature (ºC)	30.0±0.33	(29.3-31.0)	29.7±0.71	(27.9-31.1)
Bottom Temperature (ºC)	28.7±1.00	(24.2-31.2)	27.7±1.51	(24.5-30.9)
Surface Salinity (PSU)	26.1±1.58	(20.1-30.0)	25.0±1.94	(21.0-28.5)
Midwater Salinity (PSU)	27.8±1.27	(23.1-31.6)	30.4±1.39	(28.1-33.8)
Bottom Salinity (PSU)	31.4±1.26	(28.2-35.5)	32.9±1.33	(29.3-34.7)
Surface D.O. (mg/L)	6.9±0.29	(6.4-8.0)	7.0±0.29	(6.4-7.9)
Midwater D.O. (mg/L)	6.0±0.99	(0.2-7.3)	5.2±1.20	(1.8-6.9)
Bottom D.O. (mg/L)	4.1±1.44	(0.1-6.8)	1.9±1.26	(0.1-5.1)
Depth (m)	7.8±0.54	(6.7-10.1)	12.4±2.28	(6.7-16.8)

3.3. Methods

3.3.1. The Stone Crab

Two distinct species of SC, *Menippe adina* and *Menippe mercenaria*, and a *M. adina* x *M. mercenaria* hybrid occur within the nGOM (Williams and Felder 1986; Bert and Harrison 1988). The species and hybrid are typically referred to as *Menippe spp.* (Lindberg 1990; Valentine et al. 1994; Beck 1995, 1997; Gerhart and Bert 2008; Rindone and Eggleston 2011). They exhibit random mating between species (there is no assortative mating), there is no reduction of hybrid fitness (Wilber 1989), and there is no apparent size difference (Beck 1997). The only apparent difference is that *M. adina* is primarily distributed inshore and *M. mercenaria*

is primarily distributed offshore (Williams and Felder 1986; Wilber 1989); however, overlap is considerable. The name stone crab is used throughout this paper to refer to all species of the genus *Menippe* within the nGOM, however *M. adina* dominated the catch (97.5% *M. adina*, 2.5% *M. nodifrons*).

3.3.2. Stone Crab Density Estimates

Densities were estimated by counting crabs on the primary pilings of rigs while SCUBA diving. Pilings were subdivided into two strata representing the upper and lower water column. The boundary depth was 15 ft. (4.6 m) because preliminary work on and off the shoal suggested waters above 4.6 m were consistently well oxygenated, while waters below 4.6 m were sometimes hypoxic. Circumferences and lengths of pilings and auxiliary pipes were measured, and counts were converted to densities by dividing the number of SCs in a stratum by the surface area of that stratum. Counts were not made shallower than 5 ft. (1.52 m) because surge and overhead structures posed hazards to divers.

Densities were also estimated within large piles of barnacle rubble (rubble) that accumulated on the bottom surrounding rigs. Densities were estimated in the rubble at the base of rigs by filming four transects with a GoPro Hero 2 video camera attached to a 0.25 m^2 quadrat (QuadCam). Transects radiated from the north, south, east, and western sides of the rig and ended at the edge of the rubble field. A diver guided the QuadCam over the bottom on each transect at a rate of 0.1±0.010 m/s (95% CI), and signaled to the camera when the quadrat passed over SCs. Counts were converted to densities by dividing the total number of SCs counted by the total surface area filmed (summed length of four transects times 0.25 m).

3.3.3. Stone Crab Population Characterization

Subsamples of SCs were removed from rigs for estimating mean size, sex ratios, and female size at maturity. Stone crabs were randomly collected by sequentially selecting every crab encountered for ten minutes with the aid of crab tongs and wire cages (12.7 mm square mesh). Each captured SC was measured to the nearest mm carapace width (CW), sexed, and reproductive status of females assessed (presence or absence of egg masses and egg color). All stone crabs were identified to the species-level.

3.3.4. Fouling and Hydrography Characterization

The fouling community was characterized at each rig using the QuadCam and surface to bottom hydrography was recorded with a YSI 6820 V2 Sonde. The QuadCam was placed against the rig in 5 ft. (1.52 m) intervals while descending to the bottom. Individual digital images from each interval were overlaid with a 25-cell grid in Microsoft PowerPoint™. Cells were then categorized as predominately live barnacles, dead barnacles, bare rig, or sponge. Cells in each category were summed and divided by the total number of cells to calculate the category percentage of coverage. The YSI sonde was lowered at a rate of 0.04 ± 0.0037 m/s (95% CI) to record the vertical profile of dissolved oxygen (mg/L), salinity (PSU), and temperature (°C) at every rig.

The QuadCam was used to visually estimate rugosity, a measure of microtopography. The aluminum QuadCam frame was constructed with 25.4 mm angle bar and provided three points of reference for vertical relief: (1) no relief (< 1.27 mm), (2) intermediate relief: greater than the lip of the horizontal bar but less than the vertical bar (1.27 mm > relief < the 25.4 mm), and (3) high relief: greater than the vertical bar (> 25.4 mm). Cells from the 25-cell grid with no relief, intermediate relief, and high relief were assigned values of 0, 1, and 2, respectively.

Digital images from the camera provided a view of both sides of the vertical bars but only one side of the horizontal bars. Since both sides were needed to calculate rugosity, only cells along the perimeter of the vertical bars were used (n=10). Rugosity estimates were summed for each photo and sums were used as a measure of relief.

3.3.5. Statistical Analysis

All statistical tests were run in SAS 9.4. No assumption violations were detected in the analysis, results were interpreted with an alpha of 0.05, Tukey-Kramer adjustments were made when appropriate. Clustered sampling was accounted for within all statistical models to avoid pseudoreplication (Hurlbert 1984). The reported measure of dispersion was one standard error unless otherwise noted.

Multiple linear regression was used to examine relationships between patterns of SC density and habitat characteristics (Proc Genmod, SAS 9.4). Forward and backward variable selection was used with percentages of living barnacles, dead barnacles, rugosity, bottom dissolved oxygen (mg/L), depth (m), and age of rig (years) to predict crab density (SCs/m^2). Rigs were treated as repeated measure subjects with a compound symmetry correlation structure to control for non-independence of upper and lower water column density estimates (Hurlbert 1984; Zeger and Karim 1991).

Two-way ANOVAs were used to compare SC density across locations (on vs. off SS) and water column strata (upper vs. lower), and size (CW) across locations and genders (males vs. females) (Proc Glimmix, SAS 9.4). Location, water column strata, genders, and interaction terms for both ANOVAs were fixed effects. Rig name was a random effect in both models to control for non-independence of density estimates and crabs from the same rig (Laird and Ware

1982; Hurlbert 1984). The density model was fitted with a normal response distribution, and the size model was fitted with a lognormal response distribution.

Logistic regression was used to estimate female size of 50% maturity (CW_{50}) on and off SS (Agresti 2007; Proc Genmod, SAS 9.4). The response variable was reproductive status and followed a binary distribution (0=Not Ovigerous, 1=Ovigerous). Independent variables were CW (mm) and a dummy variable for location (0=Off SS and 1=On SS). Rigs were treated as repeated measure subjects with a compound symmetry correlation structure to control for non-independence of SCs from the same rig (Hurlbert 1984; Zeger and Karim 1991). CW_{50}s were calculated as:

$CW_{50} = -[(\alpha + \beta_2 * \text{Location}) / \beta_1]$,

where α is the intercept, β_2 is the slope of location, β_1 is the slope of CW (Agresti 2007).

Chi-square tests were used to test whether sex ratios differed on and off SS and distributions deviated from the expectation of 1:1 (Proc Freq, SAS 9.4). A χ^2 test of association (Agresti 2007) was conducted to determine if there were differences between locations and if SCs should be separated by location or pooled for the χ^2 test of goodness of fit (Jelinski 1991).

A proportional odds model was used to compare size-class distributions on and off SS (Agresti 2007; Proc Genmod, SAS 9.4). Individuals were classified as small-juveniles (Male CW<35mm, Female CW<30mm), large-juveniles (35mm<Male CW<70mm, 30mm<Female CW<60mm), or adults (Male CW>70mm, Female CW>60mm) following Gerhart and Bert (2008). The response variable, size-class, followed a multinomial distribution. The independent variable was location (0=Off SS, 1=On SS). Rigs were treated as repeated measure subjects with an independent correlation structure to control for non-independence of SCs from the same rig (Hurlbert 1984; Zeger and Karim 1991). SAS only supports independent correlation structures

for multinomials, but GEE uses empirical dependence to estimate appropriate standard errors for clustered data even when the correlation structure is a poor fit (Agresti 2007).

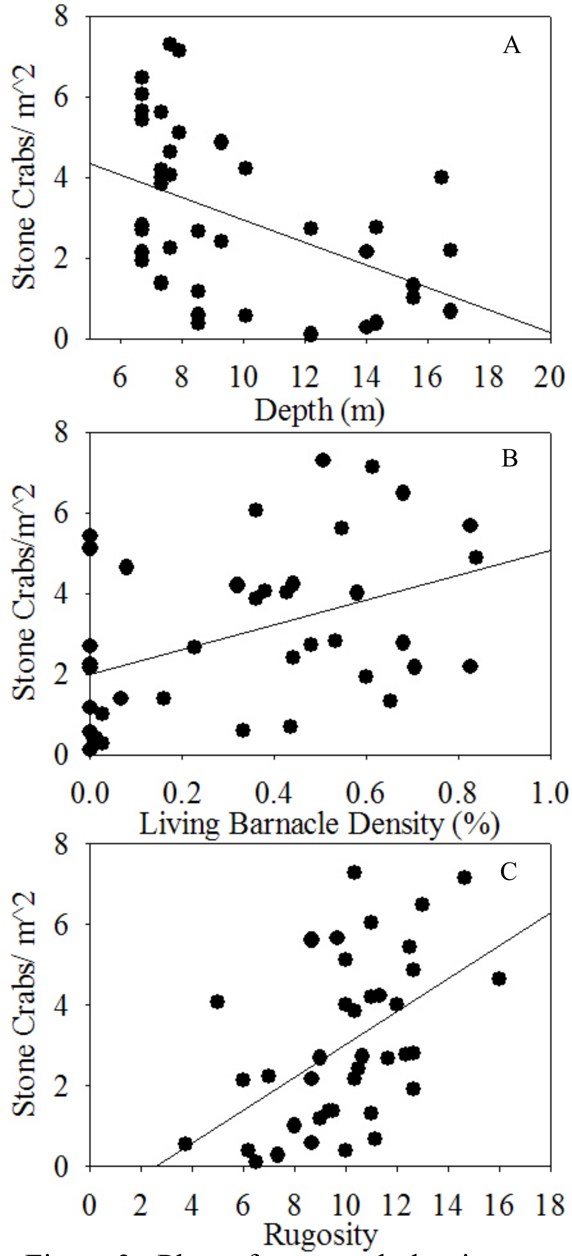

Figure 3: Plots of stone crab density on depth (m) (A), living barnacle density (LBD%) (B), and rugosity (C). Coefficients of determination were 0.26 for depth, 0.18 for living barnacle density, and 0.26 for rugosity. Density= 2.68 - 0.28*Depth + 2.76*LBD + 0.22*Rugosity.

3.4. Results

3.4.1. Analysis of Density Estimates

Stone crab densities increased with living barnacle density and rugosity, and decreased with depth (multiple linear regression). Forward and backwards selection both indicated that slopes of depth (Z= -4.39, P<0.0001; Figure 3A), living barnacle density (Z=3.24, P=0.0012; Figure 3B), and rugosity (Z=3.27, P=0.0011; Figure 3C) were significant effects. The slopes were 2.76 for living barnacle density, 0.22 for rugosity, and -0.28 for depth.

Stone crab density was higher on SS rigs than rigs off shoal (P<0.05), densities were higher in the upper than in the lower water column (P<0.05), and SCs were only observed in barnacle rubble surrounding rigs on SS. The two-way ANOVA indicated there were significant location ($F_{(1,18)}$=16.72, P=0.0007) and water column strata ($F_{(1,18)}$=12.57, P=0.0023) effects, but the interaction between the two effects was not

significant ($F_{(1,18)}$=0.11, P=0.75). Estimated densities (SCs/m^2) in the upper water column were 4.7±0.48 (on shoal) and 2.7±0.48 (off shoal), and 2.7±0.53 (on shoal) and 0.9±0.53 (off shoal) in the lower water column (Figure 4). Density estimates in the upper water column may be conservative since SCs seemed to be highly abundant in waters above 1.5 m where we were unable to sample. Crabs were only observed living within the barnacle rubble surrounding rigs on SS, but a statistical analysis was not performed because only four density estimates exceeded zero. Rubble densities were highly variable with only four rigs with SCs in their barnacle rubble (9, 4.5, 2.2, and 0.7 SCs/m^2). Fourteen other density estimates in barnacle rubble were zero (7 on shoal, 7 off shoal), and density was not estimated at two other rigs off shoal because bottom waters were too turbid.

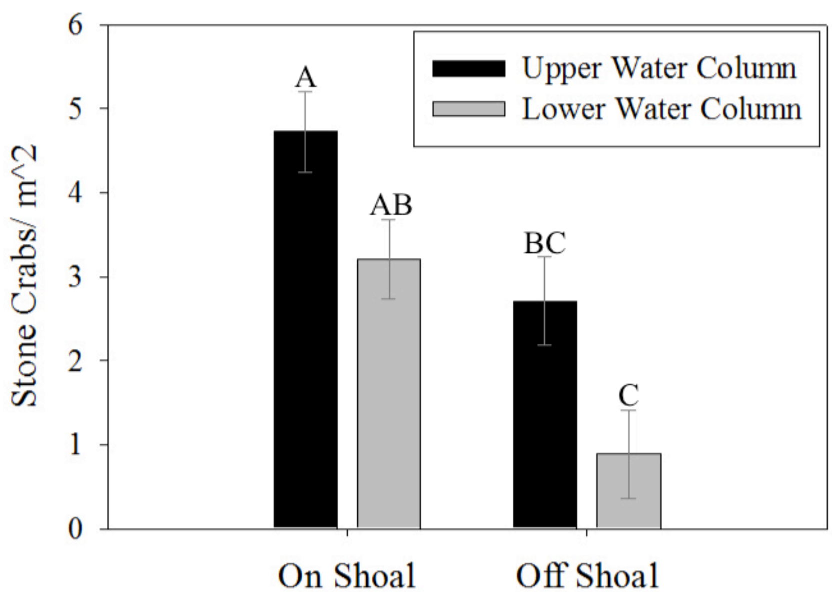

Figure 4: Stone crab density estimates at rigs on and off Ship Shoal (SS) in upper and lower water column strata. Mean densities (stone crabs/m^2) were 4.7 (upper) and 3.2 (lower) on SS, and 2.7 (upper) and 0.9 (lower) off SS. Error bars represent one standard error, and columns with common letters are not significantly different (P>0.05; pairwise t-test).

3.4.2. Analysis of Population Characteristics

A total of 378 SCs were captured from rigs (211 on and 167 off SS), including 368 *Menippe adina* and 10 *Menippe nodifrons* (Cuban stone crab). Females outnumbered males (267:111), 36.7% of females were ovigerous, and 18.4% of ovigerous females had black egg masses. CWs of captured SCs ranged between 9 and 88 mm.

Female SCs on the shoal had a marginally significant higher size-at-maturity (CW_{50}) than crabs off the shoal (P=0.057), females were larger than males (P<0.05), and there were no detectable size differences between crabs on and off the shoal (P>0.05). Logistic regression of reproductive status on CW (mm) and location indicated that CW (Z=2.98, P=0.0029) was a significant effect and location (Z=-1.91, P=0.057) was marginally significant (Figure 5). The coefficients were 0.026 for CW (mm) and -0.69 for location. Estimates of CW_{50} were 81.4 mm

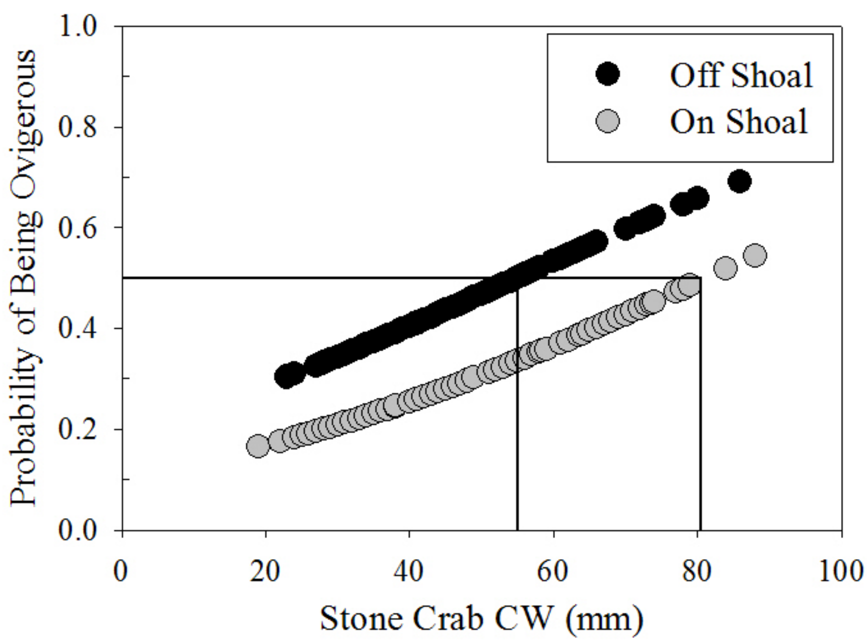

Figure 5: Predicted probability of being ovigerous for all female stone crabs captured and measured on and off Ship Shoal (n=267; 123 off SS and 144 on SS) plotted against stone crab CW (mm). Thin black lines indicate the CW_{50} for stone crabs on (81.4 mm) and off (55.0 mm) SS.

on and 55.0 mm off the shoal. The two-way ANOVA of size indicated there was no significant location effect ($F_{(1,22)}$=0.22, P=0.65), but a sex effect (F=73.48$_{(1,372)}$, P<0.0001) and an interaction between the two factors ($F_{(1,372)}$=5.17, P=0.024) were significant. Mean CWs on the shoal were 45.2±1.05 mm for females and 28.8±1.06 mm for males, and off the shoal means were 42.4±1.05 for females and 32.6±1.07 for males (Figure 6). Stone crabs smaller than 20 mm CW were probably under-represented in the samples, because they were difficult to detect and capture and could more easily escape from the wire boxes.

The sex ratio was skewed toward females on and around SS (P<0.05); however, sex ratio did not differ between crabs on and off the shoal (P>0.05). The sex ratio did not differ on and off the shoal (χ^2=1.31, P=0.25), so crabs were pooled across both locations to test the 1:1 model. Females dominated, 2.45:1, populations on rigs (χ^2=64.38, P<0.0001).

The proportional odds model indicated that SC size-class distribution was not detectably different between crabs on and off the shoal (Z=0.65, P=0.51). Size-class distribution for crabs across both locations was 28% small juveniles, 55% large juveniles, and 17% adults.

3.5. Discussion

3.5.1. Comparison of Stone Crabs On and Off Ship Shoal

Density of SCs sampled was higher on SS than in surrounding waters, suggesting rigs on the shoal provide a more suitable environment. This finding is consistent with the occurrence of higher quality blue crab (*Callinectes sapidus*) habitat on than off SS (Gelpi et al 2009) and higher catch per unit effort of SCs over sand substrate than over mud substrate (Baltz and Horst 1992). The differences in crab density may be related to a number of factors, including finer substrates, greater depths, and more frequent and thicker hypoxia off shoal. Preceding the

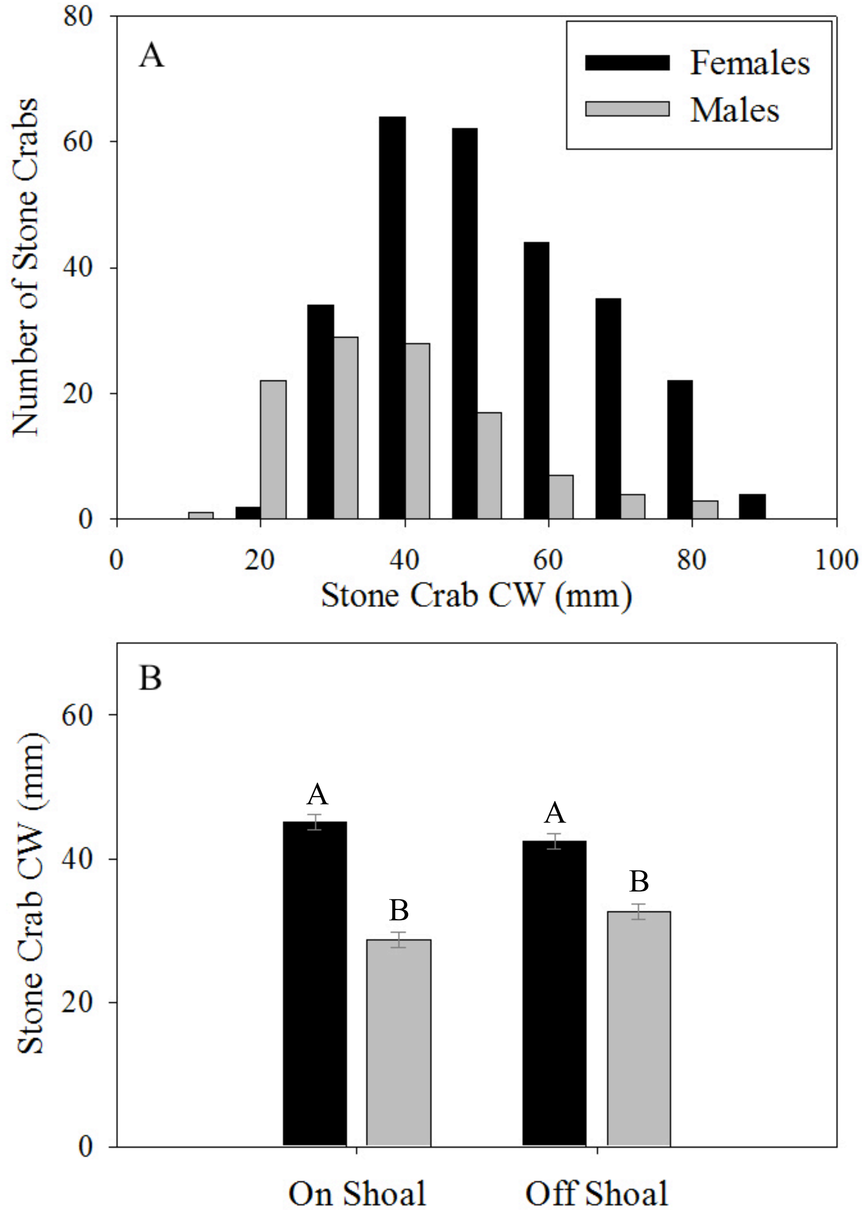

Figure 6: Size frequency distribution of male and female stone crabs (A) and stone crab CWs (mm) of males and females on and off (B) Ship Shoal (SS). Mean CWs on SS were 45.2 (females) and 28.8 (males), and mean CWs off SS were 42.4 (females) and 32.6 (males). Error bars represent one standard error, and columns with common letters are not significantly different (P>0.05; pairwise t-test).

breakup of hypoxia on and off SS during early September 2014, hypoxia was present off the shoal during all seven sampling trips from early July to late August. Hypoxia was intermittent on the shoal and present during approximately half (4/7) of the sampling trips, when it was restricted to the shoal's deepest areas on two occasions and blanketed the entire shoal on two occasions. Additionally, hypoxia affected a smaller proportion of the water column on the shoal (0.6 m vs. 2.8 m).

Thicker and more frequent hypoxia off SS may reduce SC density by excluding SCs from the bottom and crowding them and their predators into small areas of normoxic water. Since SC populations are believed to be limited by the availability of shelter (Beck 1995, 1997; Shervette et al. 2004), access to well oxygenated bottom substrate may benefit crabs on the shoal by facilitating burrowing in piles of barnacle rubble. In contrast, crabs off SS are generally less likely to benefit from refugia in bottom substrate or increased foraging opportunities during the summer. Thicker hypoxia off the shoal may also cause lower survival of crabs, due to an increase in predation by crowding predators and prey into a small area (Breitburg 1994).

The discrepancy between size-at-maturity (CW_{50}) of SCs on and off SS may be a stress response to less favorable conditions off than on the shoal. Fish can have reduced gonadal growth when chronically exposed to hypoxia (Wu et al. 2003; Landry et al. 2007; Thomas et al. 2007; Cheek et al. 2009; Thomas and Rahman 2011), although taxa have different stress tolerances and may differ in terms of their reproductive response (Schreck et al. 2001). For example, majid crabs (*Pugettia producta*) undergo early maturity (precocious maturity) when parasitized by the rhizocephalan barnacle (*Heterosaccus californicus*) (O'Brien 1984). Precocious maturity off SS may be related to direct exposure to hypoxia or indirect effects of hypoxia such as higher predation of SCs and/or reduced availability of hard bottom substrates.

3.5.2 Comparison of Stone Crab Populations on Rigs and Natural Substrates

Stone crab densities on rigs on and around SS compared favorably to densities in natural substrates. Mean densities at rigs on ($4.0/m^2$) and off SS ($1.8/m^2$) were higher than reported $0.13/m^2$ on oyster reefs in the Pamlico Sound, North Carolina (Rindone and Eggleston 2011; *M. Mercenaria*), $0.85/m^2$ within seagrass beds in St. Joseph Bay, Florida (Valentine et al. 1994; *Menippe spp.*), and roughly 0.1, 0.12, 0.14, and $0.22/m^2$ within seagrass beds in four Florida bays (Beck 1997; *Menippe spp.*). Nevertheless, density estimates in this study were not unprecedented since SCs have been observed in densities as high as 6 $/m^2$ in St. Joseph Bay, Florida (Valentine et al. 1994; *Menippe spp.*).

The occurrence of SC densities at the high end of the range reported previously may be related to the availability of prey and shelter on rigs or use of rigs as refugia from hypoxia. In this study, crab densities were positively associated with living barnacle density and rugosity. Barnacles are a known prey item of SCs (Powell and Gunter 1968; Gallaway et al. 1984), and SC densities are positively associated with rugosity (Beck 1997). Since rugosity was positively associated with large barnacle clusters, barnacles may contribute to high densities of crabs by providing food and shelter. Lastly, crabs may be temporarily concentrated on rigs during summer hypoxia when seeking refuge and adequate oxygen.

The skewed sex ratio reported here is consistent with previous studies and may be related to differential distributions of male and female stone crabs. The predominance of females (2.45F: 1M) reported here is similar to the 1.86F: 1M within Barataria Bay, LA (Baltz and Horst 1992). Sex ratios are often skewed (Powell and Gunter 1968; Wilber 1989; Baltz and Horst 1992) and may reflect gender-specific distributions. Stone crabs on subtidal reefs are distributed by gender during the summer (9F: 1M), but sex ratios are more uniform during the fall when

they mate (3F: 1M) (Wilber 1989). Since Baltz and Horst (1992) sampled from mid to late spring and this study sampled from July to September, sex ratios may reflect an offshore movement of females (Wilber 1989).

The CW_{50} estimates reported here are comparable to estimates by Gerhart and Bert (2008) in Tampa Bay, FL, where 50% of females reach morphological, physiological, and behavioral maturity (CW_{50}) between 60 and 69 mm CW. The two estimates for females on (80.4 mm CW) and off (55.0 mm CW) the shoal encompass the estimates by Gerhart and Bert (2008). Furthermore, the CW_{50} of all females (on and off SS) was 70.4 mm and fell just above the range reported by Gerhart and Bert (2008).

The lack of large SCs (none >88 mm CW) in this study is consistent with the absence of large crabs from rigs off California's coast (Page et al. 1999) and may be a result of limited shelter for larger crabs and/or an abundance of predators. Elsewhere in their range large SCs (> 88 mm) over natural substrate constitute roughly 7% of the size frequency distribution in St. Joseph Bay, FL (Beck 1995), 0% on Dog Island Reef, FL, 3% in Lanark Reef, FL, 9% in St. Joseph Bay, FL, and 4% in Apalachee Bay, FL (Beck 1997). Clusters of living barnacles are the primary form of relief on rigs. Consequently, larger crabs were almost exclusively found nestled between the rigs' crossbeams and wellheads (Figure 7), and this type of shelter was limited on the rigs.

3.5.3. Occurrence of *Menippe nodifrons* into the Northern Gulf of Mexico

Menippe nodifrons is distributed throughout the Caribbean, but there is only one record of *M. nodifrons* from the nGOM (Rathbun 1930). This is the first study since Rathbun (1930) to record *M. nodifrons* in the nGOM. *Menippe nodifrons* were substantially less abundant than *M. adina* (≈ 2.5% of all captured SCs), but they were detected at 5 rigs (20.8% of all rigs sampled).

Menippe nodifrons were small (mean CW: 38.4±3.20) and no ovigerous females were observed. Further evaluation is needed to determine to what degree the range of *M. nodifrons* has expanded to rigs in the nGOM.

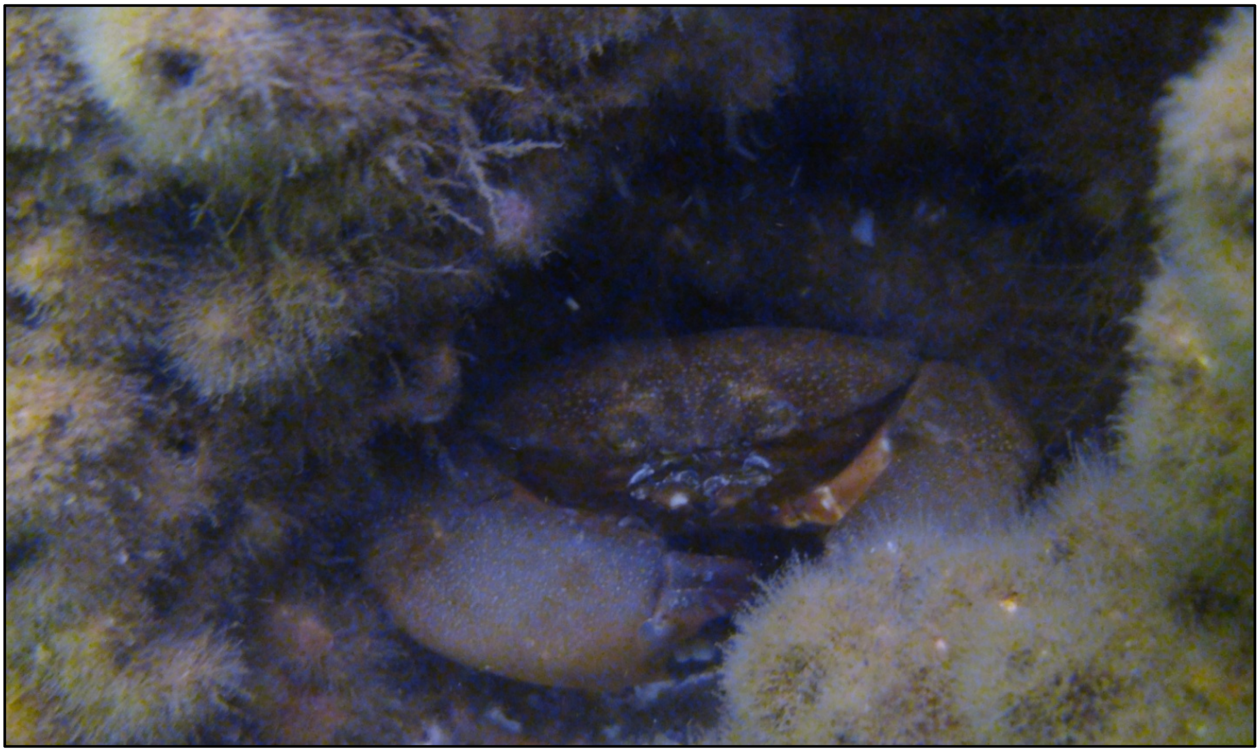

Figure 7: Adult stone crab (Menippe *adina*; specific size unknown) nestled between pieces of steel welded to the rig. These shelters were uncommon on rigs and often littered with crushed barnacle shells that stone crabs were observed preying upon.

3.5.4. Conclusions and Implications

Shallow rigs may be increasing the number of SCs in the nGOM by providing scarce hard bottom substrate in oxygenated waters and an added supply of SC zoea during spawning season. In 1998, there was between 559,494 and 870,007 m^2 of submerged rig surface area in the nGOM's federal waters in less than 50 ft. (15.24 m) (LGL and SAIC 1998). Between 1998 and the time of this study, the number of shallow rigs decreased by roughly 32%. Assuming those rigs were randomly selected for removal, roughly 380,456 to 591,605 m^2 of submerged rig surface area remained in shallow water at the time of this study. Assuming the most

conservative estimate of crab density (mean density off the shoal 1.80 SCs/m^2) is representative of densities on the Outer Continental Shelf, there were between 684,820 and 1,064,888 SCs living on shallow rigs (<15.24 m). This estimate is likely to be highly conservative because it does not account for higher density of crabs on SS and the potential for higher density on other sandy bottoms or rigs located in deeper waters of the nGOM where hypoxia is not an issue. At this point, we can only speculate that rigs improve the net production of SCs, but it is clear that many SCs use rigs as suitable habitat for growth and reproduction.

Although SCs are known to use rigs, the wide-scale use of rigs on and off SS as important forage and refuge sites is a new finding. Rigs on and off SS provide important forage and refuge sites for SCs. Higher densities on the shoal suggest that rigs are of higher relative importance on than off SS. Nevertheless, rigs off the shoal appear to support high densities of crabs by providing refuge in the normoxic part of the water column. Crabs living at rigs had a comparable sex ratio and CW_{50} to SCs throughout their range, and their densities on rigs were higher than their densities reported in natural substrates. These findings suggest further sand mining of SS and removal of rigs and their associated rubble accumulations may negatively affect SCs on and around SS.

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CHAPTER 4. SUMMARY AND CONCLUSIONS

Throughout the course of this study, many ecologically and economically important species were observed on SS, including sea turtles and young of the year *Lutjanus campechanus* and *Lutjanus synagris* (Age-0 *Lutjanus spp.*). Sea turtles were sighted 5 times on SS from July to September of 2014 (Figure 1), and were primarily sighted in the vicinity of rigs. Sea turtles were only sighted on SS when normoxic bottom waters were present, and they were not sighted off the shoal. During July of 2014, diver observations indicated a high rate of settlement of age-0 *Lutjanus spp.* to rigs on SS and no observed aggregation at rigs surrounding the shoal. Age-0 *Lutjanus spp.* were seemingly the most numerous fishes living around rigs on SS until early-August 2014, when a hypoxic event corresponded with a large reduction of Age-0 *Lutjanus spp.* on the shoal. Age-0 *Lutjanus spp.* were associated with large mounds of barnacle rubble on the

Figure 1: Loggerhead sea turtle (*Caretta caretta*) videoed near a rig in Ship Shoal, block 93. Sea turtles were sighted around rigs on Ship Shoal 5 times from July to September of 2014.

bottoms surrounding rigs, and were commonly observed in stone crab burrows. These anecdotal findings suggest SS may provide a variety of ecological functions that were outside the scope of this study and deserve further attention in future investigations.

Higher frequency and contribution of demersal fishes at SS rigs (SSR) than rigs inshore of the shoal (RIS) and rigs offshore of the shoal (ROS) suggest that SSR are of higher relative importance for demersal fishes than rigs surrounding the shoal. Fish assemblage composition was significantly different between SSR, RIS, and ROS ($P<0.05$). SIMPER analysis indicated there was 48.4% dissimilarity for the SSR vs. RIS comparison, 49.0% dissimilarity for the SSR vs. ROS, and 49.6% dissimilarity for the RIS vs. ROS. The most notable differences between assemblages were larger contributions of demersal fishes at SSR than RIS and ROS, and higher contributions of brackish-tolerant species at RIS and marine species at ROS. Mean species richness was 10.7 at SSR, 8.6 at RIS, and 9.5 at ROS. Species richness was significantly higher at SSR than RIS ($P<0.05$), but there were no significant differences for SSR vs. ROS and RIS vs. ROS ($P>0.05$). Hypoxia was intermittent at SSR and persistent at RIS and ROS. Mean hypoxia thickness was significantly greater ($P<0.05$) at RIS (2.6 m) and ROS (3.1 m) than it was at SSR (0.6 m). Higher frequency and contribution of demersal species at SSR than RIS and ROS is likely related to differences in hypoxia intensity. Since hypoxia was less frequent and thinner at SSR than RIS and ROS, more fishes and other demersal organisms may have been able to endure summertime hypoxia at SSR better than at RIS and ROS.

Rigs on and off SS provide important forage and refuge sites for stone crabs (SC), but higher SC densities and greater size at maturity at rigs on SS suggest rigs are of higher relative importance on than off the shoal. Crab densities were roughly twice as high on SS rigs as there were on rigs adjacent to the shoal (mean 4.0 vs. 1.8 SCs/m^2; $P<0.05$), and the carapace width

where 50% of females were ovigerous (CW_{50}) was 26.4 mm smaller for females off than on SS (P=0.057). Crabs at rigs on and off the shoal did not significantly differ in mean carapace width (45.2 vs. 42.4 mm and Males- 28.8 vs. 32.6 mm, respectively), size class distribution, or sex ratio. Crabs on and off SS had higher densities at rigs than those reported for natural substrates, and their sex ratio and CW_{50} were comparable to those reported for crabs in natural substrates. Although higher densities at rigs on the shoal suggest that rigs are of higher relative importance on than off the shoal, rigs off the shoal are also important because they appear to support high densities of crabs by providing refuge in the normoxic part of the water column.

Although it is widely known that reef-associated fishes and SCs are found at rigs, the relative importance of small rigs in nearshore Louisiana has not been previously documented. Higher contribution of demersal fishes and densities of SCs at SS rigs than rigs in surrounding areas suggest rigs on the shoal are of higher relative importance for demersal fishes and SCs than rigs in surrounding areas; however rigs in surrounding areas are still important because many economically and ecologically important organisms utilize these structures. The differences between fish assemblage composition and density of SCs at SS rigs and rigs in the surrounding area may be associated with less intense hypoxia on than off SS. If hypoxia is actually driving the observed differences between the two areas, rigs on SS may serve as hypoxia refugia for reef-associated organisms that have strong associations with the bottom. Over the course of this study, 3.3 million cubic yards of sediment was removed from SS, and 11 of 63 sampled rigs were removed. These findings suggest that further mining of SS and removal of rigs may be detrimental to reef-associated organisms in nearshore Louisiana.

VITA

David Reeves was born in Homewood, Alabama to Glenn and Claire Reeves. He graduated from Bayside Academy in 2008. He received his Bachelor of Science in biological sciences from Loyola University New Orleans in 2012 where he fell under the mentorship of Dr. Frank Jordan and learned to appreciate and study extremely small fishes. In partial fulfillment of his Bachelor of Science, he completed a thesis project on the utility of stream restorations for the management of Okaloosa darters (*Etheostoma okaloosae*). In August of 2012, he began working under Drs. Donald Baltz and Edward Chesney on his master's degree in the Department of Oceanography and Coastal Sciences. He will graduate in May of 2015.