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Movement patterns of red snapper *Lutjanus campechanus* based on acoustic telemetry around oil and gas platforms in the northern Gulf of Mexico

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ABSTRACT: Offshore oil and gas platforms in the northern Gulf of Mexico are known aggregation sites for red snapper *Lutjanus campechanus*. To examine habitat use and potential mortality from explosive platform removals, fine-scale movements of red snapper were estimated based on acoustic telemetry from March 2017 to July 2018. Study sites in the northern Gulf of Mexico, USA, included one platform off coastal Alabama (30.09° N, 87.88° W) and 2 platforms off Louisiana (28.81° N, 91.97° W; 28.92° N, 93.15° W). Red snapper (n = 59) showed a high affinity for platforms, with most (94 %) positions being recorded within 95 m of the platforms. Home range areas were correlated with water temperature and inversely correlated with dissolved oxygen concentrations. During summer and fall, red snapper used larger areas and many fish (54 %) emigrated from their platforms but most (83 %) returned in ≤3 d. Site fidelity for red snapper was 31 % yr^{-1} and residency time was 7 mo, but the probability-of-presence at platforms was 70 % after 1 yr, indicating the importance of platforms for this species. Overall fishing mortality was high for platforms (F = 0.86, 95 % CL = 0.47–1.40), but since the stock is managed on a quota basis this high mortality should have little effect on total stock abundance. Thus, platforms can still provide an important habitat for red snapper, and consideration of area use patterns, fishing mortality and environmental factors can reduce red snapper mortality when scheduling explosive platform removals. As such, the present study indicates that an optimum time for explosive removal would be in late summer after the red snapper fishing season is completed.

KEY WORDS: Acoustic telemetry · Platform site fidelity · Residency · Mortality · Artificial reefs

1. INTRODUCTION

1.1. Oil and gas platform removal

Oil and gas platforms (hereafter platforms) provide both ecological and economic value to the northern Gulf of Mexico. Addition of platforms has only added about 20 km^2 of artificial reef habitat to the naturally unstructured seafloor in the northern Gulf of Mexico (Reynolds et al. 2018). While the total amount of platform habitat is small compared to the total amount of natural hard substrate (1578 km^2; Gallaway et al. 2009), platforms can be very important habitat to reef fishes in areas lacking natural reef habitat. In such areas the addition of structured habitat is valuable to a number of species, ranging from encrusting organisms to economically important reef fishes (Gallaway & Lewbel 1982, Stanley & Wilson 1996, Schroeder & Love 2004, Gallaway et al. 2009).

In 2017, there were approximately 2000 platforms in the Gulf of Mexico. This number has been reduced from a peak of around 4000, and will continue to

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decline as removals exceed installations (Pulsipher et al. 2001, Kaiser & Pulsipher 2003). Platforms and all associated structures must be completely removed to 4.6 m below the seafloor 1 yr after lease termination in order to minimize safety hazards and harm to the environment (Code of Federal Regulations 2013). Total removal by explosives is one method of removal and accounts for about 40% of all platform removals (Gitschlag et al. 1997, Kaiser & Pulsipher 2003, Barkaszi et al. 2016). Underwater explosives generate shock waves and acoustic energy that result in substantial fish mortalities (Gitschlag et al. 1997, 2000, Schroeder & Love 2004). Hundreds to thousands of fish are killed during a platform explosion, with variations due to structure, water depth and removal schedule (Gitschlag et al. 1997). Atlantic spadefish *Chaetodipterus faber*, blue runner *Caranx crysos*, red snapper *Lutjanus campechanus* and sheepshead *Archosargus probatocephalus* account for nearly 85% of the total fish mortality from explosive removals in the northern Gulf of Mexico (Gitschlag et al. 2000).

1.2. Red snapper on platforms

In some areas of the Gulf of Mexico, a substantial portion of the red snapper population resides around platforms. Natural habitat is limited along the shallow West Louisiana Shelf, and in this area platforms provide the majority of habitat for age-1 and age-2 red snapper (Karnauskas et al. 2017). Red snapper live near platforms most likely for increased shelter and food resources (Stanley & Wilson 2003, Gallaway et al. 2009, Simonsen et al. 2015). Relative biomass estimates indicate that red snapper are often a dominant species on standing platforms (Reynolds et al. 2018), and that platforms may help in production of this species (Gallaway et al. 2009).

Gallaway et al. (2009) indicated that platforms provide valuable habitat for red snapper, but they may also make fish more susceptible to fishing mortality (F). Red snapper recruit to platforms around age-2, which is about the same time they begin entering the fishery (Gitschlag et al. 2003, Gallaway et al. 2009). Platforms are popular fishing sites that are easily accessible to both commercial and recreational fishers and have been estimated to attract nearly 87% of all boating activity, adding hundreds of millions of USD to the local economies for fishing-related activities (Gallaway & Lewbel 1982, Hiett & Milon 2002). Fisher surveys at popular boat launch locations off Louisiana reported that most fishers visited around 7 platforms trip^{-1} (Gordon 1993). Platforms showed a higher total mortality (Z) for red snapper (Z = 0.54; Gitschlag et al. 2003) compared to submerged artificial reefs whose locations were either published (locations available to public from state agencies) or unpublished (locations limited, Z = 0.39–0.48; Topping & Szedlmayer 2013, Williams-Grove & Szedlmayer 2016b, Szedlmayer et al. 2020). However, on a total population basis only about 3–5% of the total red snapper stock occurs on platforms (Karnauskas et al. 2017, Szedlmayer et al. 2020). While the combined effects of platform removal and platform fishing mortalities may not be large considering the total population, the effects on the local fisheries can be substantial.

1.3. Telemetry studies on platforms

Advances in telemetry have enhanced habitat use studies of fish species by providing continuous presence–absence and accurate position data (Williams-Grove & Szedlmayer 2020). Telemetry has been applied in several previous platform studies and provided important insights on the movement patterns of other species (Jorgensen et al. 2002, Lowe et al. 2009, Brown et al. 2010, Anthony et al. 2012, Mireles et al. 2019). In contrast to the Gulf of Mexico's platforms where fishing is permitted, most platforms in other areas have limited public access and thus they act as de facto marine reserves (Schroeder & Love 2004, Lowe et al. 2009). For example, telemetry studies on reef fishes (e.g. widow rockfish *Sebastes entomelas*, cabezon *Scorpaenichthys marmoratus*, lingcod *Ophiodon elongatus* and California sheephead *Semicossyphus pulcher*) off California indicated the importance of platforms as habitat to these and other economically important species (Lowe et al. 2009, Anthony et al. 2012, Mireles et al. 2019).

In the Gulf of Mexico, several studies have used telemetry to examine red snapper movement patterns on other types of artificial reefs (Szedlmayer 1997, Szedlmayer & Schroepfer 2005, Topping & Szedlmayer 2011a, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a, 2017). These telemetry studies on smaller artificial reefs were successful in tracking red snapper over long time periods (~2 yr) and reported high site fidelity (72–88% yr^{-1}). In contrast, only 2 previous telemetry studies attempted to estimate red snapper movement patterns on standing platforms, and results were less conclusive compared to the studies on smaller artificial reefs due to method difficulties and limited study durations (7–200 d; Peabody 2004, McDonough 2009).

Thus, little information is available on habitat use by red snapper around platforms.

The present study examined red snapper habitat use patterns around platforms, using the VEMCO Positioning System (VPS). This technology has provided major advances in accuracy (±2–7 m), frequency of positions (~5–10 min intervals between fish positions) and study periods (e.g. months to years), and at the time of the study was the best method for determining red snapper movement patterns (Andrews et al. 2011, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). As removal of platforms continues in the northern Gulf of Mexico with little new construction of platforms, it is important to estimate the potential future effect of this habitat loss on the red snapper stock. To help in this evaluation, movement patterns were quantified by measuring residency time, site fidelity, probability-of-presence and home range area around platforms. Red snapper positions were examined for diel and seasonal patterns and compared to environmental parameters (DO concentrations, salinity, temperature). We also estimated instantaneous natural (M) and fishing (F) mortality independent of fisher reporting, which are critical parameters for red snapper stock assessments. An important practical application of this study may be the use of red snapper movement patterns around platforms to inform the scheduling of removals, with the intent of minimizing red snapper mortalities from explosive removals. For example, can time periods be identified when red snapper are farther away from platforms, thus potentially reducing mortalities from explosive removal?

2. MATERIALS AND METHODS

2.1. Study location array design

Receiver VPS arrays were deployed on 3 platforms (East, Center and West) selected from 2000 that were available in the northern Gulf of Mexico at the beginning of 2017 (Fig. 1). We selected representative platforms with a stratified random selection process of 3 platforms. Strata were selected based on geographical differences (1) east of the Mississippi River, (2) west of the Mississippi River to longitude 92° W and (3) west Louisiana to east Texas 92°–95° W. Within each stratum, one platform was randomly selected among all platforms with at least 4 legs that were located between the nearshore State boundaries and 30 m depths for the offshore limit.

The East platform was a large complex composed of 3 connected platforms (total area = 1467 m^2) and was located over sand substrate in 17 m depths, 25 km (30.09° N, 87.88° W) southeast of Dauphin Island, Alabama, USA. Both Center and West platforms were single structures with 4 legs attached to the seafloor. The Center platform (total area = 263 m^2) was located 86 km (28.81° N, 91.98° W) southeast of Pecan Island, LA, over mud–silt substrate in 30 m depths. The West platform (total area = 297 m^2) was located 106 km (28.92° N, 93.15° W) southwest of Pecan Island, LA, on sand substrate at 23 m depths.

The East VPS array was deployed on 28 March 2017, the Center on 4 July 2017 and the West on 7 July 2017. Array design was similar to previous studies (Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a), but was adapted for the larger size of platforms with 6 Vemco VR2Tx receivers spaced for maximum detection efficiency (100% at 400 m; Piraino & Szedlmayer 2014). A center receiver was placed 20 m north of each platform with surrounding receivers placed 300 m to the northeast, northwest, southeast and southwest of the center receiver and a south receiver was placed 424 m south of the center receiver (Fig. 2). Receivers were attached to mooring lines 1.5 m (East platform) or 4.5 m (Cen-

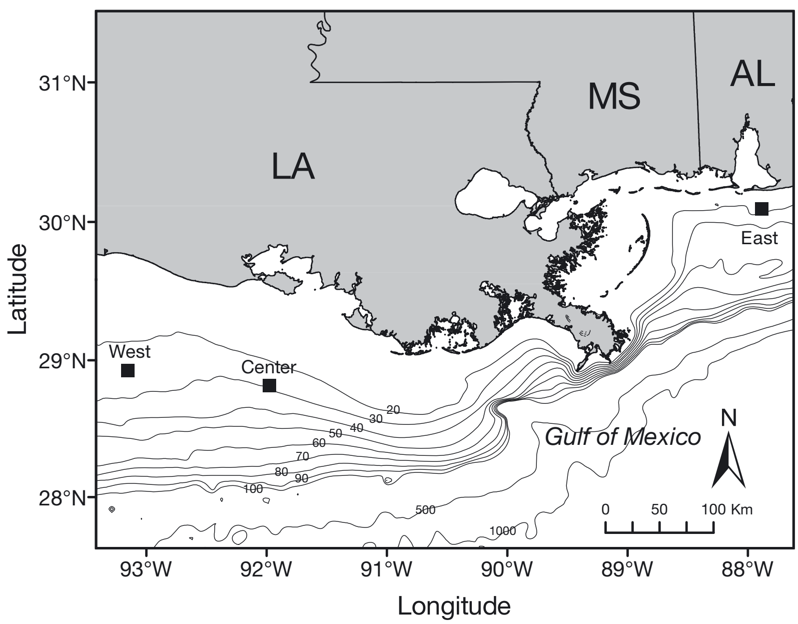

Fig. 1. Location of platforms used for studying movement patterns of red snapper in the northern Gulf of Mexico. Black squares: the 3 study platforms off coastal Alabama and Louisiana, USA

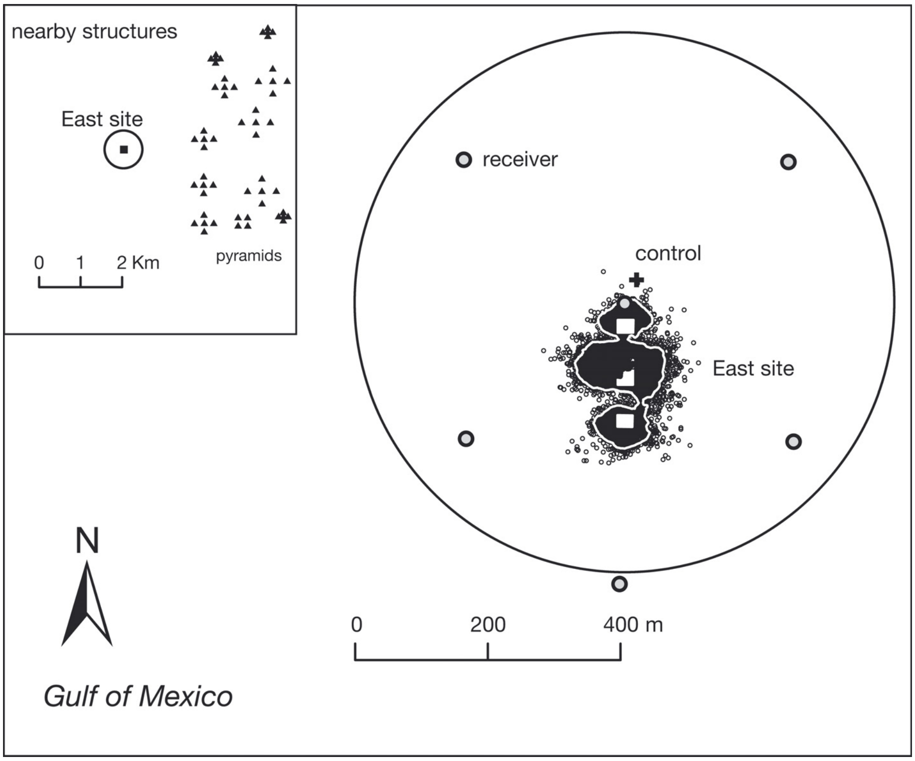

Fig. 2. East platform and positions of VEMCO VR2Tx receivers (gray circles). One receiver was placed near the platform (20 m), 4 receivers were placed 300 m northwest, northeast, southeast and southwest from the center receiver and one receiver was placed 424 m south of the center receiver. A control transmitter (cross) was placed 114 m northeast of the center receiver. Large circle: 100% detection area for transmitters by at least 3 receivers; white squares: platform to scale. Small black circles: positions of a red snapper *Lutjanus campechanus* (fish no. F206); white polygon line: the 95% kernel density estimation area contour. Inset shows the locations of nearby artificial reefs

ter and West platforms) above the seafloor depending on depth (Topping & Szedlmayer 2011a, Piraino & Szedlmayer 2014). Dissolved oxygen (DO) meters (U26-001, Onset Incorporated) were placed 40 cm above the seafloor and salinity meters (U24-002-C, Onset Incorporated) were placed below the receiver on the center receiver mooring line at each platform. These Onset remote meters sampled at 10 min intervals. Temperature, salinity and DO concentrations were also measured from a surface-vessel-operated YSI meter (Model 6920, YSI Incorporated) at each platform during all platform visits. A control transmitter (V16-6x) was placed 1.5 m above the seafloor on a mooring line approximately 100 m north of the center receiver to determine the accuracy of positional data and array performance. Receivers and environmental loggers were retrieved and replaced every 4 mo by SCUBA divers. Receiver detection data of transmitter-tagged red snappers was post-processed by VEMCO for fish positions based on the time differential of a transmitted signal arrival at 3 or more receivers (Vemco).

2.2. Tagging procedure

Red snapper individuals (n = 71) were tagged with acoustic VEMCO V16-6L transmitters (69 kHz, 20–69 s signal interval, 5 yr battery life, power: 152 dB) on the platforms, following previous tagging protocols (Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). Prior to fish tagging, DO concentration was measured at the maximum depth with the surface-operated YSI meter and if <2.5 mg l^{-1}, tagged fish were not released. Only fish >430 mm total length (TL) were tagged and released in the present study. Fish were captured with hook-and-line, anesthetized in 150 mg l^{-1} MS-222 (tricaine methanesulfonate) for 90 s, weighed (0.1 kg), measured (TL, mm), injected with 0.4 ml kg^{-1} oxytetracycline dehydrate (an antibiotic to reduce infections) in the epaxial muscle and surgically implanted with V16-6L transmitters into the peritoneal cavity. Each fish was also tagged with an external anchor tag (Floy® FM-95W) for identification by fishers and on return tagging efforts. After recovery, fish were released within a predator protection cage that remotely opened on the seafloor (Piraino & Szedlmayer 2014, Williams et al. 2015). Fish that did not leave the cage on their own initiative after a minimum of 15 min submersion in the cage were not released. At the start of the study, 12–15 transmitter-tagged fish were released at each platform, and after fish emigrated or were caught, additional fish were tagged and released on return trips to maintain the number of tagged fish around 10 fish $platform^{-1}$.

2.3. Fine-scale tracking

The VPS arrays were used to identify tagged fish as active (continuously swimming), caught (sudden disappearance near reef center, F), emigrated (tracked for a period of time before progressively moving farther away from the reef center and then disappearing) or deceased (tag becomes stationary; Williams-Grove & Szedlmayer 2016a,b). Fish positions were analyzed with R v.3.4.3 (R Core Team 2017) for home range area estimates (95% kernel density estimation [KDE]; Calenge 2006, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). The response variable was area use (95% KDE) for each platform by individual tagged red snapper, in hourly intervals for diel comparisons and monthly intervals for all other comparisons. Area use was compared to fish size (TL), diel 3 h periods and seasonal time periods with generalized linear mixed models, with individual fish as repeated measures over time, with the GLIMMIX procedure in SAS v.9.4 software (Venables & Dichmont 2004, Seavy et al. 2005, Bolker et al. 2009). After significant differences were detected with the mixed models, a Tukey-Kramer test was used to show specific differences. Diel periods were combined into 3 h intervals and then defined as day (08:00–17:00 h), night (20:00–05:00 h), dawn (05:00–08:00 h) or dusk (17:00–20:00 h). Dawn and dusk were defined based on sunrise and sunset times throughout the year from the US Naval Observatory (Washington, DC, USA). Seasons were divided into summer (June–August), fall (September–November), winter (December–February) and spring (March–May). Mean environmental measures of DO concentration, salinity and temperature were calculated by month for each platform. Effects of environmental factors on fish home range area (95% KDE) were analyzed with repeated measures ANOVA, with DO concentration, salinity and temperature as continuous predictor variables and individual fish as repeated measures over time, with the GLIMMIX procedure in SAS v.9.4 (Schabenberger 2005, Kwok et al. 2008, Williams-Grove & Szedlmayer 2017).

Fish positions (easting and northing) were measured as distances (m) from the platform, with ArcMap v.10.4.1 (ESRI) (McKinzie et al. 2014). Distances from the platforms were calculated based on the distance between a fish position and the closest point of platform structure when fish positions were outside the platform legs. Positions inside the platform structure were defined as a distance value of 0 m. Fish were considered near a platform if positions were located <95 m from the platform. This distance (<95 m) was based on the mean radius of all 95% KDE areas +1 SD of the 95% KDE for each platform, fish and month (n = 372). Fish positions that were ≥95 m were considered not associated with platform structure. After fish positions were assigned as located inside (0 m), near (<95 m) or away (≥95 m) from the platforms, percent frequencies of positions were compared among these 3 locations.

2.4. Residency, site fidelity and probability-of-presence

Fish were identified as active resident, caught (F), emigrated or deceased (M) based on detection patterns, and these categories were applied to residency, site fidelity and mortality estimations (Williams-Grove & Szedlmayer 2016a,b). Residence time was defined as the time when 50% of the transmitter-tagged fish remained at their release platform over the study period (Schroepfer & Szedlmayer 2006, Topping & Szedlmayer 2011b, Williams-Grove & Szedlmayer 2016a). Site fidelity was defined as the maximum likelihood survival (S) of fish remaining at the release platform after 1 yr at liberty (Schroepfer & Szedlmayer 2006, Topping & Szedlmayer 2011b, Williams-Grove & Szedlmayer 2016a). A known-fate model in the program MARK was used to estimate residence time and site fidelity for tagged red snapper assuming a common start date (White & Burnham 1999, Schroepfer & Szedlmayer 2006, Topping & Szedlmayer 2011b, Williams-Grove & Szedlmayer 2016a). Fish that died or were caught were right-censored (removed) from the model and thus S was based on the conditional probability of surviving only emigration events for the study period. Due to frequent emigrations and subsequent returns of transmitter-tagged individuals to the platforms, a probability-of-presence was also calculated based on the mean daily percent of transmitter-tagged fish present over 1 yr (Lowe et al. 2009, Afonso et al. 2012). In the calculation of probability-of-presence, fish that died or were caught were removed.

2.5. Mortality estimates

A known-fate model was used to estimate instantaneous mortality rates (F, M, Z; Ricker 1975) for each platform in the program MARK with a staggered entry start date and conditional probabilities. Annual estimates were based on monthly time intervals for the study period (March 2017–July 2018; Topping &

Szedlmayer 2013, Williams-Grove & Szedlmayer 2016b). Instantaneous annual mortality rates were based on total S adjusted to 12 mo (Starr et al. 2005, Topping & Szedlmayer 2013, Williams-Grove & Szedlmayer 2016b). Recreational fishing seasons were open for 42 d from 1 June–4 September 2017 in Louisiana and Alabama, for 60 d from 24 May–12 Aug 2018 in Louisiana and 27 d from 1 June–22 July 2018 in Alabama. Commercial fishing seasons were based on individual quotas and open all year round.

3. RESULTS

3.1. Tagging and VPS events

In total, 71 red snapper were tagged on 3 platforms in the northern Gulf of Mexico. Of those fish, 12 were removed from further analyses due to tagging mortality and emigration within a 6 d tagging recovery period (Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a), leaving 59 fish that survived and were tracked for extended periods (95% >30 d; Fig. 3). All fish were larger than the Gulf of Mexico federal recreational length minimum of 406 mm TL (n = 59), and ranged in size from 439–868 mm TL (mean: 563 ± 93 mm).

3.2. Fine-scale tracking

We determined 875 295 accurate (±7 m) positions (~5 min intervals) from all platforms (Figs. 2, 4 & 5). Mean home range area (95% KDE) was significantly larger at the Center (15 064 m^2) and West (19 959 m^2) platforms compared to the East platform (8380 m^2, $F_{2,312}$ = 23.87, $p < 0.0001$). Red snapper showed unique patterns of area use depending on platform, but remained close to all platforms (28.2 ± 33.9 m) with 10% of positions within the platform structure, 84% near the platform structure and 6% away from platform structure (Fig. 6). Fish size was not significantly related to mean monthly home range area ($F_{1,57}$ = 0.28, p = 0.597).

3.3. Diel area use

There was a significant diel period (3 h bins) and platform interaction effect on red snapper area use ($F_{23,4964}$ = 9.79, $p < 0.0001$). Due to this significant interaction effect, diel patterns were compared separately for each platform. Fish at the East platform indicated no significant differences in area use over diel periods ($F_{7,1061}$ = 1.62, p = 0.125; Fig. 7). Fish at the Center platform showed significantly smaller area use during dawn (06:30 h) compared to all other time periods, no difference between day (12:30–15:30 h) and night (21:30–03:30 h) and smaller area use during early day (09:30 h) compared to later in the day (12:30–15:30 h, $F_{7,1878}$ = 6.68, $p < 0.0001$; Fig. 7). Fish at the West platform showed significantly increased area use during the midday (09:30–15:30 h) compared to all other time periods ($F_{7,2025}$ = 14.88, $p < 0.0001$; Fig. 7).

3.4. Seasonal area use and environmental measures

There was a significant interaction effect of season × platform on area use by red snapper, and differences were likely due to location and environmental variation among platforms ($F_{11,303}$ = 17.62, $p < 0.0001$). Due to this significant interaction effect, patterns of area use on platforms were compared separately. Red snapper at the East platform showed significantly smaller areas in the spring compared to other seasons ($F_{3,108}$ = 3.33, p = 0.022), whereas fish at the Center and West platforms used significantly smaller areas in the winter compared to other seasons (East: $F_{3,83}$ = 11.39, $p < 0.0001$; West: $F_{3,112}$ = 33.45, $p < 0.0001$; Fig. 8).

For all platforms, monthly area use by red snapper had a significant positive relation with temperature ($F_{1,303}$ = 112.9, $p < 0.0001$) and an inverse relation with DO concentrations ($F_{1,303}$ = 54.8, $p < 0.0001$). Fish at the Center and West platforms showed larger area use during months with higher temperatures and lower DO concentrations (Fig. 9) Relations between monthly area use patterns and temperature and DO concentrations were less apparent at the East platform and in general had less range and lower area use compared to Center and West platforms (Fig. 9). Area use was not significantly affected by salinity ($F_{1,277}$ = 0.61, p = 0.43) and ranged from 30–38 ppt by month. These mean monthly salinities at platforms were well within the upper and lower thresholds for Lutjanidae (Huff & Burns 1981, Castillo-Vargasmachuca et al. 2013).

3.5. Site fidelity and residency

Many fish (46%; 27 of 59) showed homing behavior, with long-term, short-term or both types of homing events. Long-term homing events (n = 24) were defined as absences from a platform for >3 d before

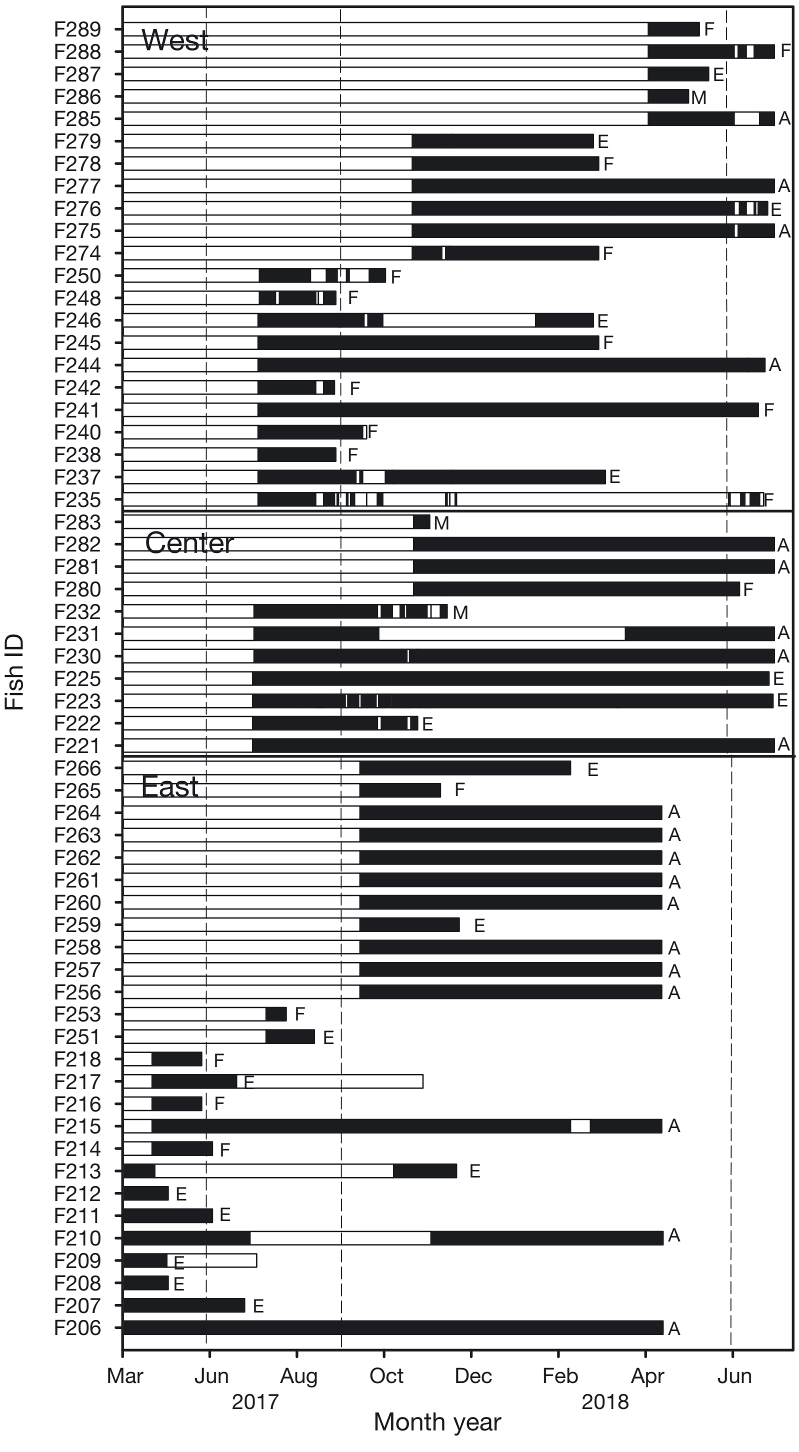

Fig. 3. Tracking periods for red snapper *Lutjanus campechanus* (n = 59) on platforms in the northern Gulf of Mexico. Black bars: active on platform; vertical dashed lines: fishing seasons from June–September 2017 and after June 2018. Letters represent final status of fish: A: active at end of study; E: emigrant at end of study; M: natural mortality; F: fishing mortality

subsequent returns (i.e. after 4–184 d). Short-term homing events (n = 119) were defined as absences from platforms for ≤3 d with subsequent returns. Fish that left and returned after ≤3 d were still considered resident to their original tagging location, whereas fish that were absent for >3 d were considered emigrants with respect to residency and site fidelity calculations. This residence criterion was based on the time duration of absences for fish (n = 17) that showed multiple emigrations and returns, with most (86 %) absences ≤3 d. For example, fish no. F223 left and returned to the Center platform 41 times (all ≤3 d) and was resident at the platform for 387 d until making a final emigration. Several fish showed both short-term and long-term homing events at the Center platform (n = 1), West platform (n = 7) and East platform (n = 1), with most occurring in the summer and fall months. Among all platforms, 8 fish showed permanent one-time emigrations (no returns) ranging from 34–385 d after tagging to the end of the study.

Site fidelity on all platforms was 31 % yr^{-1} (total $S = 0.28$, 95 % CL = 0.13–0.51) and residency time was 7 mo (Fig. 10). Site fidelities and residency times varied among platforms. Fish at the East platform had the lowest site fidelity at 27 % yr^{-1} (total S = 0.24, 95 % CL = 0.06–0.71) and residency time was 5 mo. Fish at the Center platform had a site fidelity of 38 % yr^{-1} (total $S = 0.35$, 95 % CL = 0.11–0.75) and residency time was 12.5 mo. Fish at the West platform had the highest site fidelity at 42 % yr^{-1} (total $S = 0.39$, 95 % CL = 0.22–0.66) and residency time was 4.5 mo. In contrast, probability-of-presence was 70 % over 1 yr for all platforms (polynomial regression, $r^2 = 0.99$, $F_{6,358} = 61568$, $p < 0.001$; Fig. 10).

3.6. Fishing and natural mortality

F was determined for 18 of 59 transmitter-tagged red snapper. Most fishing mortalities determined from VPS positions were validated by fisher-reported recaptures (89 % reporting rate), with time between tagging and capture ranging from 15–373 d. Total instantaneous

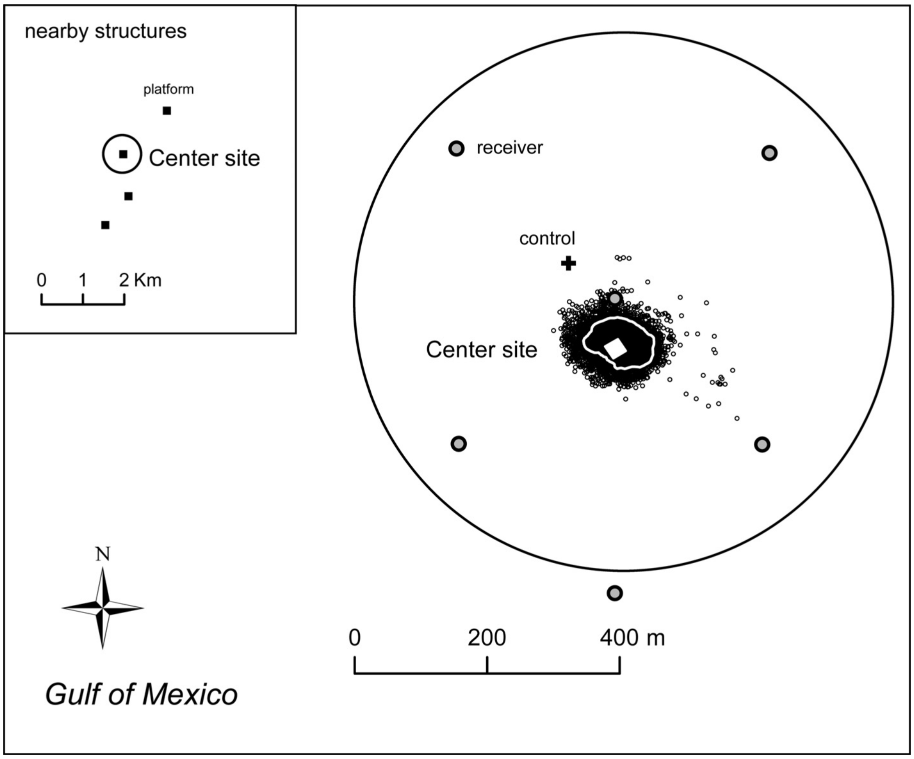

Fig. 4. Center platform and positions of VEMCO VR2Tx receivers (gray circles). See Fig. 2 for further details. Small black circles: positions of a red snapper *Lutjanus campechanus* (fish no. F281); white polygon line: the 95% kernel density estimation area contour

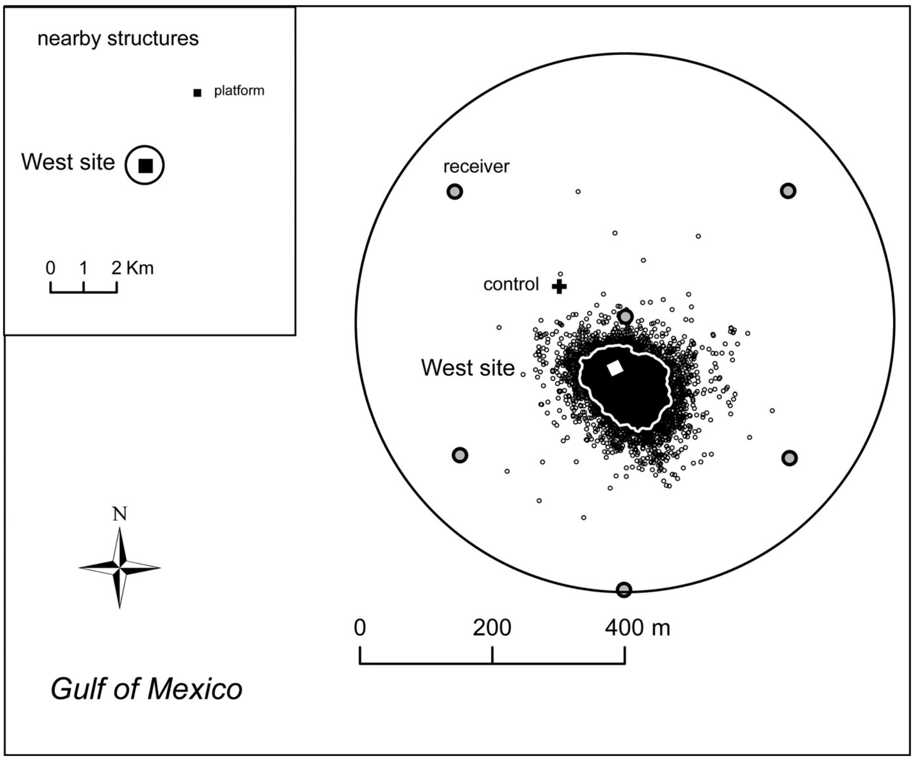

Fig. 5. West platform and positions of VEMCO VR2Tx receivers (gray circles). See Fig. 2 for further details. Small black circles: positions of a red snapper *Lutjanus campechanus* (fish no. F277); white polygon line: the 95% kernel density estimation area contour

annual F for all fish at all platforms was 0.86 (Table 1, Fig. 11). Variations in F occurred among platforms, with F = 0.73 (East platform), F = 0.12 (Center platform) and F = 1.48 (West platform) (Table 1).

A total of 3 natural mortalities occurred over all platforms, with $S_M^{(12/16)}$ = 0.92 (95% CL = 0.77–0.97) and M = 0.08 (95% CL = 0.03–0.26, 12–145 d after release; Fig. 11). Natural mortalities (n = 2) were detected at the Center platform with an annual S_M = 0.79 (95% CL = 0.45–0.95) and M = 0.23 (95% CL = 0.05–0.80) and at the West platform (n = 1) with an annual S_M = 0.92 (95% CL = 0.59–0.98) and M = 0.09 (95% CL = 0.01–0.53).

Z for all platforms was 0.94 (95% CL = 0.53–1.49) but varied among platforms. At the East platform, Z = 0.73 (95% CL = 0.24–1.64), at the Center platform, Z = 0.35 (95% CL = 0.10–0.96) and at the West platform, Z = 1.57 (95% CL = 0.81–2.50).

4. DISCUSSION

In this study, we successfully tracked red snapper (n = 59) around 3 platforms in the northern Gulf of Mexico. Over 875 000 accurate fish positions (±7 m) were recorded continuously (~5 min intervals) over the 16 mo study period and provided a greater understanding of how red snapper use platforms as habitat. Red snapper had a high affinity for platforms, with 94% of all positions recorded near the structure (within <95 m), indicating that these platforms provide important habitat for this species, similar to studies on other artificial reef structures in the northern Gulf of Mexico (Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a).

4.1. Diel patterns

Significant diel differences in area use patterns have been reported for red snapper on artificial reefs, with different patterns among studies. For example, in studies that examined small artificial reefs (concrete pyramids and metal cages), red snapper showed greater area use during the night (Topping & Szedlmayer 2011a,b), greater areas during the day (Piraino & Szedlmayer 2014) or diel patterns that depended on location (Williams-Grove & Szedlmayer 2016a). The present study showed both significant and non-significant diel patterns depending on the platform. Fish at the East and Center platforms showed little difference in area use during day and night, while fish at the West platform had greater area use in the day. One difference was that light intensity varied among platforms, and this variation in artificial light intensity could explain the diel differences observed among platforms. The East and Center platforms had extensive illumination (24 h); in contrast, the West platform (where fish area use was greatest during the day) only displayed small navigation lights. Red snapper are an opportunistic species that feed on a variety of reef and open-habitat associated prey items (Ouzts & Szedlmayer 2003, Szedl-

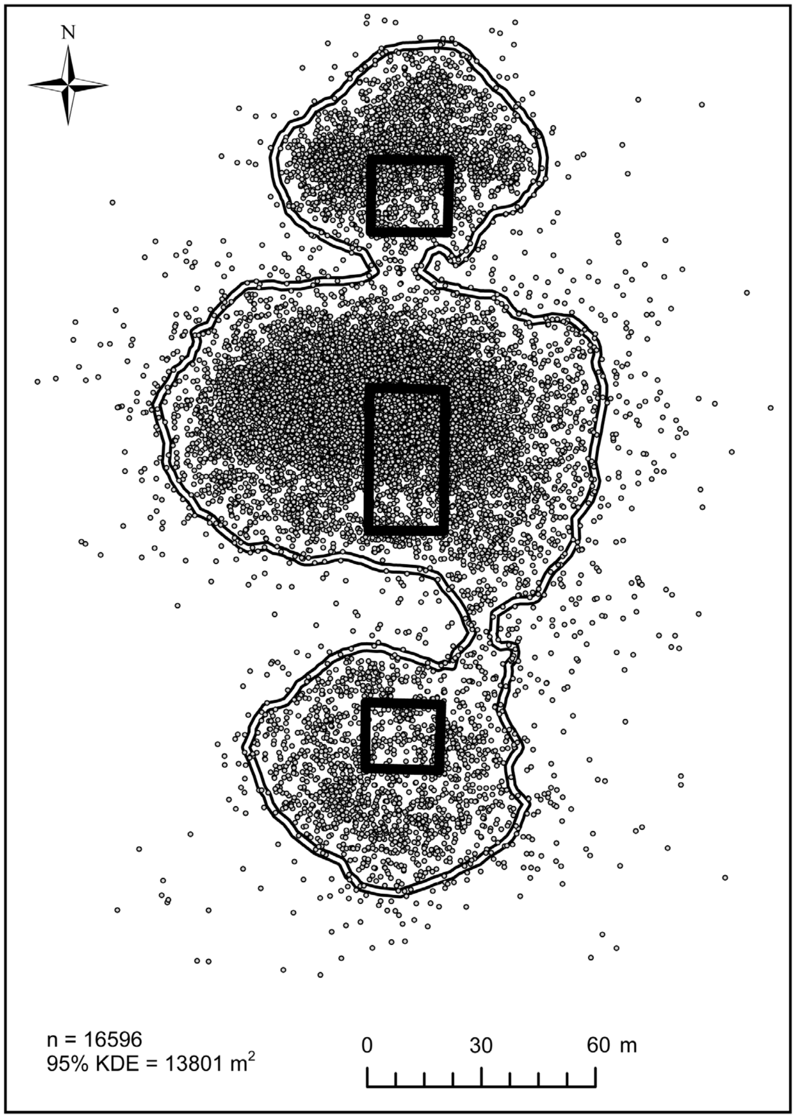

Fig. 6. Example of home range (95% kernel density estimation [KDE] area) of a red snapper *Lutjanus campechanus* on the East platform (fish no. F206). Gray dots: VEMCO Positioning System-calculated positions; double black lines: home range (95% KDE area); black polygons: perimeter of 3 drilling structures that were attached to the seafloor and connected with the superstructure above the waterline

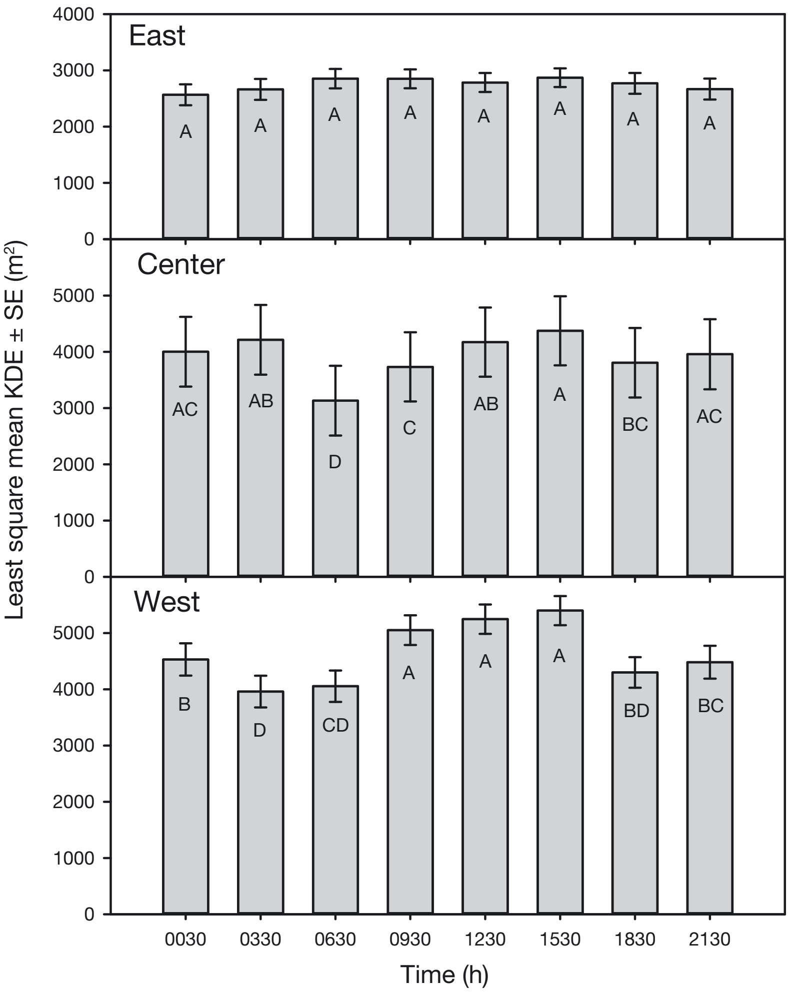

Fig. 7. Comparison of diel area use for red snapper *Lutjanus campechanus* on platforms in the northern Gulf of Mexico. Gray bars: least square mean home range (95% kernel density estimation [KDE] area) for 3 h intervals. Different letters indicate significant differences within a platform ($p \leq 0.05$)

mayer & Lee 2004, Wells et al. 2008, Simonsen et al. 2015, Schwartzkopf et al. 2017, Szedlmayer & Brewton 2020). Standing platforms aggregate a large number of fish species, including small schooling fish (e.g. antenna codlet *Bregmaceros atlanticus*) that have been identified in red snapper diets (Stanley & Wilson 1997, Simonsen et al. 2015, Reynolds et al. 2018). Platform lights tend to attract prey items to the illuminated surface waters and likely enhance the ability of the visually oriented red snapper to locate prey at night (Simonsen et al. 2015). This creates foraging opportunities during both day and night and could explain the lack of diel area use patterns observed on the East and Center platforms.

Larger area use during the day compared to night and crepuscular periods has been related to red snapper potentially reacting to increased predation pressure during these lower light periods (Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). Similar behavior might be expected around platforms due to associated larger predators (Stanley & Wilson 1997, 2004, Reynolds et al. 2018). This pattern was observed at the Center platform, with the smallest area use recorded at dawn when larger predators were likely more active, but not at the East or West platforms. Previous studies have reported mixed results on the effects of platform lighting. Keenan et al. (2007) suggested that platforms provide an enhanced foraging environment for larval, juvenile and adult fishes by providing sufficient light to locate and capture prey, as well as by attracting and concentrating positively phototaxic prey. Supporting this contention, Foss (2016) indicated that a higher abundance of fish prey items was observed in the diets of red snapper at lit platforms. In contrast, Barker & Cowan (2018) suggested that although fishes are attracted to the vertical relief of the structure, they may be avoiding the artificial light field at the surface either to escape nocturnal predation or to forage away from the platform. One difficulty with these previous studies and the present study is the small sample size of compared platforms. Thus, the patterns observed here regarding area use by red snapper on lighted versus unlighted platforms need to be interpreted with caution.

4.2. Seasonal movements

Seasonal differences in red snapper area use were correlated with environmental changes. Area use decreased during the winter months at the Center and West platforms, as temperature decreased and DO concentrations increased. This is consistent with previous observations that red snapper congregate near platforms during winter (Stanley & Wilson 1997). Metabolic rates in most fish are lower in the winter; thus, fish need less prey and forage over smaller areas compared to the

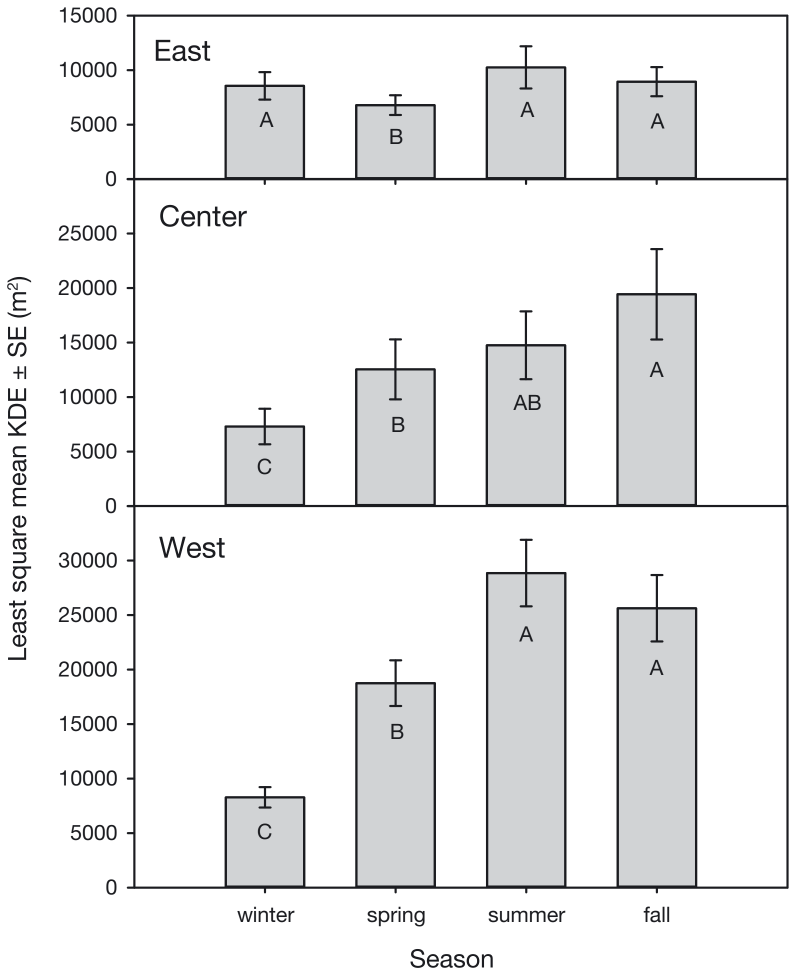

Fig. 8. Seasonal areas of red snapper *Lutjanus campechanus* on 3 platforms in the northern Gulf of Mexico. Gray bars: least square mean home range (95% kernel density estimation [KDE] area). Different letters indicate significant differences ($p \leq 0.05$)

warmer summer months (Johnston & Dunn 1987). Red snapper area use was larger in the summer and fall months and coincided with most (96%) short-term homing events. Temperatures were higher and DO concentrations were lower during the summer and fall, and red snapper likely expanded their foraging area to meet increased metabolic rates. Previous red snapper studies have observed similar increased area use in the summer in relation to temperature (Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). In contrast, the East platform did not show a decrease in area use during the winter (Fig. 8). Monthly area use patterns at the East platform had less range and smaller areas compared to the Center and West platforms. This decreased area use at the East platform and lack of a seasonal pattern may be related to the larger size of the East platform: the East platform was 3 times larger than the Center and West platforms. This greater size may allow less need to forage away the platform and thus reduce seasonal differences compared to the smaller sized Center and West platforms.

Red snapper showed larger area use during periods of hypoxia (<2 mg l^{-1}) in the late summer and early fall (July–September). Several other species have also displayed this pattern; for example, Atlantic croaker *Micropogonias undulates*, pinfish *Lagodon rhomboids*, bay anchovy *Anchoa mitchilli*, spot *Leiostomus xanthurus*, summer flounder *Paralichthys dentatus* and mudminnows *Umbra limi* all responded to hypoxic conditions by moving higher up in the water column or leaving affected areas (Johnston & Dunn 1987, Rahel & Nutzman 1994, Rabalais et al. 2001, Bell & Eggleston 2005, Craig & Crowder 2005). Previous studies have also reported that red snapper move up in the water column above hypoxic bottom conditions based on telemetry (Williams-Grove & Szedlmayer 2017) and hydroacoustic surveys on platforms (Stanley & Wilson 2004). To further investigate vertical responses to abiotic variables, future platform studies should tag red snapper with depth transmitters and deploy remote environmental meters.

4.3. Homing behavior

Overall, 46% of transmitter-tagged red snapper (n = 27) displayed homing behavior, with both short-term (<4 d; 83%) and long-term (4–184 d; 17%) periods absent from platforms with subsequent returns to their home platform. Homing behavior has been well documented in many fishes, ranging from pelagic to reef-dwelling species, and has been related to reproduction, shelter and foraging (Matthews 1992, Ogura & Ishida 1995, Robichaud & Rose 2001, Kolm et al. 2005, Døving et al. 2006, Loher 2008, Lowe et al. 2009, Mitamura et al. 2009, Rooker et al. 2014, Herbig & Szedlmayer 2016, Lewandoski et al. 2018). For example, a tracking study observed homing behavior in vermilion rockfish *Sebastes miniatus* and lingcod

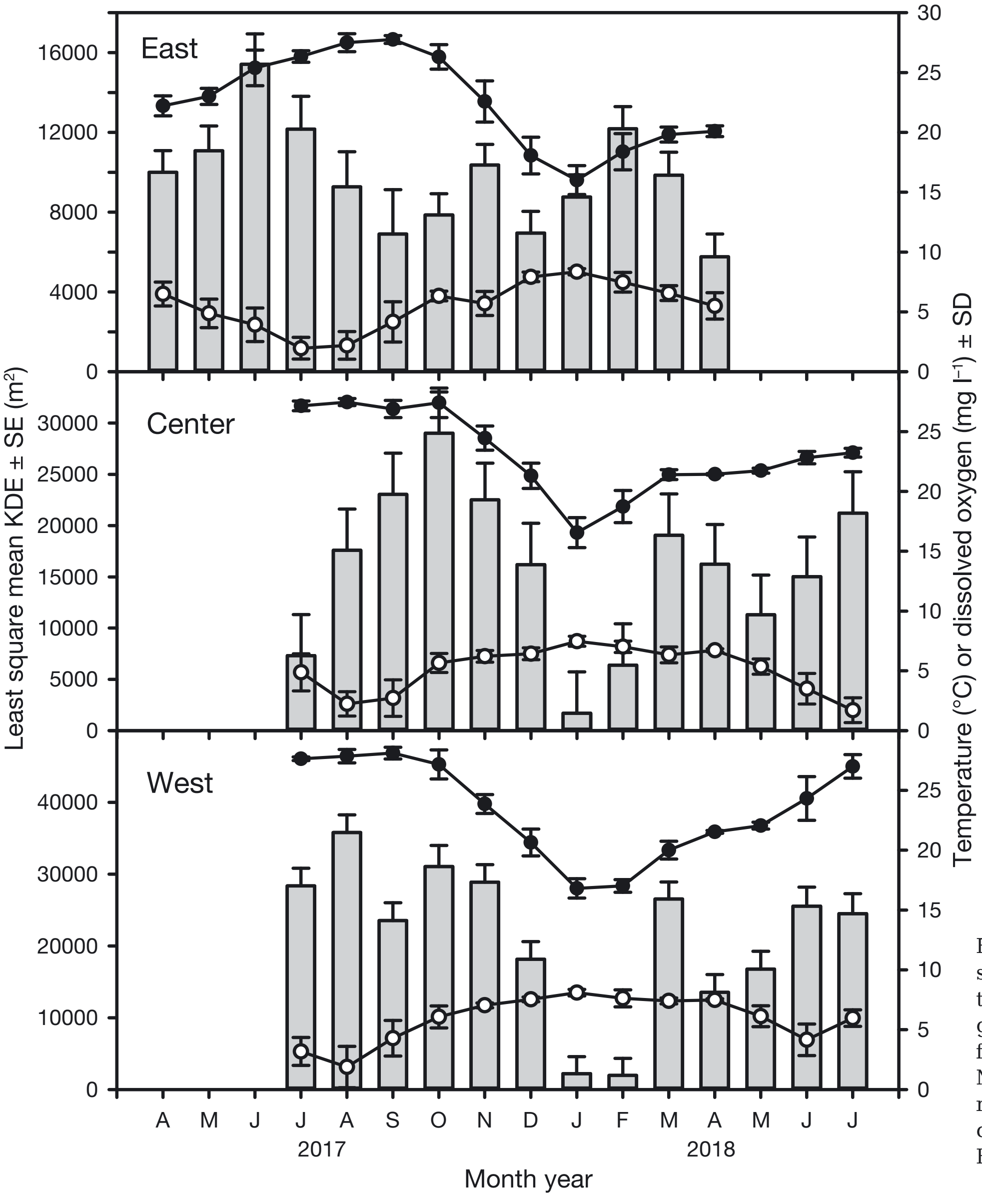

Fig. 9. Monthly area use for red snapper *Lutjanus campechanus* to temperature and dissolved oxygen (DO) concentration on platforms in the northern Gulf of Mexico. Gray bars: least square mean home range (95% kernel density estimation [KDE] area). Black circles: temperature; white circles: DO

Ophiodon elongatus on platforms with movements among platforms and natural reefs (Anthony et al. 2012). In that study, when vermilion rockfish and lingcod were translocated from platforms to natural reefs, they moved back to the platforms over 11–19 km distances in <24 h, indicating that platforms provided preferred habitat over natural reefs for these species (Anthony et al. 2012).

Homing behavior has also been previously reported for red snapper in the northern Gulf of Mexico, with fish returning to their original tagging site after extended time periods (23–90 d; Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). Red snapper in the present study returned to their original platform after both short (≤3 d) and long periods away (4–184 d). Short-term movements (1–4 h) have previously been documented in red snapper on gas pipelines with frequent movements outside the receiver range (Szedlmayer & Schroepfer 2005). Movements outside the receiver range in the present study were likely to nearby open habitat or reef structures for foraging. Benefits of emigrating to these secondary sites likely outweighed the risk associated with moving away from protective reef habitats by increasing foraging opportunities and prey availability. How red snapper navigate between reefs is still unknown; however, it is possible that each platform has its own unique sound or chemical signature that aid in homing (Lowe et al. 2009).

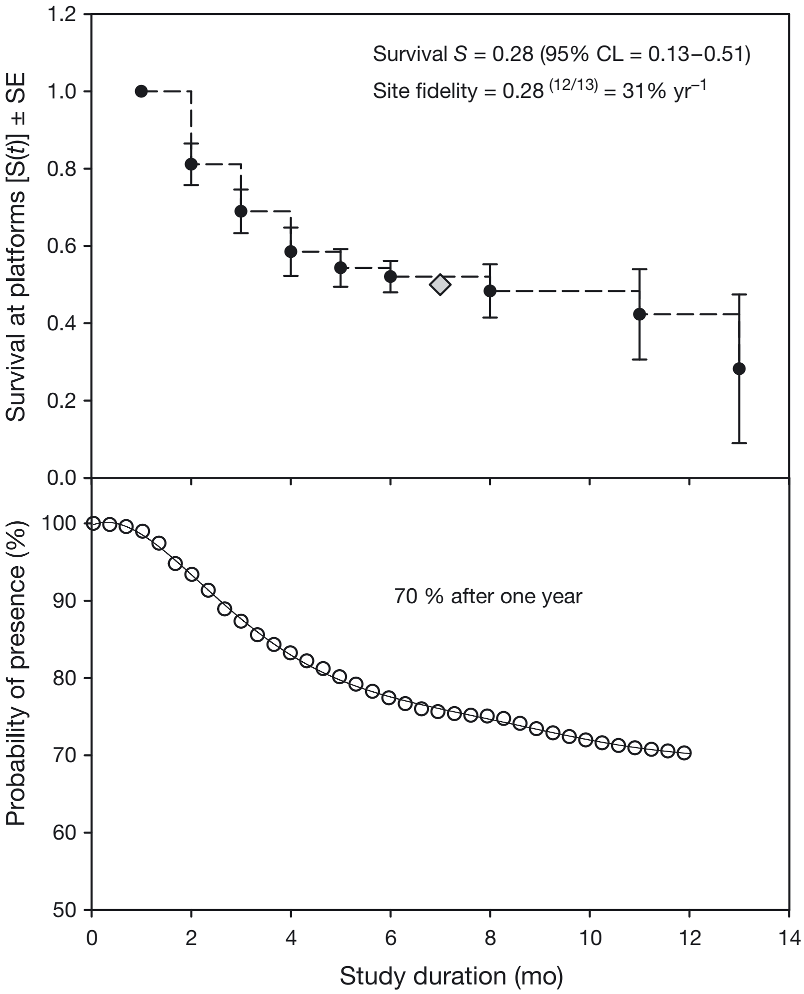

Fig. 10. Red snapper *Lutjanus campechanus* survival (S) and probability-of-presence on platforms in the northern Gulf of Mexico. For the survival plot, dashed lines are the proportion of fish that were resident each month and points and error bars are estimates of S for each month. Gray diamond: median residence time (7 mo). For the probability-of-presence, the black line is a 6 factor polynomial regression ($r^2 = 0.99$) of cumulative probability of presence on time since tagging. Open circles: cumulative percent presence at 10 d intervals after tagging

4.4. Residency, site fidelity and probability-of-presence

Red snapper site fidelity (31% yr^{-1}) and median residency time (7 mo) were lower than other telemetry-based estimates on smaller artificial reefs (Szedlmayer & Schroepfer 2005, Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). The first long-term (5 yr) tracking study of red snapper on artificial reefs indicated a median residency time of 18 mo and a site fidelity of 72% yr^{-1} (Topping & Szedlmayer 2011b). More recent studies also observed high site fidelity of 82–88% yr^{-1} and residency of 10–23 mo (Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a).

In contrast, lower red snapper site fidelities were reported on a 'ship' artificial reef (27% after 200 d) and around a complex of concrete culverts and a tugboat (58% after 200 d; Garcia 2013). Larger reefs, like platforms and ships, are complex habitats that support high abundances of large fish (Stanley & Wilson 1996, 1997, 2000, Reynolds et al. 2018). These higher abundances can create both intraspecific and interspecific competition for limited resources, causing red snapper to make short-term foraging emigrations for increased prey at other sites, as indicated in the present study on the Center and West platforms.

Fish at the East platform had the lowest site fidelity (27% yr^{-1}) and had fewer short-term homing events. However, 4 fish that made long-term emigrations did return to the East platform. This platform was located in close proximity (1.5 km) to many smaller artificial reefs (Alabama Department of Conservation and Natural Resources 2016, Mudrak & Szedlmayer 2020b; Fig. 2). Small artificial reefs are typically dominated by red snapper, and thus interspecific competition may be reduced in comparison to larger platforms (Mudrak & Szedlmayer 2012). Fish at the East platform may have emigrated and taken up residence on nearby smaller artificial reefs to reduce interspecific competition and predation pressure from the typically larger predators attracted to platforms. This suggestion was supported by 2 reported captures of transmitter-tagged red snapper from a small artificial reef in close proximity to the East platform. In turn, the reduced number of short-term emigrations and returns at the East platform may also be attributable to F occurring at other reef sites after leaving the platform.

Red snapper residing on platforms clearly showed different behavior and movement patterns compared to smaller submerged artificial reefs (Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a). They had a much greater tendency to emigrate away from the

Table 1. Fishing mortality (F, and 95% CI) of red snapper for each platform and overall (total)

Platform	Tracked	Caught	Survival	95% CI	F	95% CI
East	26	5	0.48	0.19–0.79	0.73	0.24–1.64
Center	11	1	0.88	0.49–0.98	0.12	0.02–0.71
West	22	12	0.23	0.09–0.47	1.48	0.74–2.41
Total	59	18	0.42	0.25–0.63	0.86	0.47–1.40

platform with subsequent returns. These multiple excursions indicate that estimates of residency and site fidelity may be misleading and underestimate the actual importance of platform habitat for this species, because in the present study if a red snapper was absent for >3 d it was considered permanently emigrated; i.e. 15 transmitter-tagged red snapper emigrated then returned 24 times after absences of 4–184 d. Although useful for comparisons to previous studies, our definition of residency and site fidelity does not account for these returns of red snapper after absences of >3 d from their tagging platforms. To further examine the importance of platforms for red snapper and account for these returns, a probability-of-presence was estimated based on the percentage of days spent on the platform compared to the total days tracked (Lowe et al. 2009, Afonso et al. 2012). This estimate indicated that transmitter-tagged red snapper spent 70% of their time residing on a platform over a 1 yr period. This probability-of-presence would also likely be an underestimate, because some fish that emigrated and did not return to a platform may have been caught by fishers at other sites, thus being artificially prevented from returning. This higher probability-of-presence indicates the importance of platforms as red snapper habitat, and concurs with previous studies of artificial habitat for this species (Topping & Szedlmayer 2011b, Piraino & Szedlmayer 2014, Williams-Grove & Szedlmayer 2016a).

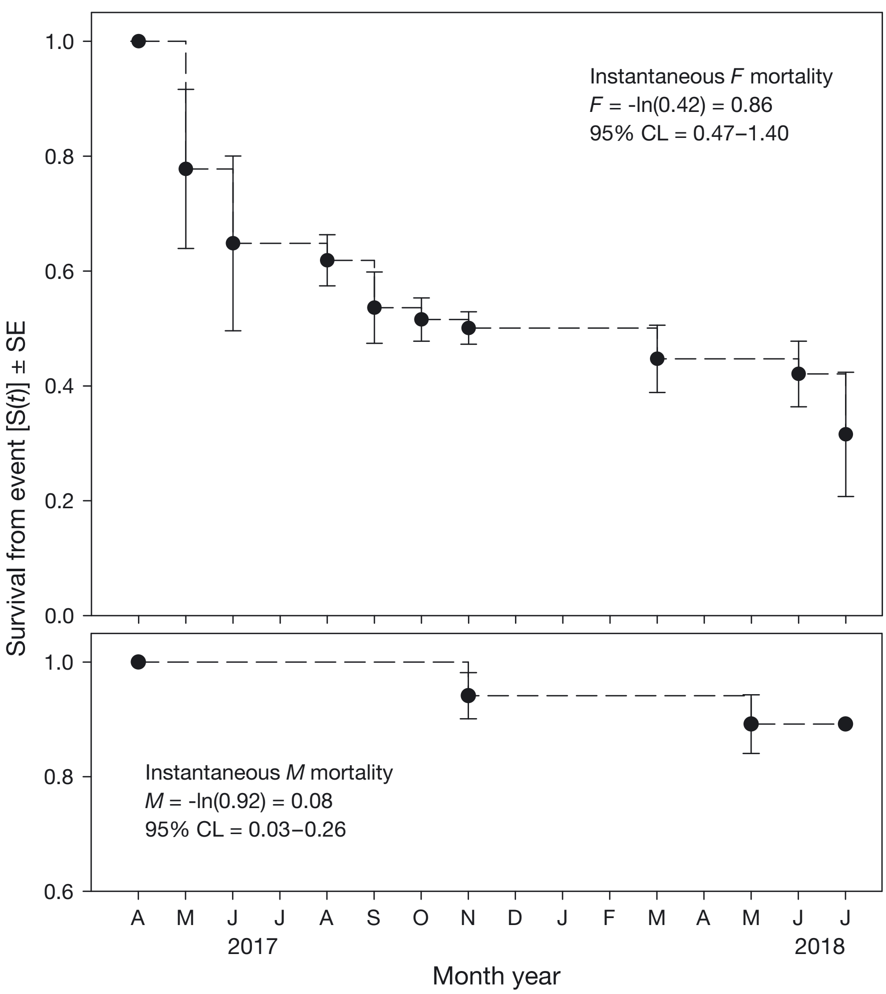

Fig. 11. Red snapper *Lutjanus campechanus* survival (S) from fishing mortality (F) or natural mortality (M) on platforms in the northern Gulf of Mexico. Dashed line: proportion of fish that survived F or M at the end of each month. Instantaneous F and M were based on S at 12 mo. Points and error bars are S for each month when either F or M occurred

4.5. Mortality

High F (0.86) in the present study led to high Z (0.94). These estimates were much higher in comparison to estimates of Z on smaller artificial reefs (Z = 0.39–0.54; Topping & Szedlmayer 2013, Williams-Grove & Szedlmayer 2016b, Szedlmayer et al. 2020). Likewise, Z in the present study was greater than age-based methods of Z on platforms (Z = 0.54; Gitschlag et al. 2003). Higher F on platforms compared to smaller submerged artificial reefs (F = 0.22–0.44; Topping & Szedlmayer 2013, Williams-Grove & Szedlmayer 2016b, Mudrak & Szedlmayer 2020) was most likely due to platforms requiring less effort by fishers to locate and apply fishing effort compared to submerged reef habitats (Gordon 1993). Fishing mortality on the present platforms was also much higher than the maximum F threshold indicated in previous stock assessments (F_{MFMT} = 0.059, SEDAR 2018). However, the fraction of the total stock associated with platforms may be small (Karnauskas et al. 2017, Szedlmayer et al. 2020), and because the fishery is managed on a quota allocation to each state region, it is of little concern that F is high on a particular habitat type (Gulf of Mexico Fishery Management Council 2019).

The estimate of M in the present study (0.08) was similar to previously reported M = 0.11 (Topping & Szedlmayer 2013), M = 0.10 used in previous stock assessments (M = 0.10, SEDAR 2013; M = 0.094, SEDAR 2018) and a slightly lower M = 0.04 reported by Williams-Grove & Szedlmayer (2016b). These low rates of M observed on the platforms and in previous studies were likely due to high rates of F (i.e. fish were caught before they had a chance to die of natural causes) along with the high life expectancy of red snapper (>40 y; Szedlmayer & Shipp 1994, Wilson & Nieland 2001). Also, the size of tagged red snapper (mean ± SD TL: 563 ± 93 mm) in the present study were most likely at the life stage with the lowest M (Williams-Grove & Szedlmayer 2016b). The mortalities that were observed likely occurred from predation, as it is well known that larger predators (e.g. great barracuda *Sphyraena barracuda*, goliath grouper *Epinephelus itajara* and sharks *Carcharhinus* spp.) reside around platforms (Ajemian et al. 2015, Reynolds et al. 2018).

4.6. Implications for removal schedule

Methods for removal of platforms range from toppling to complete removal (Continental Shelf Associates 2004). Explosive removal is one commonly applied method for complete removal based on safety, economics and simplicity (Kaiser & Pulsipher 2003, Barkaszi et al. 2016). However, explosive removals can result in substantial mortality of resident fishes (Continental Shelf Associates 2004). The safe range for red snapper from the detonation point is 230 m (Young 1991, Continental Shelf Associates 2004). Almost all red snapper positions (99%) in the present study were within the affected 230 m zone with a mean distance of 28 m from platform structure, thus most red snapper would not survive explosive removals. However, if explosive removals are applied, our study suggests that removals during the late summer after the red snapper fishing season would be the optimum time to reduce red snapper mortalities. F on platforms was high (0.86), and this may create a time period of lower red snapper densities prior to immigration of new fish (Stanley & Wilson 1997, Nieland & Wilson 2003, Gallaway et al. 2009). Also, area use was greater and movements away from platforms were more frequent during the summer and fall when DO concentrations were lower or hypoxic, again suggesting that late summer into fall (July–November) would be an optimal time to carry out explosive removals to reduce red snapper mortality.

Other removal options may be viable for the northern Gulf of Mexico. Creating artificial reef habitat by toppling or partial removal should be considered by operators and Gulf of Mexico coastal states to maintain red snapper populations in targeted areas. Platforms that are converted to artificial reefs for fish stock enhancements have an estimated lifespan of >300 yr and have proven to be suitable habitat for red snapper and other sport fishes (Schroeder & Love 2004, Ajemian et al. 2015, Reynolds et al. 2018). The conversion of platforms to artificial reefs would potentially help maintain red snapper populations at their present levels in areas without natural reefs, in contrast to removals that likely would reduce red snapper stocks in these areas (Gallaway et al. 2009, Lowe et al. 2009). However, the relatively ease of locating such platforms may increase F, and any decisions to remove or create new artificial reefs out of non-producing platforms needs to consider red snapper vulnerability to harvest.

4.7. Conclusions

Platforms provide important habitat for red snapper in the northern Gulf of Mexico, as red snapper were closely associated with platform structures

(94% of positions within or near the platform). Individuals showed similar area use during both day and night at the East and Center platforms, whereas fish at the West platform showed larger area use during the day. These diel patterns were likely related to both foraging behavior and platform lighting. Seasonal patterns of area use were related to changes in both temperature and DO concentrations. Fish showed the largest area use and made frequent emigrations with quick returns in the late summer and early fall, which again was most likely linked to foraging behavior. Red snapper had an overall site fidelity of 31% yr^{-1} and a median residency time of 7 mo on platforms, and this is lower than previous estimates on smaller submerged artificial reefs. However, site fidelities and residency times are known underestimates, as it is unknown how long a fish was present at each platform before the study began (Williams-Grove & Szedlmayer 2016a). In addition, based on probability-of-presence calculations, red snapper were residing on platforms more frequently than indicated by survival analysis and over a 1 yr period spent 70% of their time over on the platforms.

F was high (0.86) and *M* was low (0.08), suggesting that platforms may make red snapper more vulnerable to the fishery. However, the proportion of the total red snapper stock present on platforms is small (Karnauskas et al. 2017, Szedlmayer et al. 2020), and because the stock is managed under a quota system, high *F* on a particular habitat type like platforms would probably have little effect on the overall stock (Gulf of Mexico Fishery Management Council 2019). Despite this increased *F* and small proportions, platforms are still important, particularly in areas where there are little other reef habitats (natural or artificial, e.g. West Louisiana shelf), and can provide the basis for a local fishery. However, only 3 out of approximately 2000 platforms in the northern Gulf of Mexico were examined in the present study, and there remains a need for further studies of platform use by red snapper.

Considering the practical application when scheduling platform removals, factors such as area use patterns, *F* and environmental conditions should be evaluated to reduce red snapper mortalities. As such, we suggest that an optimum time for explosive removal would be in late summer, after the red snapper fishing season is completed.

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