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Original Article

Experimental assessment of circle vs. J hook performance and selectivity in the northern Gulf of Mexico recreational reef fish fishery

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Few data exist to evaluate the performance or assess the potential impacts of hook regulations on catchability or selectivity of recreational fisheries in the northern Gulf of Mexico. The purpose of this study was to test the effects of hook type (circle vs. J hook) and hook size (1/0, 4/0, and 7/0) on catch composition, traumatic hooking, species-specific catches, and size-selectivity of red snapper, *Lutjanus campechanus*, and grey triggerfish, *Balistes capriscus*. Selectivity was estimated by conditioning size distributions from hook-specific catches against *in situ* size distributions observed with a remotely operated vehicle. Deep hooking (hook set in gills or beyond) was low in all hook treatments for red snapper (<10%) and grey triggerfish (<6%), but was generally higher with J hooks, especially for other fishes caught with the largest J hook (34%). Hook type did not significantly affect catches, but catches decreased significantly with increasing hook size in all groups except red snapper. Selectivity curves were dome-shaped for both focus species in all hook treatments and selection peaks were similar among treatments for red snapper. Peak selectivity was 78.1 mm larger for J hooks than circle hooks for grey triggerfish. Overall, study results indicate that the circle hook regulation may have reduced traumatic hooking mortality by up to 50%, and that catchability is similar between hook types for both red snapper and grey triggerfish when controlling for hook size. Strong dome-shaped selection estimated for nearly all selectivity curves suggest logistic size-selectivity assumptions in assessment models are likely inappropriate for recreational sectors targeting red snapper or grey triggerfish.

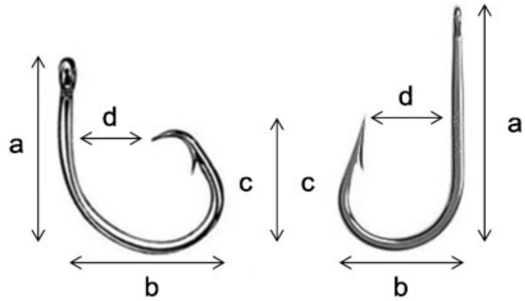
Keywords: circle hook, grey triggerfish, Gulf of Mexico selectivity, red snapper, reef fish, traumatic hooking.

Introduction

The reauthorized Magnuson-Stevens Fishery Conservation and Management Act mandated that overfishing must end in U.S. federal waters and bycatch and bycatch mortality must be reduced to the lowest extent practicable (MSFCMA, 2007). Recreational fishing effort in the northern Gulf of Mexico (nGOM) is among the highest in the U.S. (Coleman *et al.*, 2004), and traditional management strategies used to regulate fishing mortality result in tens of millions of discarded reef fishes each year (NMFS, 2011). Diverse fish communities inhabiting continental shelf reef sites (Dance *et al.*, 2011) prevent fishermen from effectively avoiding non-target species during closed seasons and undersized individuals during open seasons (Garner and Patterson, 2015). In addition to the effects of barotrauma, the catch-and-release process can further reduce discard survival through increased air exposure, excessive bleeding, and damage to vital organs (Burns *et al.*, 2002; Cooke and Suski, 2004).

Amendment 27 to the Reef Fish Fishery Management Plan (RF-FMP) mandated recreational fishermen use circle hooks when targeting reef fishes in the nGOM to reduce traumatic

Table 1. Experimental hooks, model number, sample size (number of sites fished *n*), and dimensions (mm) of Mustad circle and J hooks used in this study.



Hook	Mustad Model #	*n*	distance a (total length)	distance b (width)	distance c (front length)	distance d (gape)
1/0 J	3407DT	10	36.13	14.22	13.88	11.63
4/0 J	3407SSD	12	46.49	19.86	18.86	14.77
7/0 J	3407DT	11	64.19	26.71	23.29	21.88
1/0 C	39945BLN	11	18.48	16.81	11.80	8.17
4/0 C	39945BLN	13	25.73	21.96	15.24	12.74
7/0 C	39945BLN	15	34.45	30.14	21.92	15.53

Image indicates dimension measured.

hooking related discard mortality of red snapper (GMFMC, 2007). Many authors have demonstrated the conservation benefits from circle hook use for a variety of fishes without significant reductions in catch (see review by Cooke and Suski, 2004). However, traumatic hooking rates can actually increase when hook size is extreme relative to fish gape (Cooke *et al*., 2005). Prior to 2008, no peer reviewed empirical assessment had been conducted to examine the conservation benefits of circle hooks for reef fishes targeted in the nGOM. Fishery managers and other stakeholders have expressed concern that the gear regulations mandated in Amendment 27 may have altered the selectivity patterns in the reef fish fishery or the mortality rate of discarded fish (GMFMC, 2007). If true, failing to account for these changes can result in poor estimation of important size classes (e.g. older spawners) that affect stock status estimates and decrease model sensitivity to changes in stock biomass (Arreguín-Sánchez, 1996; Ichinokawa *et al*., 2014; Sampson, 2014). Fishery selectivity can vary at multiple spatial and temporal scales in response to changes in fleet behaviour or gear regulations (Linton and Bence, 2011; Sampson and Scott, 2011; Martell and Stewart, 2014). Although it is difficult to envision changes in the spatial distribution of the fishery due to circle hook regulations, it seems reasonable that the switch to circle hooks would primarily affect a change in contact selectivity. Recent studies have been conducted to examine contact selectivity across the full range of circle hook sizes commonly used to target reef fishes in the nGOM recreational sector (e.g. Patterson *et al*., 2012; Garner *et al*., 2014), but selectivity has not yet been compared between circle and J hooks.

The objectives of this study were to examine the effect of hook type and hook size on the species composition of the catch, traumatic hooking, species-specific catches, and selectivity of red snapper, *Lutjanus campechanus*, and grey triggerfish, *Balistes capriscus*, via fishing experiments conducted at artificial reef sites in the nGOM. Red snapper was a focus species given that its conservation was the principal management goal in Amendment 27, under the assumption that circle hook usage would reduce release mortality, thus aiding stock rebuilding for this overfished species (GMFMC, 2007). Grey triggerfish was a focus species given its overfished status and concerns that the shift to circle hooks may have caused a change in the relationship between catch per unit effort (CPUE) and fishery-dependent abundance indices (SEDAR, 2011; SEDAR, 2015a).

Material and methods

Sample collection

Sampling trips were conducted between October 2013 and July 2014 aboard four charter boats with home ports between Destin, FL and Orange Beach, AL. All four captains had > 20 years of experience as permitted participants in the nGOM reef fish fishery. Relatively small (total reef volume < 25 m^3) artificial reef sites were chosen haphazardly by Captains without influence from researchers. Prior to fishing each site, a VideoRay Pro4 micro remotely operated vehicle was deployed to survey the reef fish community with the point count method described in Patterson *et al*. (2009). Only relatively isolated (distance to nearest neighbouring reef >0.5 km) artificial reef sites were sampled to avoid confounding effects of experimental fishing attracting reef fishes from neighbouring reefs. The ROV was equipped with a red laser scaler (parallel 5-mW 635-nm class IIIa lasers mounted 7.5 cm apart) to estimate reef fish length from video samples (Patterson *et al*., 2009). A GoPro Hero 3+ was mounted on the front of the ROV to provide high definition video to identify fishes.

Reef fish community structure was estimated from GoPro video files in the laboratory and all fishes observed were identified to the lowest taxonomic level possible. Fish length (mm) was estimated by calculating the ratio of the distance between lasers and fork length (FL) measured on the video monitor. Length estimates were bias corrected based on a random probability draw from a normal distribution with mean equal to 3% and standard deviation equal to 0.6% (Patterson *et al.*, 2009). Fork length estimates were converted to TL for the appropriate species using species-specific linear regressions derived from individuals captured in previous studies (Dance *et al.*, 2011; Addis *et al.*, 2013).

Upon completing the ROV survey at each site, six fishermen deployed two-hook bottom fishing rigs that consisted of a 1.5-m main leader constructed of 30-kg monofilament and two 0.5-m leaders extending from the main leader. Terminal tackle tied to each of these secondary leaders consisted of experimental hooks: 1/0, 4/0, or 7/0 Mustad model 39945BLN circle hooks or 1/0, 4/0, or 7/0 Mustad model 3407DT/SSD J hooks (Table 1). The hook models and sizes used in this experiment were chosen specifically to minimize differences in dimensions between hook types paired by size (e.g. 1/0 circle and J hooks). Hook types paired by size had a mean difference (±SE) in hook width, front length, and gape dimensions of 2.71 (0.67), 2.36 (1.15), and 3.95 (2.20) mm, respectively, (Table 1). A single hook treatment (i.e. size*type combination, e.g. 1/0 J hook) was fished at a given site, with one hook on each bottom rig baited with cut squid (*Loligo sp.*) and the other with cut fish (northern mackerel, *Scomber scombrus*). The hook treatment fished among sites on a given day was selected with systematic random sampling.

Experimental fishing was conducted for 30 min at each sampled reef. Captured fishes were identified to species, measured to the nearest mm (FL and TL), and weighed to the nearest 0.01 kg. Hooking location was recorded for each fish and scored as top, bottom, or corner jaw, deep (gills, esophagus, or stomach) or foul hooked (body). Deep and foul hooked locations composed the traumatic hooking category while all three jaw locations composed the non-traumatic hooking category. All fishes not retained for hard parts sampling were released immediately after data was recorded, but no attempt was made to ascertain the fate of discarded fishes (i.e. survival or mortality). All triggerfish and every n^{th} red snapper were retained for aging, with a goal of sampling 20 red snapper and 20 grey triggerfish per trip. Age was estimated for red snapper via opaque zone counts in sagittal otoliths (Patterson *et al.*, 2001) and grey triggerfish age was estimated via translucent zone counts in dorsal spine sections (Johnson and Saloman, 1984). After fishing each site, a Sea-Bird 19*plus* V2 SeaCAT Profiler was deployed to measure depth (*m*), water temperature (°C), salinity, and dissolved oxygen (mg L^{-1}). Wave height (*m*) also was recorded.

Statistical analyses

Eight of the reef fish species included in the Gulf Council's Reef Fish Fishery Management Plan were observed and included in statistical analyses of community structure: red snapper, grey triggerfish, vermilion snapper (*Rhomboplites aurorubens*), red porgy (*Pagrus pagrus*), lane snapper (*Lutjanus synagris*), greater amberjack (*Seriola dumerili*), grey snapper (*Lutjanus griseus*), and groupers (*Epinephelus* spp. and *Mycteroperca* spp). Tomtate (*Haeumulon aurolineatum*) were also included in community structure analyses due to their frequency and abundance at reef sites and use as bait by recreational fishermen (Garner and Patterson, 2015). Statistical analyses were conducted in Primer 6 (version 6.1.15; PRIMER-E Ltd) with PERMANOVA+ (version 1.0.5; Anderson *et al.*, 2008) to test the effect of hook type and hook size on catch composition and all other statistical analyses conducted in R (version 3.1.1; R Core Team, 2014). The experiment-wise error rate was set to $\alpha = 0.05$ *a priori* for all significance tests. A two-factor permutational multivariate analysis of variance (PERMANOVA) model was computed to test for differences in reef fish species composition between ROV video surveys and hook-specific catches. The Bray-Curtis similarity matrix was calculated on square-root transformed count data. The PERMANOVA model was computed using 9999 permutations with pairwise PERMANOVAs run when main effects were significant (Anderson et al., 2008).

Logistic regression models were computed to test the effect of hook type and size on the probability of traumatic hooking for each of the four groups. Ln-transformed fork length (mm) was included as a covariate in each logistic regression model, and the effects of hook type, hook size, and FL were assumed to be additive (Fox and Weisberg, 2011; Baguley, 2012). The effects of hook type and hook size on catches of all reef fishes, red snapper, and grey triggerfish were tested with negative binomial regression (generalized linear model) including the environmental covariates (i.e. depth, dissolved oxygen, water temperature, salinity, and wave height) in the R package "Mass" (Venables and Ripley, 2002). Due to the high percentage of zeroes in catches (zero other fishes were caught at 18% of reef sites), other reef fishes (i.e. excluding red snapper and grey triggerfish) were modelled with zero-inflated negative binomial regression in the R package "pscl" (Zeileis *et al.*, 2008) with the equation

$$\mathrm{Y} \sim f(y_j)\begin{cases} 0 & P(Y=0)1-P_i \\ \sim NB\left(e^{b_0+\ b_{ixi}+\ldots+\ b_{nxn}},\ \sigma^2\right) & P(Y>0)=\ P_i \end{cases} \tag{1}$$

where the catch at each reef site (y_j) is modelled as both a binomial function fit to the observed counts of other fishes at each site from the ROV survey and as a negative binomial function of hook type and hook size including environmental covariates (b_i) (Fox and Weisberg, 2011; Baguley, 2012).

Hook-specific selectivity functions were estimated separately for red snapper and grey triggerfish in AD Model Builder (Fournier *et al.*, 2012) following the method described in Patterson *et al.* (2012). Assuming natural mortality is negligible during sampling events, relatively intense fishing effort concomitant with the limited spatial extent of reef sites allow the estimation of catch and ROV observations with the equations

$$\begin{cases} C_{lhk} = \dfrac{f_{hk} q_h S_{lh} N_{lk}\left(1-e^{-F_{lk}}\right)}{F_l} \\ V_{lk} = v d N_{lk} \\ F_{lk} = \sum_h f_{hk} q_h S_{lh} \end{cases} \tag{2}$$

where C_{lhk} is the number of fish of length l caught by each hook treatment h at each site k, V_{lk} is the number of each species scaled by lasers, and N_{lk} is the number of fish of length l at site k. The variables v and d represent the visual effort and relative detectability of the ROV survey, while the variables f and q represent the fishing effort and relative power of each hook type; S represents the selection function. Hook-specific ROV effort (e) was calculated as the number of sites fished with each hook-treatment. Hook-specific fishing effort (f) was calculated by multiplying the number of sites fished with each hook treatment by the number of fishermen fishing at each site. The detectability parameter d is confounded with the fishing power parameters (q_h) without additional information to estimate F. Therefore, d was fixed conservatively to a value of 0.1 for red snapper and 0.5 for grey triggerfish, assuming that approximately 10% of red snapper and 50% of grey triggerfish present at each site were measured. ROV survey data were pooled across all sample sites fished with the same hook-treatment and catch data were similarly pooled across sites. Data were pooled across all hook sizes for each hook type in the general circle or J hook models.

Values for C and V are observed while the effort parameters v and f are controlled with little error necessitating estimation of only q, S, and N. Assuming the size distribution of fish is measured with little error during the visual survey the system of equations can be rearranged to give

$$C_{lhk} = \frac{f_{hk} q_h S_{lk} V_{lk} (1 - e^{-F_{lk}})}{v d F_{lk}} \tag{3}$$

Assuming the total species-specific catch for each hook size is approximately normally distributed N (μ, σ^2) and the proportion of the catch for each length bin ($p_{\mathrm{lhk}} = C_{\mathrm{lhk}}/C_{\mathrm{hk}}$) is approximately multinomial with mean $\mathrm{E}\{X_i\} = np_i$ and variance $\mathrm{Var}(X_i) = np(1\text{-}p_i)$, maximum likelihood for q (relative fishing power) and S in each hook-specific model can be estimated by minimizing the negative log-likelihood expression

$$L \;=\; 0.5\sum\nolimits_{h,k}\left[\left(\frac{c_{hk}^{obs} \;-\; c_{hk}}{\sigma}\right)^2 - \log_e \sigma^2\right] + \;\sum\nolimits_{h,k} n_{h,k} \;\sum\nolimits_{l} p_{lhk}^{obs}\; log_e p_{lhk} \tag{4}$$

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

The selectivity parameter S was modelled as a mathematical function of length l using the exponential-logistic equation:

$$S_l = \frac{e^{\beta\alpha(\theta - l)}}{1 - \beta(1 - \; e^{\alpha(\theta - l)})} \tag{5}$$

where α is the shape parameter of the ascending limb, β is the shape parameter of the descending limb, θ is the median size at peak selectivity, and l is the midpoint of each size bin. Initial parameter values were assumed to be similar among all hook-specific selectivity models with the parameter controlling the descending limb (β) assumed near zero (i.e. flat-topped). Parameters were then fit in a stepwise fashion. Nested models were run with the β parameter fixed at zero to determine if estimating β parameters significantly improved model fit vs. the null hypothesis that each $\beta_{\mathrm{i}} \approx 0$. Log-likelihood values from models with fixed (reduced models) or estimated β_{i}'s (full models) were compared with likelihood ratio tests with degrees of freedom equal to the difference in k estimated parameters between full and reduced models and $P({\chi_{\mathrm{k}}}^2 \geq \Delta G^2; \alpha = 0.05)$ calculated as

$$\Delta G^2 \;=\; 2(LL_{\mathrm{reduced}} - LL_{\mathrm{full}}) \tag{6}$$

Results

A total of 56 001 individuals comprising 55 species were identified in ROV video surveys from 72 artificial reef sites, 19 009 individuals comprised the nine fishery species included in statistical analyses. Each hook treatment was fished at 10–15 different artificial reef sites (Table 1). Fishery species comprised 48.9% of all individuals observed in ROV surveys, with tomtate and red snapper constituting 49.0 and 34.5% of fishery species, respectively

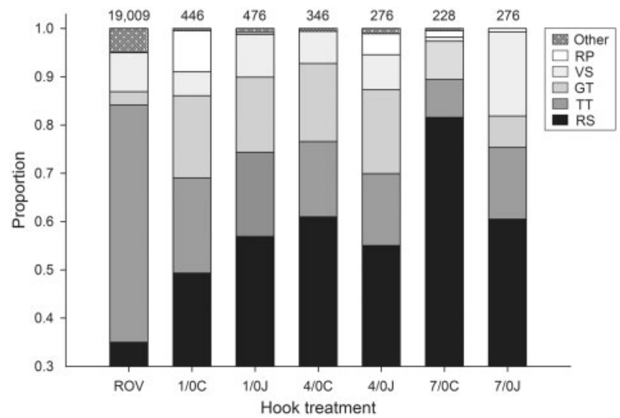


Figure 1. Percentage of fishery species observed in remotely operated vehicle (ROV) video samples of northern Gulf of Mexico reef fish communities or in hook-specific catches. Species abbreviations: RS = red snapper, TT = tomtate, GT = grey triggerfish, VS = vermilion snapper, RP = red porgy, and Other = lane snapper, greater amberjack, grey snapper, and groupers. Greater amberjack, grey snapper, and groupers comprised 2.4, 2.4, and 0.3% of fishes observed in ROV surveys, respectively. Other fishes comprised ≤ 1% of hook-specific catches. Sample sizes are shown atop bars.

(Figure 1). The species composition observed during ROV video samples was significantly different from the species composition in each of the hook-specific catches (PERMANOVA; all $p < 0.001$). Among hook-specific catches, the effect of hook type was not significant ($p = 0.875$) but hook size ($p = 0.003$) significantly affected species composition; the interaction term was not significant ($p = 0.817$). In pairwise comparisons of hook size, species composition of the catch for 7/0 hooks was significantly different from catches for 1/0 ($p = 0.006$) and 4/0 ($p = 0.009$) hooks. Compared to their relative abundance in ROV video samples, red snapper and grey triggerfish were caught in greater proportion in all hook treatments. Among hook-specific catches, tomtate, and grey triggerfish comprised similar proportions among all hook sizes, while red snapper catch proportions were similar among J hook sizes but increased with increasing circle hook size (Figure 1). The greatest proportion of catch of vermilion snapper was observed in the 7/0 J hook treatment (Figure 1). Groupers (primarily scamp, *Mycteroperca phenax*), other lutjanids (i.e. lane snapper and grey snapper), and greater amberjack were rarely caught (≤1%) with any hook treatment.

Overall, the traumatic hooking rate (i.e. proportion of individuals hooked deeply or foul hooked) was < 10% in all but four hook treatments among fish groups (Figure 2). Traumatic hooking occurred in < 9.0% of all reef fishes, < 10% of red snapper, and < 6.0% of grey triggerfish. However, with red snapper and grey triggerfish excluded (i.e. other fishes), traumatic hooking incidence increased with increasing hook size from 0.7% with 1/0 circle hooks to 33.7% with 7/0 J hooks (Figure 2d). Of the other fishes, only tomtate and vermilion snapper were hooked traumatically; 92.3% and 72.5% of traumatic hooking events occurred in J hook treatments for these two species, respectively. The probability that fish suffered traumatic hooking was significantly affected by FL (logistic regression, $p \leq 0.001$), hook type ($p \leq 0.001$), and hook size ($p \leq 0.001$) in the all reef fishes model, with the probability of traumatic hooking decreasing with increasing fish size and being greater for larger hooks and J hooks

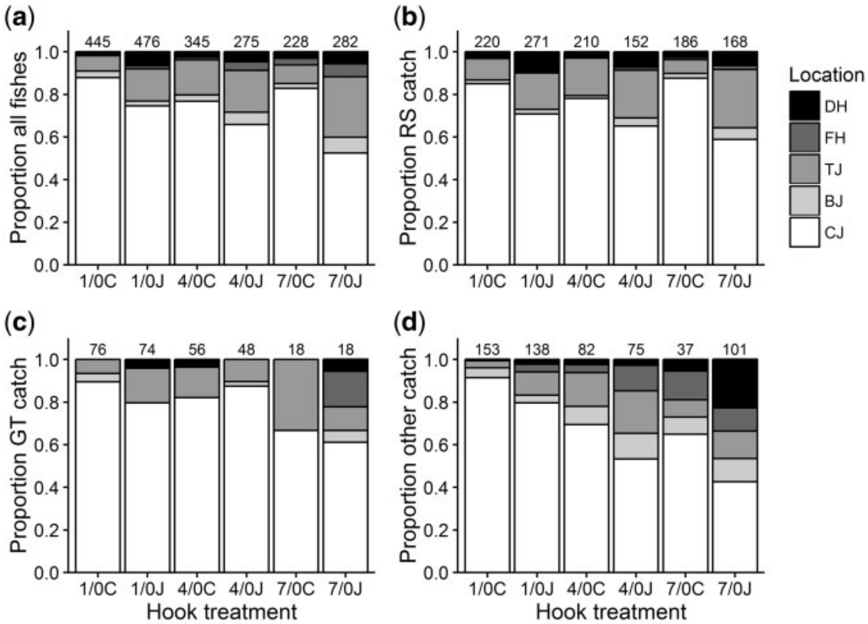


Figure 2. Hooking location for (a) all fishes, (b) red snapper, (c) grey triggerfish, and (d) other fishes caught with each hook treatment. Location abbreviations: DH = deeply hooked (gill arches or beyond), FH = foul hooked (hooked on body), TJ = top jaw, BJ = bottom jaw, and CJ = corner of jaw. The number of observations in each treatment is shown atop bars.

Table 2. Output from logistic regression models comparing the effect of FL (mm), hook type (circle vs. J hook), and hook size (1/0, 4/0, or 7/0) on traumatic hooking probability for all fishes, red snapper (RS), grey triggerfish (GT), and other fishes (excluding RS and GT).

Group	Comparison	Coefficient	Odds ratio	SE	z value	*p*-value
All fishes	FL	−0.004	0.995	0.001	−4.525	**<0.001**
	J vs. circle	1.227	3.412	0.202	6.071	**<0.001**
	4/0 vs. 1/0	0.427	1.533	0.236	1.807	0.071
	7/0 vs. 1/0	1.266	3.547	0.215	5.897	**<0.001**
Red snapper	FL	−0.001	0.999	0.002	−0.667	0.504
	J vs. circle	1.089	2.972	0.274	3.979	**<0.001**
	4/0 vs. 1/0	−0.114	0.890	0.310	−0.373	0.709
	7/0 vs. 1/0	−0.005	0.995	0.306	−0.017	0.987
Grey triggerfish	FL	0.017	1.017	0.005	3.141	**0.002**
	J vs. circle	1.693	5.433	0.917	1.847	0.065
	4/0 vs. 1/0	−0.824	0.439	0.982	−0.840	0.401
	7/0 vs. 1/0	1.436	4.204	0.858	1.675	0.094
Other fishes	FL	−0.013	0.988	0.003	−3.612	**<0.001**
	J vs. circle	1.121	3.068	0.357	3.135	**0.002**
	4/0 vs. 1/0	1.459	4.300	0.440	3.316	**0.001**
	7/0 vs. 1/0	2.871	17.656	0.410	7.002	**<0.001**

Coefficients indicate the change in the log (ln) odds of traumatic hooking with each unit change in X_i (FL) or relative to the base treatment level (1/0 hook). Odds ratios (the back-transformed probability values), standard errors (SE), and critical values (z statistic) are also shown; $\alpha = 0.05$.

(Table 2). Hook type ($p \leq 0.001$) was a significant factor in the red snapper logistic regression model, with J hooks being 2.9 times more likely to result in a traumatic hooking event. Only FL ($p = 0.002$) was significant in the grey triggerfish model, with the probability of traumatic hooking decreasing for larger fish. Although hook type was not significant ($p = 0.065$), the odds of grey triggerfish being traumatically hooked were 5.4 times higher for J vs. circle hooks. All variables significantly affected traumatic hooking probability for other fishes ($p < 0.001$) with the 7/0 hook being 17.7 times more likely to result in a traumatic hooking event compared to a 1/0 hook.

Generalized linear models indicated that hook type did not significantly affect catches of all fishes ($p = 0.578$), red snapper ($p = 0.947$), grey triggerfish ($p = 0.375$), or other fishes ($p = 0.593$) (Figure 3). Hook size had a significant effect on catches of all fishes and grey triggerfish but not red snapper or other fishes. Relative to 7/0 hooks, 4/0 and 1/0 hooks positively increased the expected catch estimate of all fishes (4/0: log count = 0.34, $p = 0.094$; 1/0: log count = 0.72, $p < 0.001$) and grey triggerfish (4/0: log count = 1.22, $p = 0.005$; 1/0: log count = 1.26, $p = 0.005$). Hook size did not significantly affect red snapper (4/0: $p = 0.0942$; 1/0: $p = 0.082$) or other fishes catches (4/0: log count = 0.44, $p = 0.254$; 1/0: log count = 0.51, $p = 0.159$) relative to 7/0 hooks. The visual count of other fishes was a significant predictor of other fishes catch ($p = 0.002$) with the log odds for zero catch of other fishes decreasing by 0.07 with each unit

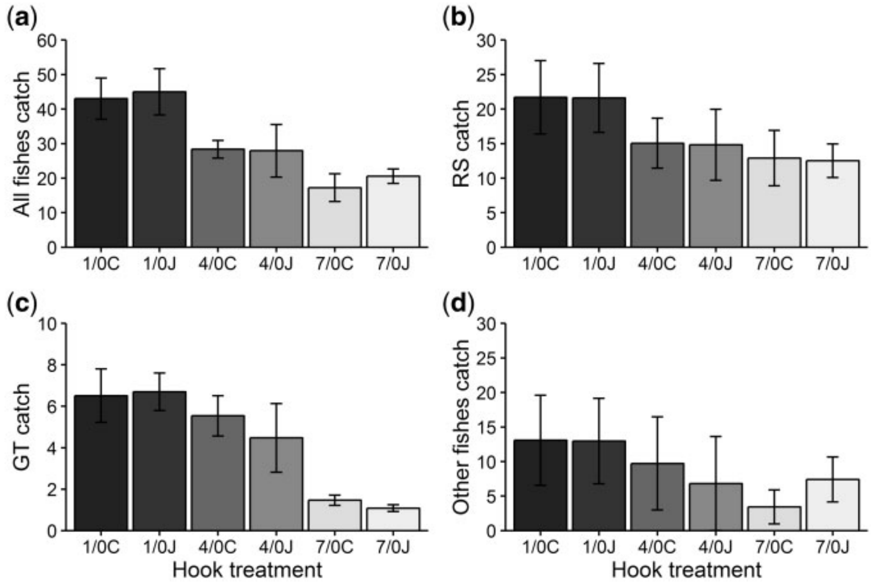


Figure 3. Plots of mean standardized catches estimated with generalized linear models for (a) all fishes, (b) red snapper, (c) grey triggerfish, and (d) other fishes for each hook treatment. Error bars are 95% confidence intervals.

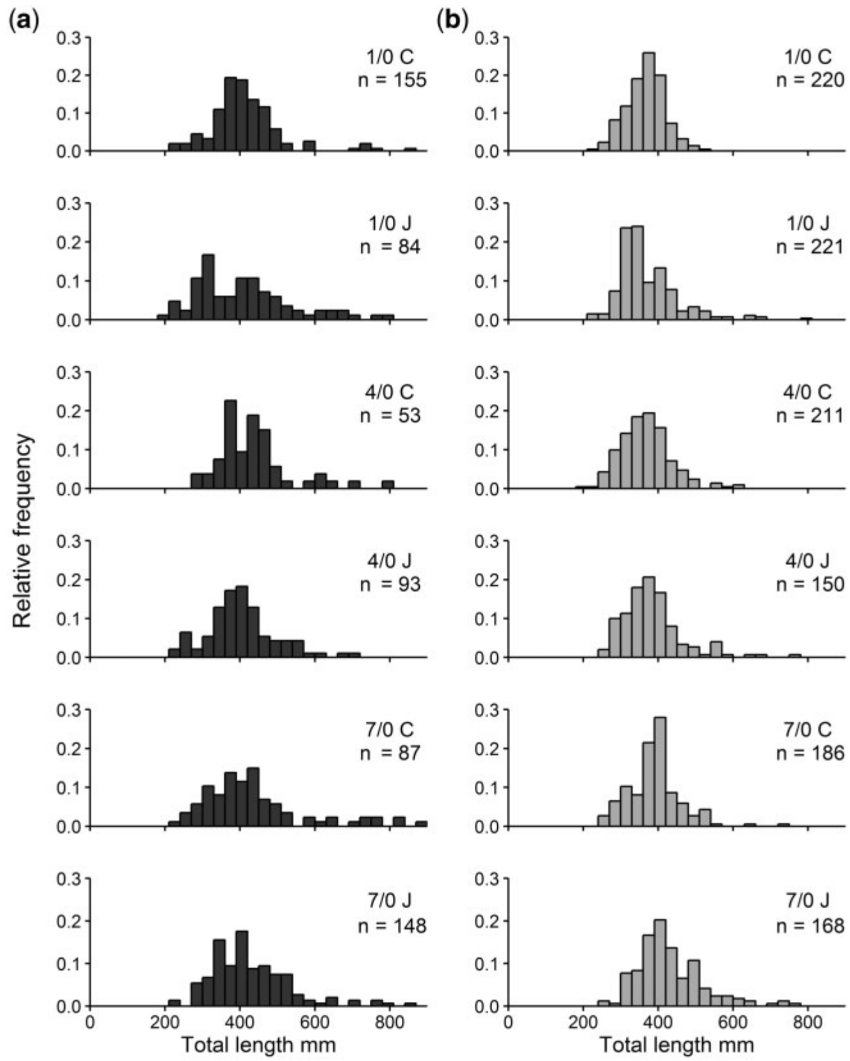


Figure 4. Relative frequency size distributions of red snapper (a) scaled by lasers and (b) caught with experimental hooks pooled across reef sites fished with each hook treatment. The number of observations is shown on each panel.

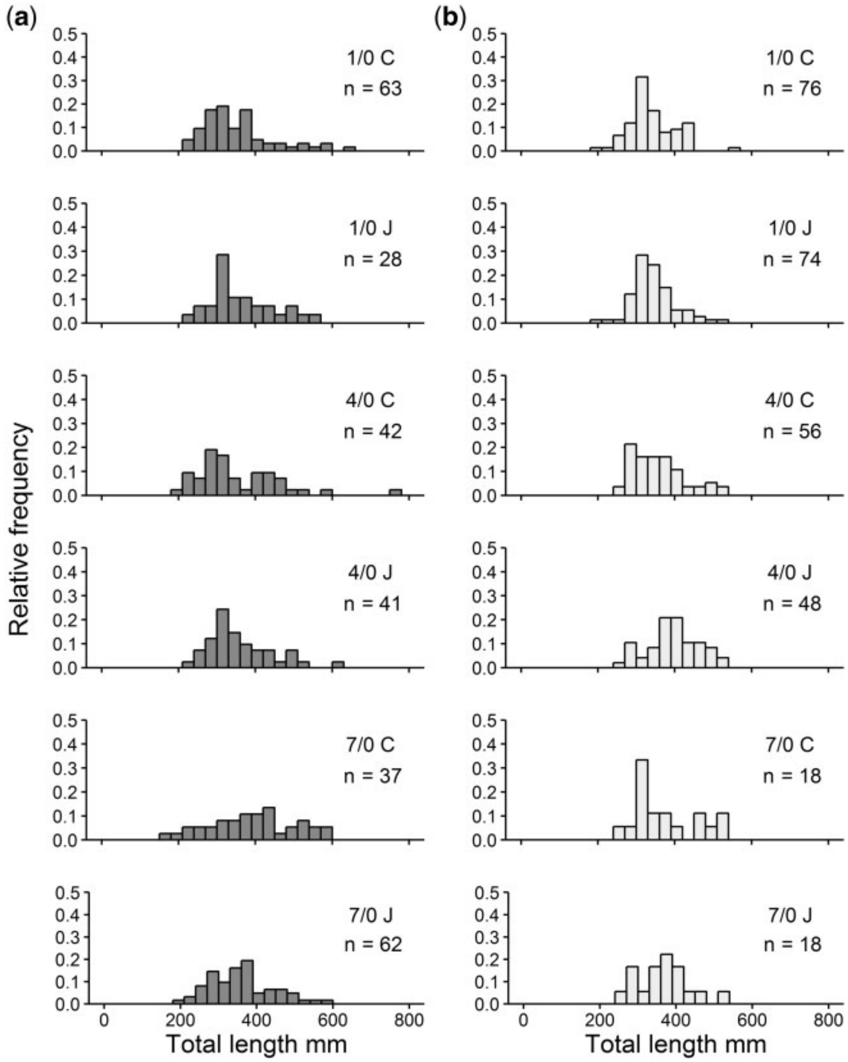


Figure 5. Relative frequency size distributions of grey triggerfish (a) scaled by lasers and (b) caught with experimental hooks pooled across reef sites fished with each hook treatment. The number of observations is shown on each panel.

increase in other fishes present at reef sites. The Vuong test indicated the zero-inflated negative binomial provided a significantly improved fit (z-statistic = 4.3, $p < 0.001$) over the simple negative binomial model (Zeileis *et al.*, 2008). Environmental covariates did not have a significant effect on catches except for depth, which had a significant negative effect on catch in the all fishes model (log catch = –0.04; $p = 0.012$) and other fishes model (log catch = –0.12; $p = 0.007$).

Size distributions of laser-scaled red snapper (Figure 4a) were broader than those observed in hook-specific catches (Figure 4b). Modes of laser scaled red snapper occurred between 350 and 450 mm TL in all hook treatments except for 1/0 J hooks, for which the mode was approximately 320 mm TL. A key difference between red snapper catch size distributions vs. laser-scaled distributions from ROV video was that fish greater than 600 mm TL were observed in all laser-scaled size distributions but were nearly absent from all hook-specific catches. Grey triggerfish had smaller sample sizes than red snapper for both laser-scaled individuals (Figure 5a) and hook-specific catches (Figure 5b), with modes occurring between 300 and 400 mm FL in nearly all hook treatments. For both species, lesser catches with larger hooks resulted in fewer sampled individuals, especially for grey triggerfish.

Selection curves estimated for red snapper were dome-shaped for all hook treatments (Figure 6a), as well as for models computed with pooled circle or J hook data (Figure 6c; Table 3). Models in which β parameters were estimated resulted in significantly improved fits in both hook-specific and pooled-data models (Table 4). Among hook-specific models, the smallest size at peak selection occurred for 4/0 J hooks (267 mm TL) and was largest for 7/0 J hooks (410 mm TL), a difference of 143 mm (Table 3). However, peak selectivity occurred below the current red snapper recreational minimum length limit (MLL) in all hook treatments except the 7/0 J hook, which exceeded the MLL by only 4 mm. Peak selection was similar between paired circle and J hook sizes and differed by only 20 mm TL between hook types in pooled-data models. Estimated selection probability decreased more slowly in the 7/0 J hook treatment with 631 mm TL red snapper having a 0.5 selection probability compared to < 0.20 at 631 mm TL in all other hook treatments. Selectivity of all hook treatments other than 7/0 J hooks was strongly dome shaped.

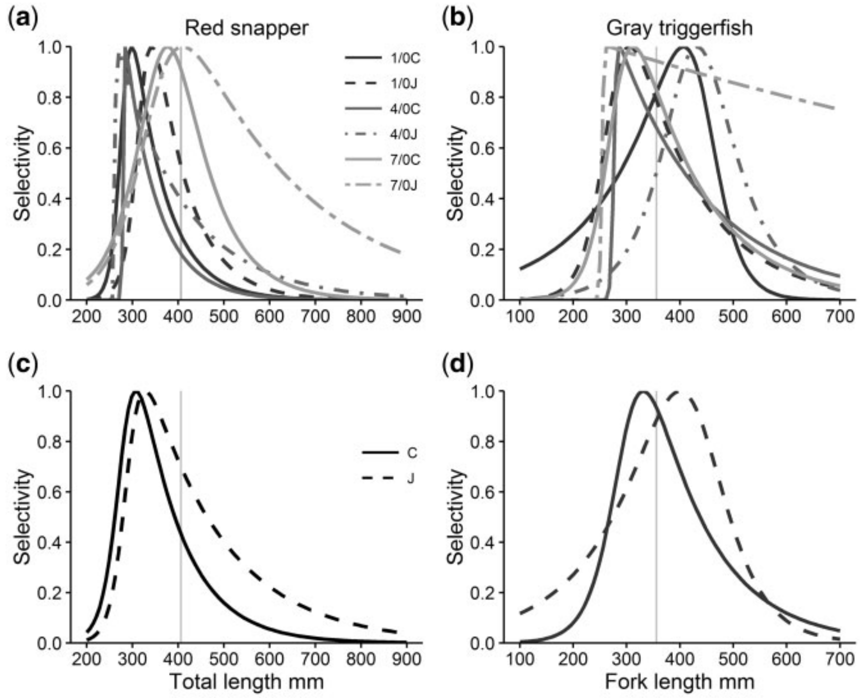


Figure 6. Maximum likelihood selectivity functions estimated for red snapper (a and c) and grey triggerfish (b and d). Plots of hook-specific selectivity functions appear in the top row (a and b), while plots shown in the bottom row were computed with data pooled across all sizes of each hook type (c and d). Vertical grey lines indicate the current minimum size limit for red snapper (406 mm TL) and grey triggerfish (356 mm FL) in the recreational fishery.

Selection curves estimated for grey triggerfish were also strongly dome-shaped for all but 7/0 J hooks (Figure 6b); circle and J hook models computed with pooled data also were strongly dome-shaped (Figure 6d). Estimating β parameters significantly improved fit in all hook-specific models ($p < 0.05$) except the null model ($p = 0.095$) for grey triggerfish (Table 4). Size at peak selection was variable and showed no trend with increasing hook size for either hook type. Peak selection was estimated above the current grey triggerfish recreational MLL of 356 mm FL for the 1/0 circle and 4/0 J hook treatments only. Selectivity models estimated with data pooled across hook sizes within a given hook type resulted in peak selectivity estimates above the current grey triggerfish MLL (356 mm FL) for J hooks (411 mm FL) but not circle hooks (333 mm FL; Table 3; Figure 6d).

Discussion

Empirical data presented here suggest that the circle hook regulation likely reduced traumatic hooking rates of nGOM reef fishes. Overall, traumatic hooking rates were low (< 10%) for red snapper and grey triggerfish, but the reduction in traumatic hooking facilitated by circle hook use (~50%) would translate to hundreds of thousands fewer regulatory discards experiencing a traumatic hooking event. Our study provides a robust evaluation of the circle hook effect because we avoided use of pseudo-circle hooks (Cooke and Suski, 2004) and hook type treatments were paired by size to control for potential confounding by differing hook dimensions. Failure to control for different hook dimensions in empirical studies may lead to spurious conclusions because hook size has a strong effect on the incidence of traumatic hooking (Cooke *et al.*, 2005) and catch metrics, particularly catch rates (Mapleston *et al.*, 2008; Patterson *et al.*, 2012; Garner *et al.*, 2014). We also controlled for potential confounding from competing hook treatments by fishing a single hook treatment at a given reef site and randomizing hook treatments among a large number of sites.

Circle hook use showed much greater potential conservation benefit to other reef fishes for which traumatic hooking was 18 times more likely when fishing with large J hooks. Circle hooks are generally thought to function most effectively, and maximize conservation benefit, when fishermen target suction feeding fishes capable of fully engulfing the hook into the bucco-pharyngeal cavity (Cooke and Suski, 2004; Cooke *et al.*, 2005; Lukacovic and Uphoff, 2007). A moderately large oral gape relative to body size enabled tomtate and vermilion snapper to consume the large hook treatments while facilitating proper circle hook functionality. In contrast to the conservation benefits observed for suction feeding fishes (Cooke *et al.*, 2005; Lukacovic and Uphoff, 2007), both grey triggerfish and red porgy may be less likely to deeply ingest a hook before a fishermen detects a bite due to species-specific feeding behaviours. Other authors have reported significant conservation benefit to GOM reef fishes from circle hook use (Sauls and Ayala, 2012). However, our data showed much lower traumatic hooking rates for red snapper and no traumatic hooking of other large predatory reef fishes. One explanation for the difference in findings is that traumatic hooking rates may be affected by gear orientation in addition to hook type and size (Beckwith and Rand, 2005). A two-hook bottom rig was chosen to emulate fishing techniques commonly used by charterboat fishermen when targeting smaller reef fishes in the nGOM. However, nGOM recreational fishermen also commonly target red snapper and larger reef fishes with a single medium or large hook attached at the terminal end of a long (~2 m) leader tied to

Table 3. Maximum likelihood parameter estimates for red snapper and grey triggerfish selectivity with data pooled across experimental hook types (C and J), as well as parameter estimates from hook-specific models.

Species	Hook treatment	α	β	θ
Red snapper	C	0.056	0.192	307.3
	J	0.059	0.101	327.7
	1/0 C	0.093	0.152	298.0
	1/0 J	0.069	0.190	341.7
	4/0 C	0.762	0.019	284.7
	4/0 J	0.842	0.008	267.3
	7/0 C	0.032	0.391	376.8
	7/0 J	0.026	0.146	409.5
Grey triggerfish	C	0.045	0.254	332.8
	J	0.032	0.652	410.9
	1/0 C	0.040	0.746	400.8
	1/0 J	0.010	0.001	332.6
	4/0 C	0.411	0.022	287.1
	4/0 J	0.047	0.554	446.4
	7/0 C	0.049	0.165	311.3
	7/0 J	0.558	0.001	265.3

The parameter θ = median fish TL (mm) at full selectivity. The parameters α and β are both shape determining parameters.

Table 4. Likelihood ratio tests fit for full or reduced selectivity models for red snapper and grey triggerfish.

Species	Source	df	MLE	G^2	*p*-value
Red snapper	$\text{Null}_{\text{pooled}}$	2	3182.8	51.5	**<0.001**
	C_{pooled}	1	3185.1	56.1	**<0.001**
	J_{pooled}	1	3160.5	7.0	**0.008**
	$\text{Full}_{\text{pooled}}$		3157.0		
	Null	6	3342.3	132.5	**<0.001**
	1/0 C	1	3313.2	74.4	**<0.001**
	1/0 J	1	3298.4	44.7	**<0.001**
	4/0 C	1	3315.9	79.8	**<0.001**
	4/0 J	1	3299.3	46.6	**<0.001**
	7/0 C	1	3316.2	80.4	**<0.001**
	7/0 J	1	3314.9	77.8	**<0.001**
	Full		3276.0		
Grey triggerfish	$\text{Null}_{\text{pooled}}$	2	494.0	4.3	0.114
	C_{pooled}	1	492.2	0.7	0.403
	J_{pooled}	1	493.7	3.7	0.056
	$\text{Full}_{\text{pooled}}$		491.9		
	Null	6	510.3	10.8	0.095
	1/0 C	1	509.6	9.4	**0.002**
	1/0 J	1	509.8	9.8	**0.002**
	4/0 C	1	507.7	5.7	**0.017**
	4/0 J	1	510.3	10.8	**0.001**
	7/0 C	1	509.0	8.2	**0.004**
	7/0 J	1	510.0	10.1	**0.002**
	Full		504.9		

The model in which the hypothesis that a given $\beta_i = 0$ is listed in the Source column; all β_i's were set equal to zero in null models and all β_i's were estimated in full models. Also shown for each test are the degrees of freedom ($\text{df} = \text{df}_{\text{full model}} - \text{df}_{\text{reduced model}}$), maximum likelihood estimate (MLE; negative log likelihood), test statistic (G^2), and one-tailed probability value (*p*-value) from the χ^2 distribution. *p*-values ≤ 0.05 indicate a significant improvement in model fit compared to the full model.

a swivel below a 150–250 g slip sinker (Garner and Patterson, 2015). Fishing rigs in which a heavy sinker is placed prior to the hook and not affixed to the line likely reduce a fisherman's ability to detect a strike and increase the probability that a fish will deeply ingest the hook (Beckwith and Rand, 2005; Grixti *et al.*, 2007).

Assessing capture efficiency (as a proxy for catchability) in response to changes in gear regulations is particularly important to facilitate acceptance of new gear by fishermen and for consistency with fishery-dependent CPUE indices in assessment models. Reduced hooking efficiency with circle hooks has been reported for some fish species in the literature, but the authors compared proportions of captures to total hook sets for non-isolated target species (e.g. Cooke *et al.*, 2003; Jones, 2005; Sales *et al.*, 2010; Lennox *et al.*, 2015); were unable to control for gear orientation or hook dimensions (Bacheler and Buckel, 2004; Sauls and Ayala, 2012); or utilized hook-and-line gear types not-comparable to those used in this study (e.g. Arterburn and Berry, 2002; Kerstetter and Graves, 2006; Vecchio and Wenner, 2007; Pacheco *et al.*, 2011). After controlling for hook dimensions and correcting for environmental covariates, we found no evidence for an effect of hook type on catches for a variety of nGOM reef fishes commonly targeted by the recreational fishery. Hook size had a significant effect on catches for most groups suggesting empirical results are likely confounded when hook dimensions are not controlled in the experimental design.

Circle hook use was thought to be minimal in the nGOM recreational reef fish fishery prior to 2008. Therefore, shifts in catchability due to the circle hook requirement in 2008, if present and unaccounted for, could bias indices of abundance computed from fishery-dependent data (Linton and Bence, 2011; Martell and Stewart, 2014). Fishermen have voiced concerns to the GMFMC regarding decreased catches (e.g. grey triggerfish) after the circle hook requirement went into effect in 2008, and grey triggerfish catchability was thought to have declined by 47% following the mandate (SEDAR, 2015a). However, the assumption of decreased catchability originated from an unpublished study that did not control for either hook type or hook size. Standardized recreational CPUE indices presented in the 2015 stock assessment report indicate a decrease in grey triggerfish catches for some fishery sectors only during the first year of the mandate with a concomitant increase in CPUE observed for some eastern GOM recreational sectors during the same year (SEDAR, 2015a). Our results indicate no effect of circle and J hooks on catches when controlling for hook size, thus are inconsistent with a decline in catchability following the circle hook regulation. Rather, declining catch rates for grey triggerfish during the post-2007 data collection period may correspond to concomitant declines in stock biomass (SEDAR, 2015a). Clearly, catchability estimates have important implications for estimates of grey triggerfish spawning stock biomass, productivity, and the rebuilding schedule.

Changes in selectivity associated with gear regulations can result in poor estimation of fishing mortality rates exerted on fully selected age-classes and sustainable harvest levels (Sampson, 1993; Ichinokawa *et al.*, 2014; Sampson, 2014). Results from this study indicated smaller grey triggerfish were selected with circle hooks but similar-sized red snapper were selected with both hook types. Models fit to data pooled across hook sizes of a given type represent a more robust estimate of gear selectivity in the fishery because fishermen currently use a wide variety of circle hook sizes and designs when targeting reef fishes (Garner and Patterson, 2015) and presumably used a similarly wide range of J hook sizes prior to 2008. For red snapper, the difference in size at peak selection between hook types equates to less than one age-class for a species that lives in excess of 50 years and can achieve TL > 900 mm (SEDAR, 2013). Similar selection curves have been reported in previous studies when targeting red snapper with similarly-sized and larger circle hooks than were tested in this study (Patterson *et al.*, 2012; Garner *et al.*, 2014), and J hooks appear to have similar selection peaks and functional form. Despite little empirical evidence for a selection shift, specifying time-varying selection after 2007 in red snapper stock assessments did improve model fits to observed fishery-dependent data (SEDAR, 2013; SEDAR, 2015b). Empirical evidence reported here suggests that incorporating flexible form equations and including time-varying components in the updated grey triggerfish stock assessment (SEDAR, 2015a) improved upon previous assessment models in which logistic selection was assumed (SEDAR, 2011). Dome-shaped selection and increased selection of smaller sized grey triggerfish by circle hook gear may have reduced sensitivity to changes in population abundance for fishery-dependent indices. Dome-shaped selection in the recreational fishery emphasizes the importance of fishery-independent video surveys for which selectivity is assumed to be asymptotic and thus, sensitive to population-level changes in larger, older spawners.

Overall, results reported here are consistent with the overwhelming majority of peer reviewed studies that previously reported significant conservation benefit resulting from the use of circle hooks. Controlling for hook dimensions between hook types, which should also be conducted in future studies of hook performance, permitted reliable tests of the effect of hook type on reef fish catches. Our results indicate that the circle hook regulation instituted in US federal waters of the GOM in 2008 likely provided conservation benefit to several reef fish species without altering catches.

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