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ARTICLE

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Abstract
Circle hooks are required when targeting reef fishes in the U.S. federal waters of the Gulf of Mexico. However, limited data is available to evaluate circle hook performance (e.g., hooking location and catch rate) or selectivity in this fishery. Therefore, a fishing experiment was conducted to test the performance of a range of circle hook sizes (2/0 and 4/0 Mustad 39940BLN and 9/0, 12/0, and 15/0 Mustad 39960D) in the recreational reef fish fishery, as well as to estimate hook selectivity directly for Red Snapper *Lutjanus campechanus*, the most targeted reef fish in the northern Gulf of Mexico. Reef fish communities were surveyed with a micro remotely operated vehicle equipped with a laser scaler and then fished with one of five circle hook sizes. Hooking location typically was in the jaw for all hooks examined, with the mean percentage of jaw hooking being 94.1% for all reef fishes and 92.9% for Red Snapper. Fish size generally increased with hook size but at the cost of a reduced catch rate. The percentage of the catch constituted by Red Snapper decreased from 73% for 2/0 hooks to 60% for 9/0 hooks but then increased to 84% for 15/0 hooks. Dome-shaped (exponential logistic) selectivity functions resulted when fitting candidate models to hook-specific Red Snapper size at catch and remotely operated vehicle laser-scaled size distribution data. While Red Snapper median size at full selectivity increased with circle hook size, the difference in that parameter between the smallest and largest hooks was only 66 mm, or a difference of approximately one age-class. Results of this study suggest that mandating the use of large (e.g., ≥12/0) circle hooks would have relatively little effect on either Red Snapper catch rate or selectivity but would decrease the catch rate for other reef fishes, which would be problematic during closed Red Snapper seasons when fishermen attempt to target other species.

Marine fisheries bycatch is a significant global issue that is anathema to efficient fishery resource utilization and counter to principles of ecosystem-based fisheries management. Bycatch and associated discards have long been recognized as potential limitations to successful fisheries management (Alverson et al. 1994; Myers et al. 1997), and calls to address and minimize bycatch have resonated for more than a decade (Crowder and Murawski 1998; Hall et al. 2000; Francis et al.

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2007). In the USA, minimizing bycatch and the mortality of bycatch, to the extent practicable, are among the National Standards of the Magnuson-Stevens Fishery Conservation and Management Act. However, that mandate is particularly difficult to meet for fisheries in which multiple species are targeted with a single gear (Alverson et al. 1994; Kelleher 2005; Johnson et al. 2012).

Globally, there are perhaps no greater examples of multispecies fisheries than reef fish fisheries, and that certainly is true in the northern Gulf of Mexico (nGOM). There are currently 31 species listed in the Gulf of Mexico Fishery Management Council's (Gulf Council) Reef Fish Fishery Management Plan, but dozens of other species not listed in the plan also may be caught while targeting managed species. The mosaic of species-specific fishing seasons, size limits, and bag (recreational) or trip (commercial) limits further complicates the management of nGOM reef fish resources. As a result, regulatory discards constitute an increasing percentage of the total harvest for many nGOM reef fishes. For example, dead discards are estimated to constitute approximately 33% of the total harvest in the nGOM recreational Red Snapper *Lutjanus campechanus* fishery (SEDAR 2013), and the estimated number of dead discards in the recreational fishery for Gag *Mycteroperca microlepis* often exceeds total (recreational plus commercial) landings (SEDAR 2006).

The issues of discarding and associated release mortality are exacerbated by biological characteristics common to many nGOM reef fish species, as well as by the traditional conservation measures routinely employed by the Gulf Council to manage them. The diversity of reef fishes in the region means it is not possible to target a single species (Dance et al. 2011) or to fully avoid undersized fish or closed-season species (Patterson et al. 2012). Barotrauma is a significant issue affecting the survivorship of regulatory discards, given that most reef fishes in the region have physoclistous gas bladders (Rummer 2007) and many make ontogenetic migrations across the shelf to deeper waters as they grow (Wilson and Burns 1996; Mitchell et al. 2004; Lindberg et al. 2006; Albañez-Lucero and Arreguín-Sánchez 2009). Therefore, size and bag limits aimed at either maximizing yield per recruit or minimizing fishing mortality often have the unintended effect of increasing the number of dead discards, thus decreasing the percentage of total harvest constituted by landed catch and potentially hindering stock recovery for overfished species.

Alternative management strategies have been proposed to mitigate discarding issues, but there is limited data available to guide management. In 2007, the Gulf Council mandated the use of non-stainless-steel circle hooks (50 C.F.R. 622.41; GMFMC 2007) based on research indicating circle hooks decrease the incidence of traumatic hooking and may mitigate discard mortality to some extent (see reviews by Cooke and Suski 2004 and Serafy et al. 2012). Therefore, circle hooks were viewed as a means to potentially increase efficiency in the fishery by reducing waste and increasing value or profit for stakeholders (Ihde et al. 2011; Graves et al. 2012). However, no stipulation was made by the Gulf Council as to the size of circle hooks that could be used in the reef fish fishery due to a lack of data on circle hook performance and selectivity. In the first work examining those issues in the nGOM, Patterson et al. (2012) reported that circle hook size significantly affected reef fish catch rates, as well as the size composition of the catch. They also developed an experimental approach to estimate hook selectivity directly by conditioning the size composition of hook-specific catch on in situ fish size distribution estimates derived from a laser scaler deployed on a micro remotely operated vehicle (ROV).

We report results from a study designed to further investigate the potential for circle hooks to mitigate discards in the nGOM recreational reef fish fishery, with particular emphasis on Red Snapper. Specific objectives were to (1) compare the relative abundance of fishery species (reef fishes included in the Gulf Council's Reef Fish Fishery Management Plan plus Tomtate *Haemulon aurolineatum*, a small [<30 cm] grunt for which a bait fishery exists) observed at artificial reef sites to catch composition; (2) provide estimates of traumatic hooking rates; (3) compare catch rates among hook sizes; and (4) compute selectivity models for Red Snapper for five circle hook sizes typically used in the nGOM recreational reef fish fishery. This study builds upon the earlier work of Patterson et al. (2012) by expanding the range of circle hook sizes examined and increasing the precision of Red Snapper hook selectivity models.

METHODS

Sampling procedures.—Selectivity experiments were conducted at nGOM artificial reef sites during summer and fall 2011 aboard four charter boats currently operating in the recreational reef fish fishery between Orange Beach, Alabama, and Destin, Florida. All charter boat captains had more than 20 years of experience in the fishery. The captains chose the sites for each sampling trip without influence from the researchers. Prior to fishing at a given site, video sampling of the reef fish community was conducted with a VideoRay Pro4 micro ROV using the point-count method (Patterson et al. 2009). In this method, multiple spins are conducted with the ROV at various depths to sample a 15-m-wide cylinder with the reef at its center. The ROV was also equipped with a red laser scaler (twin 5 mW 635-nm class IIIa red lasers mounted in parallel 7.5 cm apart) to estimate reef fish lengths from video samples (Patterson et al. 2009). Following ROV sampling, a Sea-Bird 19*plus* V2 SeaCAT Profiler was deployed at each site to measure depth, conductivity, water temperature, and dissolved oxygen concentration.

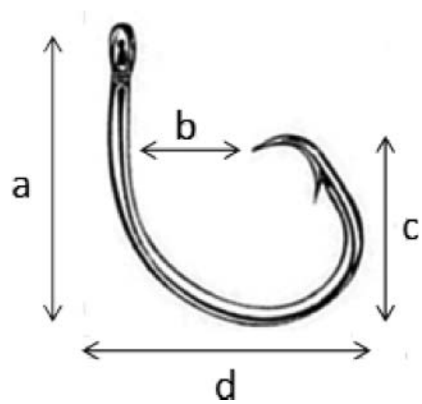
The digital video was analyzed in the laboratory to estimate reef fish community structure. All fishes observed in ROV video data were identified to the lowest taxonomic level possible. Fish length was estimated from the video observations by scaling fish fork length (FL) from the distance measured between laser spots relative to the FL in the digital images. For conditions observed in situ, the mean bias of underestimating fish length was estimated to be 3.0% with a standard deviation of 0.6% (Patterson et al. 2009). Therefore, FL estimates were bias-corrected based on a random probability draw and normally distributed bias with the mean equal to 3.0% and standard deviation equal to 0.6%. Fork length estimates then were converted to total length (TL) based on species-specific linear regressions relating those two parameters that were derived from individuals captured in this and other studies (e.g., Patterson et al. 2001b; Addis et al. 2013). Fishing experiments were conducted only at relatively small artificial reef sites (total reef volume <25 m^3) to reduce the potential for observational error in ROV video analysis associated with attracting distant individuals during fishing.

FIGURE 1. Circle hook sizes and model numbers that were used to test the effect of hook size on reef fish catch rate and selectivity during fishing experiments in the northern Gulf of Mexico. The scale is in centimeters.

After the ROV video sampling was complete, each site was fished with hook-and-line gear for 30 min. Six fishermen each deployed a two-hook bottom rig, which consisted of a 1.5-m leader constructed of 27-kg test monofilament with two short leaders extending approximately 0.5 m horizontally from the main leader and a 230-g lead weight attached to the bottom of the main leader. Terminal tackle was one of five circle hook types: 2/0 or 4/0 Mustad model 39940BLN or 9/0, 12/0, or 15/0 Mustad model 39660D hooks (Table 1; Figure 1), which encompass the range of hook sizes that cooperating charter boat captains indicated are typically used in the nGOM recreational reef fish fishery. Two different hook models were necessary to encompass the full range of hook sizes typically used in the fishery. All bottom rigs deployed at a given site consisted of a single hook type randomly chosen prior to the fishing effort at that site. Hooks were baited with either cut squid *Loligo* spp. or Mackerel Scad *Decapterus macarellus*, with bait size scaled to hook size. Hooking location was noted for each captured fish, which was identified to species, weighed to the nearest 0.1 kg with a digital scale, and measured to the nearest millimeter for FL and TL. Hooking location was scored as corner jaw, top jaw, bottom jaw, foul hooked (hooked on body), or deeply hooked (gills, pharynx, or esophagus), with the latter two categories constituting traumatic hooking.

Statistical analyses.—Statistical analyses were conducted in R (Crawley 2007; Kabacoff 2011) and PRIMER 6 with PERMANOVA + software packages (Anderson et al. 2008). The difference in fishery species composition estimated from

TABLE 1.Dimensions (mm) of the Mustad circle hooks that were used in this study to test the effect of hook size on reef fish hook location, catch rate, composition, and selectivity. The image indicates the hook dimensions that were measured.



Hook size	Mustad model number	Distance a (total length)	Distance b (gape)	Distance c (front length)	Distance d (width)
2/0	39940BLN	21.9	11.2	12.7	18.3
4/0	39940BLN	25.4	12.6	15.4	22.9
9/0	39960D	31.0	8.1	18.3	21.9
12/0	39960D	38.5	12.8	26.9	32.5
15/0	39965D	56.9	18.8	40.8	46.8

ROV video samples versus hook-specific catches was tested with permutational multivariate ANOVA (PERMANOVA; $\alpha = 0.05$; 9999 permutations; Anderson et al. 2008). The percent abundance of fishery species was square root transformed and then a Bray–Curtis similarity matrix was computed prior to running the PERMANOVA model. Pairwise tests were also conducted with PERMANOVA. The difference in hooking location proportions was tested among hook sizes with contingency table analysis (χ^2; $\alpha = 0.05$). The effect of fish length and hook size on the probability of traumatic hooking also was tested with logistic regression (χ^2; $\alpha = 0.05$).

Generalized linear models (GLMs; $\alpha = 0.05$) were computed to test for the effect of hook type and environmental covariates (depth, water temperature, salinity, dissolved oxygen, and wave height) on total catch rates and those for Red Snapper only. Predicted values from the models constituted standardized catch rate estimates. The effect of hook size on fish length (FL or TL; mm) was tested with one-way ANOVA ($\alpha = 0.05$) models for all fish and Red Snapper only. Fish length was $\log_e$ transformed to meet parametric assumptions. Pairwise tests were performed with Tukey's honestly significant difference (HSD) test when models were significant.

Hook-specific selectivity functions were computed for Red Snapper in AD Model Builder (Fournier et al. 2012) with the approach described in Patterson et al. (2012). Hook-specific catch at size (TL) was conditioned on the in situ size distribution of fish observed during ROV-based video sampling at fished sites corresponding to each hook size using the following model:

$$\begin{cases} C_{lhk} = \dfrac{f_{hk} q_h S_{lh} N_{lk} \left(1 - e^{-F_{lk}}\right)}{F_{lk}} \\ V_{lk} = edN_{lk} \\ F_{lk} = \sum_h f_{hk} q_h S_{lh} \end{cases}, \tag{1}$$

where N_k is equal to the number of Red Snapper of length l at site k, C_{lhk} is the number of Red Snapper caught by each hook size h, and V_{lk} is the number of Red Snapper scaled by lasers during the corresponding ROV sample. The variable f is equal to the value for fishing effort for each hook size (calculated by multiplying the number of trips by the number of sites sampled by the number of hooks fished per site). The variable e is equal to the value of the visual effort for ROV samples (calculated by multiplying the number of trips by the number of sites sampled) and has a corresponding hook size fished at each site. The detectability parameter d (the probability of an individual Red Snapper observed at a site also being scaled by lasers) was set at 0.1 (given approximately 10% of fish observed at reef sites were scaled with lasers). The variable q is equal to the relative fishing power of each hook size, and the parameter S represents the selectivity function. Three candidate selectivity models were fit to the observed data:

$$\text{Logistic } \left\{ \frac{1}{1 + e^{-\alpha(l-\theta)}}, \right. \tag{2}$$

$$\text{Double logistic } \left\{ \frac{1 - 1/\left(1 + e^{-\beta(l-\theta_2)}\right)}{1 + e^{-\alpha(l-\theta_1)}}, \right. \tag{3}$$

and

$$\text{Exponential logistic } \left\{ \frac{e^{\beta\alpha(\theta - l)}}{1 - \beta\left(1 - e^{\alpha(\theta - l)}\right)}, \right. \tag{4}$$

where α and β are shape parameters of the function (more flat topped as β approaches 0), θ is the length (mm) corresponding to the peak in the selectivity function, and l is the midpoint of the size interval l. If the value of the shape parameter β is nonsignificant then a value of 0 would be used by default and the function would appear flat topped rather than dome shaped. However, the shape of the logistic function can only be flat topped, regardless of the value of the β parameter.

Assuming the relative size distribution of the fish visually surveyed is close to the true size distribution, the previous equations (1) can be rewritten as follows:

$$\begin{cases} C_{lhk} = \dfrac{f_{hk} q_h S_{lh} V_{lk} \left(1 - e^{-F_{lk}}\right)}{edF_{lk}} \\ F_{lk} = \sum_h f_{hk} q_h S_{lh} \end{cases}. \tag{5}$$

Assuming that the total species-specific catch for each hook size at each location is approximately normally distributed with mean μ and variance σ^2 and that the proportion of the catch for each length bin is approximately multinomially distributed with mean E $\{X_i\} = np_i$ and variance Var $(X_i) = np_i(1\text{-}p_i)$, then maximum likelihood estimates can be obtained for the remaining parameters q, d, and S by minimizing the log-likelihood expression as follows:

$$L = 0.5 \sum_{h,k} \left[\left(\frac{c_{hk}^{obs} - c_{hk}}{\sigma} \right)^2 - \log_e \sigma^2 \right] + \sum_{h,k} n_{h,k} \sum_l p_{lhk}^{obs} \log_e p_{lhk}, \tag{6}$$

where n is the effective sample size and the superscript obs is used to distinguish the observed data from the predicted value.

Data from each experiment were pooled across all samples sites for a given hook size. Model priors and input parameters were the same for all hook sizes (assuming no effect of hook size) and the parameter β was flat topped (approximately 0). The remaining parameters were estimated with a stepwise approach and the Akaike information criterion for small sample size (AICc) was used to assess the appropriateness of the input parameters (Hurvich and Tsai 1995; Burnham et al. 2011).

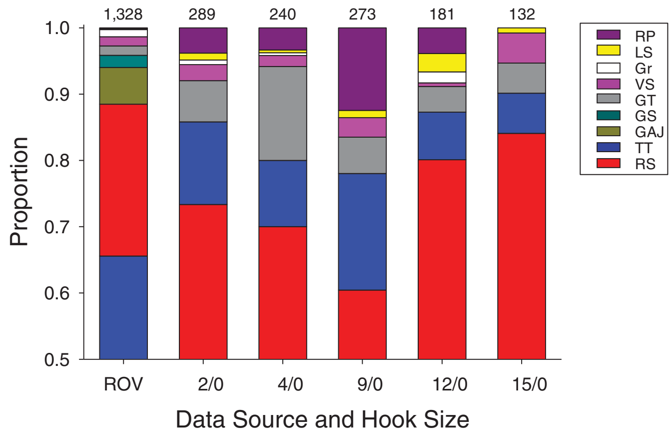


FIGURE 2. Percentage of fishery species observed in remotely operated vehicle (ROV) video samples of northern Gulf of Mexico reef fish communities versus hook-specific species composition of reef fish catches. The species abbreviations are as follows: RP = Red Porgy *Pagrus pagrus*, LS = Lane Snapper *Lutjanus synagris*, Gr = groupers (family Epinephelidae), VS = Vermilion Snapper *Rhomboplites aurorubens*, GT = Gray Triggerfish *Balistes capriscus*, GS = Gray Snapper *Lutjanus griseus*, GAJ = Greater Amberjack *Seriola dumerili*, TT = Tomtate, and RS = Red Snapper. Sample sizes are shown atop the bars.

RESULTS

There were 109 reef fish taxa that were observed in the ROV video samples from 52 artificial reef sites; 86.0% of individuals were identified to species, 39.9% of which were fishery species. Of the 14,424 individuals observed among fishery species, 1,328 were scaled with lasers during ROV sampling. Among the 52 sample reefs, 2/0, 12/0, and 15/0 hooks were fished at 10 sites each, and 4/0 and 9/0 hooks were fished at 11 sites. Fishery species composition was significantly different between ROV video samples and hook-specific catches (PERMANOVA: $P < 0.001$). Pairwise tests indicated that the species composition observed in ROV video samples was significantly different than each of the hook-specific catch compositions (PERMANOVA: $P < 0.05$). Among hook-specific catches, only the 2/0 and 4/0 catch compositions were significantly different from the 15/0 catches (PERMANOVA: $P < 0.01$).

Red Snapper constituted only 22.9% of the total individuals among fishery species observed in ROV video samples but comprised as much as 84.1% of the total catch among hook sizes (Figure 2). Tomtate showed the opposite trend, in that they comprised 65.6% of the total individuals observed in ROV samples but comprised no greater than 17.6% of the total number of fish caught among hook sizes. Gray Triggerfish and Red Porgy were caught with 4/0 and 9/0 hooks in greater

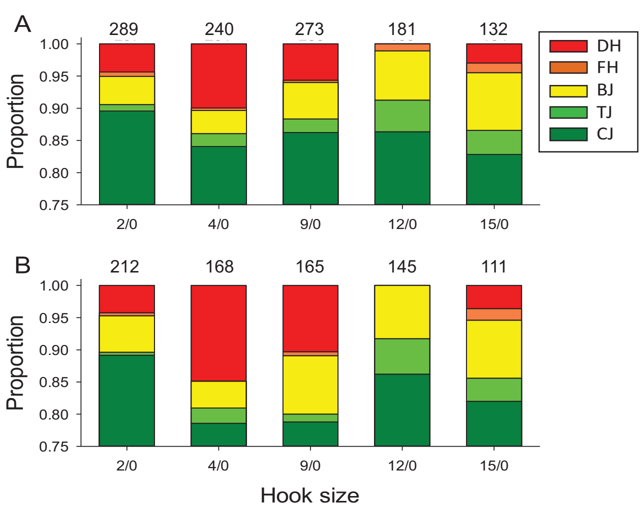


FIGURE 3. Hooking location for **(A)** all species and **(B)** Red Snapper caught with circle hooks. Location abbreviations are as follows: DH = deeply hooked (gill arches or beyond), FH = foul hooked (hooked on body), BJ = bottom jaw, TJ = top jaw, and CJ = corner of jaw. Sample sizes are shown atop the bars.

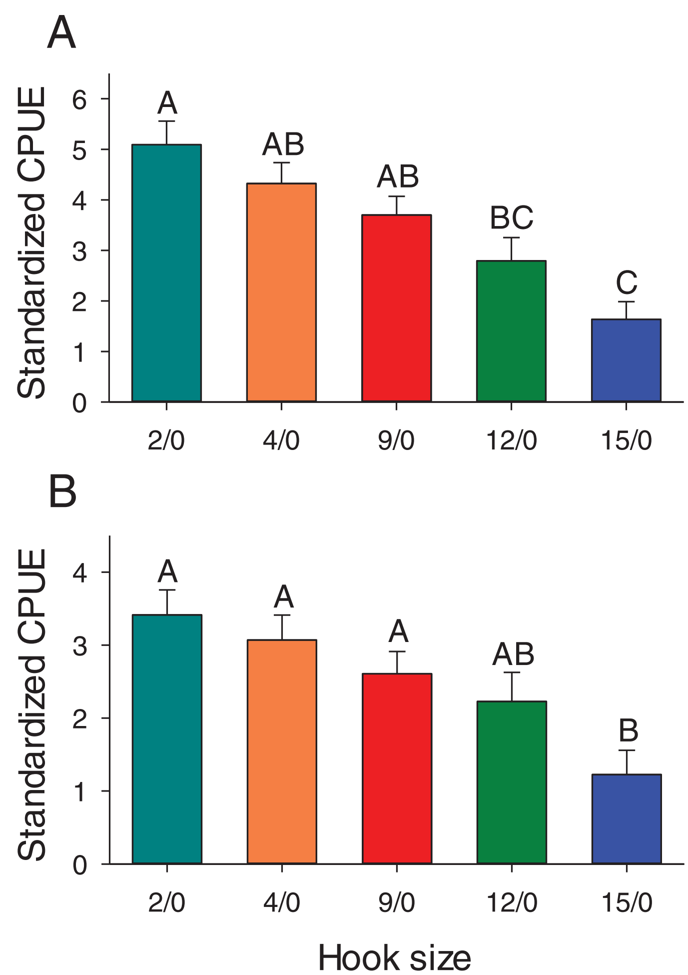


FIGURE 4. Mean (error bars show SE) standardized CPUE for **(A)** all fishes and **(B)** Red Snapper among experimental circle hooks. A shared letter above the bars indicates that the standardized CPUE is not significantly different between those hook sizes ($P > 0.05$). The unit of measurement for both panels is fish per hook-hour.

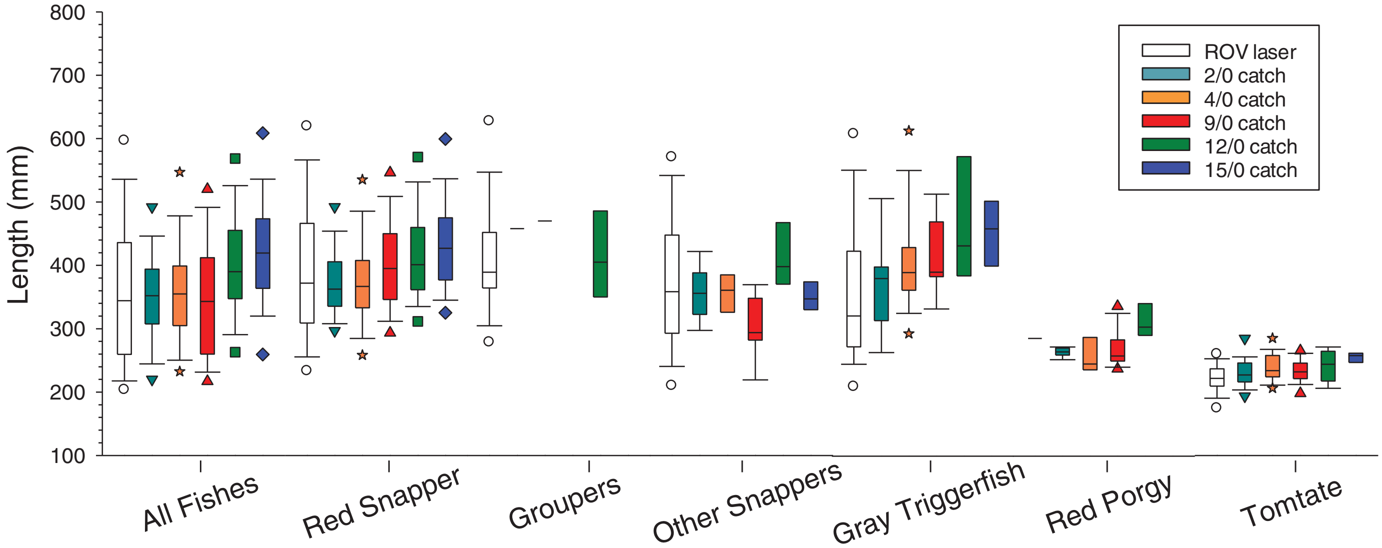


FIGURE 5. Box plots of laser-scaled and hook-specific lengths of northern Gulf of Mexico reef fishes sampled during this study. Total length is reported for all species except Gray Triggerfish, for which fork length is reported. The top and bottom dimensions of the boxes indicate the 25th and 75th percentiles, respectively, while the midlines indicate the median values, the extended bars indicate the 5th and 95th percentiles, and the symbols indicate observations beyond those percentiles.

proportion than their observed abundance, and Gray Snapper and Greater Amberjack were never captured at any site despite being observed at 61.5% and 40.4% of the sites, respectively. At least one Red Snapper was captured at all but two sites. The percentage of hook-specific catches constituted by Red Snapper ranged from 60.4% for 9/0 hooks to 84.1% for 15/0 hooks, with catches for both 2/0 (73.4%) and 4/0 (70.0%) hooks having higher percentages of Red Snapper than 9/0 hooks (Figure 2).

Results from contingency table analysis indicated that hooking location was significantly different among experimental hooks for all fish (χ^2: df = 16, $P < 0.001$) and for Red Snapper only models (χ^2: df = 16, $P < 0.001$). The highest incidence of deep hooking occurred with 4/0 hooks (10.0% for all fishes, 14.9% for Red Snapper; Figure 3), but almost no traumatic hooking occurred with 12/0 hooks. For all other hook sizes, the incidence of deep hooking was ≤5% for all fishes, but deep hooking occurred in 10% of Red Snapper when using 9/0 hooks. Most (>80.0%) fish were hooked in the corner of the jaw, but Red Snapper were hooked in the corner of the jaw less frequently than other species. Logistic regression results indicated fish FL did not have a significant effect on traumatic hooking probability for all fishes ($P = 0.887$). Fish TL also did not significantly affect Red Snapper traumatic hooking rates ($P = 0.055$). The probability of traumatic hooking in all fishes was lowest for the 12/0 hook (0.011) and highest for the 4/0 hook (0.104). The probability of traumatic hooking in Red Snapper was also lowest for the 12/0 hook (∼0.000) and highest for the 4/0 hook (0.135).

A significant decline in catch rate with increasing hook size was observed for all fishes (GLM: $P < 0.001$) as well as for Red Snapper alone (GLM: $P = 0.013$; Figure 4). The GLM results indicated that the hook effect was significant for all fishes ($P < 0.001$) and Red Snapper only ($P = 0.013$), while wave height was the only significant covariate in both models ($P < 0.001$ for all fishes, $P = 0.011$ for Red Snapper). Mean standardized catch rate for all fishes was greatest for 2/0 hooks (5.1 fish/hook-hour) and lowest for 15/0 hooks (1.6 fish/hook-hour; Figure 4A). Mean standardized catch rates for Red Snapper also were highest for 2/0 hooks (3.4 fish/hook-hour) and lowest for 15/0 hooks (1.2 fish/hook-hour; Figure 4B). Decreases in catch rate with increasing hook size coincided with increases in the proportion of catch comprised by Red Snapper.

There were significant differences in fish length among experimental hooks for all reef fishes combined (ANOVA: $P < 0.001$) and for Red Snapper alone (ANOVA: $P < 0.001$). Pairwise tests indicated FL for all species caught with 12/0 and 15/0 hooks was significantly different than FL of fish caught with 2/0, 4/0, and 9/0 hooks (Tukey's HSD: $P < 0.001$), but FL was not significantly different between 12/0 and 15/0 hooks (Tukey's HSD: $P = 0.324$). There was no significant difference in FL among 2/0, 4/0, and 9/0 hooks ($P \geq 0.23$). For Red Snapper, TL was significantly different among all hook comparisons ($P \leq 0.01$), except between 2/0 and 4/0, 9/0 and 12/0, and 12/0 and 15/0 hooks ($P \geq 0.43$). There was an increasing trend in median FL with increasing hook size for all fishes, Red Snapper, and Gray Triggerfish (Figure 5). Median FL for all reef fishes and other snappers was less than the in situ median FL estimated from ROV data for the 9/0 hook only, which also had the smallest gape. Trends were difficult to ascertain for groupers, Red Porgy, and Tomtate due to low sample sizes, especially when using large hooks.

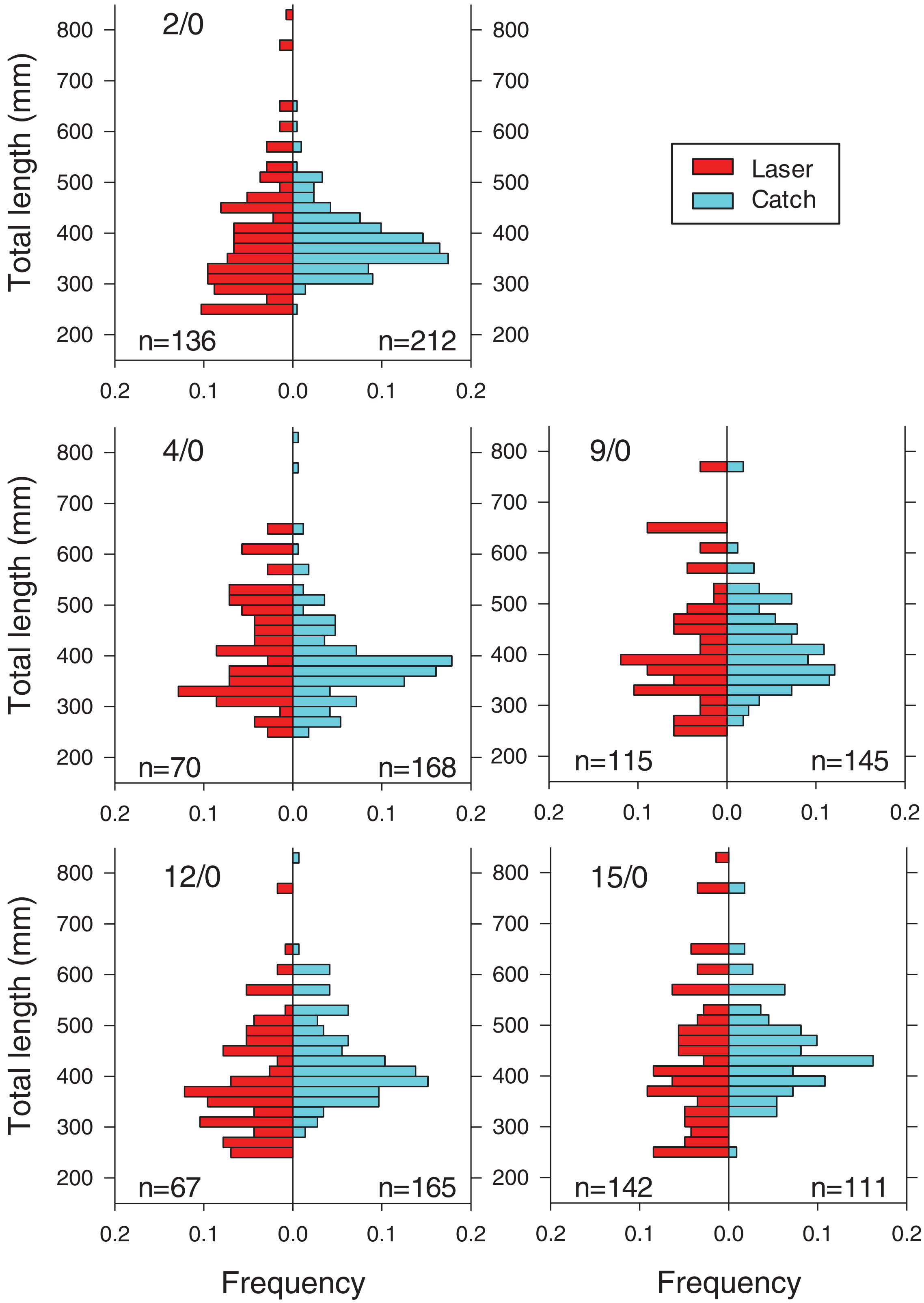


FIGURE 6. Size distributions of Red Snapper scaled with an ROV's laser scaler and caught with different-sized circle hooks. Sample sizes (n) are shown on each panel. The current minimum size limit is 406 mm TL for the recreational fishery.

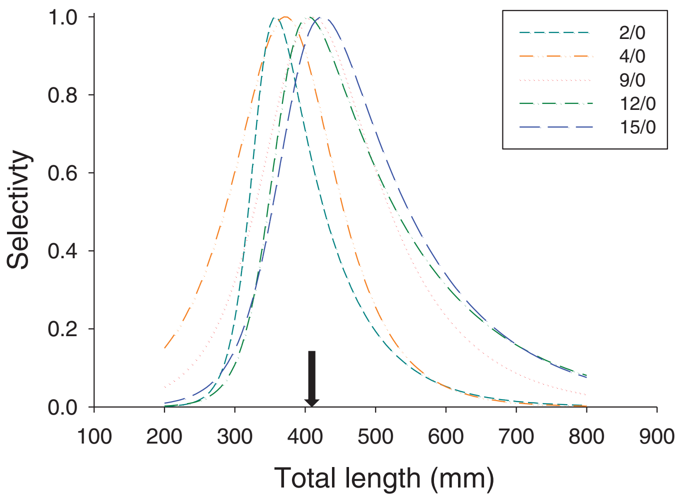


FIGURE 7. Hook-specific maximum likelihood selectivity functions estimated for Red Snapper captured during this study. The arrow indicates the current minimum size limit (406 mm TL) for the recreational fishery.

The size distributions of laser-scaled Red Snapper versus hook-specific catches reveal a lower percentage of fish greater than 600 mm TL in the catch than observed in situ on reefs for all hooks except 12/0 hooks (Figure 6). A second pattern apparent in the size distribution data was a decreasing percentage of the catch being constituted by fish less than 400 mm TL as hook size increased. Maximum likelihood fits of hook selectivity models to these data resulted in the selection of the exponential logistic model as the best overall fit to the data (AIC*c* = 4,807 for the logistic model, 4,526 for the double logistic model, and 4,503 for the exponential logistic model). Resulting hook-specific models were dome-shaped; in all cases the shape determining parameter, β, was significantly different than 0 (Figure 7; Table 2), and AIC*c* values were reduced when β was estimated empirically rather than given an assumed null value of 0. Predicted proportions of catch at size indicated that selectivity models fit the data well (Figure 8). Although Red Snapper showed an increasing trend in median TL from 2/0 to 15/0 circle hooks, TL at full selectivity (θ) increased by only 66 mm between the largest and smallest hooks (Table 2).

DISCUSSION

The results of this study demonstrate that clear shifts in both species and size selectivity occurred among experimental circle hooks within the size range typically used in the nGOM recreational reef fish fishery. The majority of fishes observed at artificial reef sites were not captured with any hook size tested in this experiment, but Red Snapper constituted a greater proportion of the catch than of the ROV video samples. The observed increase in the proportion of Red Snapper caught with larger hooks resulted from the declining catch rates of other reef fishes rather than an increasing Red Snapper catch rate with hook size. Fishermen in the nGOM often report difficulty in avoiding undersized Red Snapper during open seasons or any Red Snapper during closed seasons (Cullis-Suzuki et al. 2012; Scyphers et al. 2013), which likely is due to a combination of factors. Smaller reef fishes are likely unable to effectively take larger circle hooks into their mouths due to gape limitation (Cooke and Suski 2004). However, Red Snapper have large gapes relative to the circle hook dimensions tested. In addition, less efficient hooking rates for smaller size-classes of Red Snapper may be compensated for by aggressive feeding behavior and their ubiquitous distribution across the nGOM shelf (Dance et al. 2011; Patterson et al. 2012).

The range of hook sizes selected for this study was based on observations of hooks used in the fishery, including those used by cooperating charter boat captains. The Mustad 39960D hooks were selected for consistency with fishing experiments reported by Patterson et al. (2012), and the 2/0 and 4/0 39940BLN hooks were added to include hooks smaller than the 9/0 39960D hooks. However, testing the effect of hook size on circle hook performance among the hooks examined was problematic because measurement ratios of gape distance to either total length or front length differed between the 39940BLN and 39960D models. For example, 2/0 and 4/0 model 39940BLN hooks had a wider gape distance but shorter front and total lengths than 9/0 model 39960D hooks. Red Snapper catch composition was lowest for the smallest gape hook and highest for the largest gape hook. Previous studies have identified the ratio of hook width to mouth gape as a limiting factor (Cooke and Suski 2004), and the decrease in catch diversity observed for the two largest hook sizes in the current study supports this contention. However, front length was also important in predicting selectivity as smaller fish were caught

TABLE 2. Hook-specific maximum likelihood parameter estimates (CV in parentheses; CV = 100·SD/mean) from exponential logistic hook selectivity models. The parameter q = fishing power and θ = median fish TL (mm) when fully selected; parameters α and β are both shape determining parameters.

Hook size	q	α	β	θ
2/0	0.404 (0.034)	0.065 (0.008)	0.202 (0.045)	358.0 (6.1)
4/0	0.466 (0.050)	0.031 (0.005)	0.524 (0.102)	371.8 (10.2)
9/0	0.542 (0.055)	0.029 (0.005)	0.341 (0.133)	410.7 (19.7)
12/0	0.265 (0.030)	0.046 (0.006)	0.147 (0.054)	404.3 (9.1)
15/0	0.165 (0.017)	0.035 (0.006)	0.215 (0.087)	424.3 (15.4)

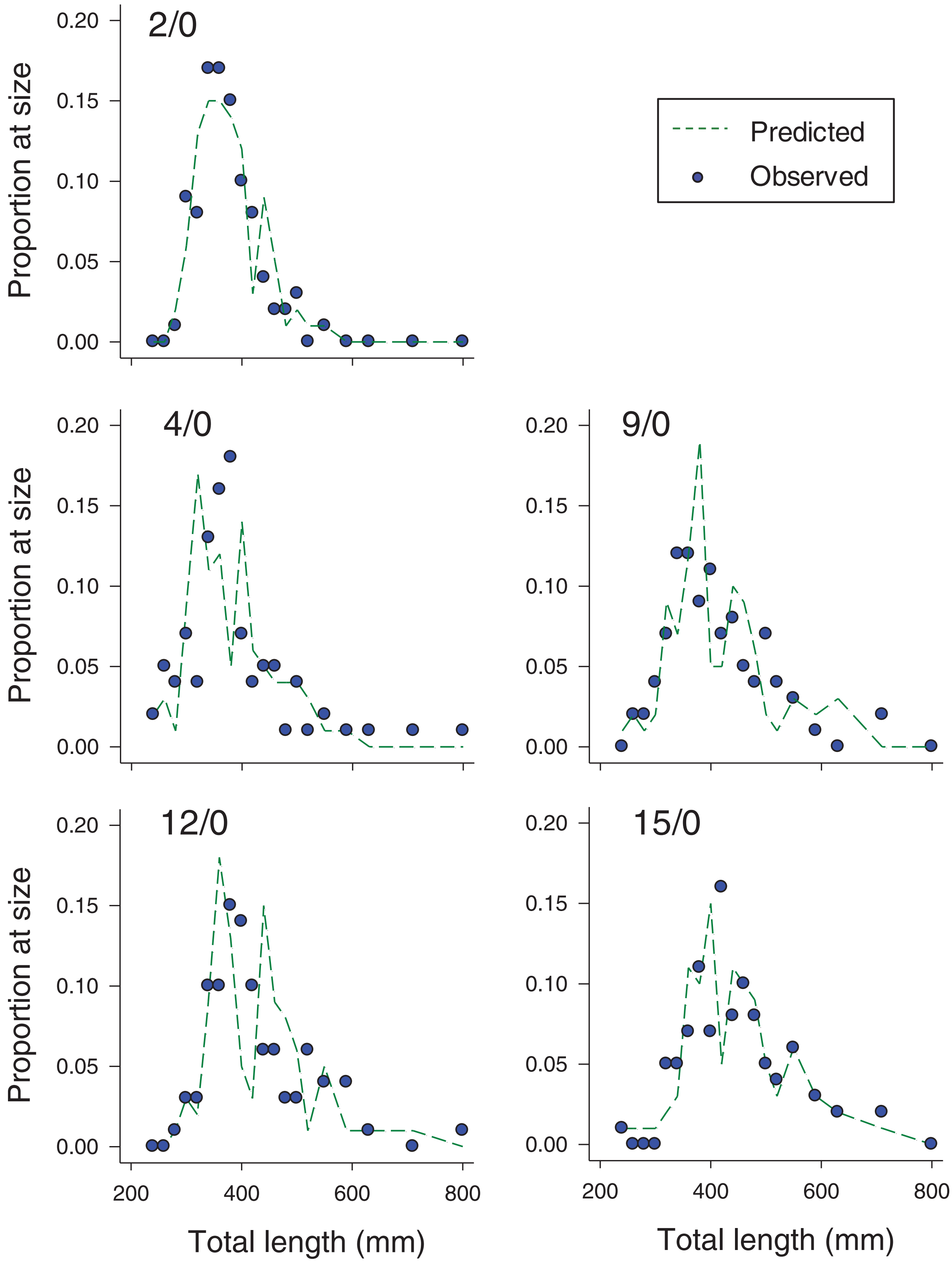


FIGURE 8. Predicted versus observed proportion at size of Red Snapper captured with 2/0, 4/0, 9/0, 12/0, and 15/0 circle hooks during the fishing experiment. Predicted proportions at size resulted from exponential logistic selectivity models fit to the observed proportion-at-size data for each hook comparison combination.

on hooks with shorter front lengths. Among species other than Red Snapper, gape appears to be the most important dimension in determining selectivity as these other species were a greater proportion of the catch, and a greater size range of fish was captured, when using the smallest gape hook (9/0). These results highlight the need to report hook dimensions as well as sizes in hook performance or selectivity studies given the lack of a uniform hook size scale among manufacturers and given differences in hook dimensions among models produced by a given manufacturer.

The prevalence of traumatic hooking was generally low (<10%) among the hooks examined, although it was slightly higher for Red Snapper than for other species. Deep hooking was virtually nonexistent for 12/0 and 15/0 hooks but was higher for 4/0 and 9/0 hooks than for 2/0 hooks. Traumatic hooking rates reported in other studies range from 1.3% to 44.0%, depending on species and hook type, with the highest rates of deep hooking observed for severely (<10°) offset hooks (Prince et al. 2002; Aalbers et al. 2004; Bacheler and Buckel 2004; Cooke and Suski 2004; Sauls and Ayala 2012). The two smaller hooks used in this study (2/0 and 4/0 Mustad 39940BLN hooks) were offset by 4°, while the other three hooks (9/0, 12/0, and 15/0 Mustad 39960D hooks) had 0° offset. The authors of previous studies reported differences in hook performance measures, such as catch rate, catch efficiency, and traumatic hooking rate, between offset and nonoffset hooks, but results are somewhat equivocal due to differences in mouth morphology among the species examined and the degree of offset among hook types (Cooke and Suski 2004; Ostrand et al. 2005; Graves and Horodysky 2008; Mapleston et al. 2008). Prince et al. (2002) observed higher rates of traumatic hooking in Sailfish *Istiophorus platypterus* for severely offset hooks (15°), but traumatic hooking rates were similar to those observed in this study for minor (<5°) and nonoffset hooks. Therefore, it seems unlikely that the slight offset of the 2/0 and 4/0 hooks examined in the current study had much impact on the incidence of deep hooking, but the effect of hook offset was not examined. Future experiments could be designed to test the effect of slight to severe offsetting on circle hook performance in the nGOM reef fish fishery, as well as to test for differences in traumatic hooking rates between circle and J hooks.

Sample sizes were sufficient to estimate hook selectivity directly only for Red Snapper with the method of Patterson et al. (2012). The advantages of this approach are that hook selectivity is conditioned on the estimated in situ size distribution of fish targeted during experimental fishing and the shape of the selectivity function is estimated directly from the data, not imposed externally. Patterson et al. (2012) reported selectivity functions for the same model 9/0, 12/0, and 15/0 circle hooks examined in the current study, but their sample sizes were lower and their analysis was somewhat more complicated due to simultaneously fishing two hook sizes at a given reef site. That resulted in the shape-determining parameter, β, not being significantly different from 0 for 15/0 hooks, which produced a logistic versus dome-shaped function. Exponential logistic selectivity functions computed in the current study resulted in dome-shaped functions for all the hook sizes examined. Median TL at full selectivity increased with increasing hook size and was approximately $\geq$406 mm (the Red Snapper minimum length limit) for 9/0, 12/0, and 15/0 hooks. However, the potential reduction in sublegal discards would likely be negligible in the fishery as charter boats already use larger hooks to target Red Snapper during open seasons (Garner et al., in press). In addition, the absolute difference in size at full selectivity from the smallest to largest hooks was only 66 mm TL, which in turn translates to a difference of approximately one year-class for a species capable of living more than 50 years (Patterson et al. 2001a; Wilson and Nieland 2001). It is unknown, but it could be tested, whether a larger shift in selectivity would result for hooks that otherwise matched the dimensions of the 2/0 and 4/0 hooks examined here but had gape widths proportional to the larger hooks.

The results of this study have clear implications for the assessment and management of nGOM Red Snapper, and likely for other species also. Often the default shape is logistic for selectivity functions in integrated stock assessments, or their form is estimated internally in assessment models with informative or uninformative priors. There is strong evidence provided here and by Patterson et al. (2012) that the selectivity function for the nGOM recreational Red Snapper fishery has a dome shape and it may also apply to commercial gear for which the terminal tackle is large circle hooks (15/0) and for which a logistic-shaped selectivity function is currently assumed (SEDAR 2013).

Beyond stock assessment implications, study results also have important implications for fisheries management. The results reported here are consistent with the inference by Patterson et al. (2012) that while requiring larger hooks in nGOM reef fish fishery would shift the catch to larger fish, it also would likely exacerbate the issue of discarding given that mostly Red Snapper would be caught during closed seasons when fishermen target other species. Fishermen alter their terminal tackle during seasons closed to Red Snapper attempting to maximize catch efficiency of other species, often by switching to smaller hooks to target species such as Gray Triggerfish or Vermilion Snapper (Garner et al., in press). However, the smaller hooks used in this study had higher rates of deep hooking for Red Snapper, which the circle hook regulation was intended to prevent. Bait size for a given hook size and type also may affect the species and size composition of the catch (Arterburn and Berry 2002; Watson et al. 2005), which was not tested in the current study. Future experiments could be conducted to test various hook and bait combinations to determine the potential for increases in size selectivity in addition to bycatch reduction in the nGOM recreational reef fish fishery.

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