

EFFECT OF CIRCLE HOOK SIZE ON REEF FISH CATCH RATES, SPECIES COMPOSITION, AND SELECTIVITY IN THE NORTHERN GULF OF MEXICO RECREATIONAL FISHERY

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ABSTRACT

The effect of circle hook size on reef fish catch rates, species composition, and selectivity was tested in the northern Gulf of Mexico recreational fishery. Fish communities first were sampled at natural ($n = 19$) and artificial ($n = 23$) reefs with a micro remotely operated vehicle (ROV) equipped with a laser scale. Fishing experiments ($n = 69$) then were conducted with 9/0, 12/0, and 15/0 circle hooks. Hook size significantly affected fish catch rates, species composition, and size. Small invertivore fishes constituted 33.4% of the catch taken with 9/0 hooks, but were nearly absent from the catch made with larger hook sizes. In contrast, red snapper, *Lutjanus campechanus* (Poey, 1860), constituted only 25.3% of fishery species total abundance in video samples, but ranged from 59.1% of the 9/0 hook catch to nearly 90% for 15/0 hooks. A novel maximum likelihood approach was developed to estimate exponential-logistic selectivity functions for each hook size from ROV-based estimates of red snapper size distributions and observed hook-specific catch at size. Both the 9/0 and 12/0 hooks displayed dome-shaped selectivity functions, while the 15/0 hook size was estimated to have a logistic-shaped function. However, observed catch-at-size data displayed a dome-shaped pattern for 15/0 catches when paired with 9/0 hooks, but an indistinct pattern when paired with 12/0 hooks. Overall, study results suggest that regulating circle hook size would affect reef fish catch rates and size in the northern Gulf of Mexico recreational fishery, but potential conservation benefits may be confounded by unintended effects.

Bycatch of undersized fishes and non-targeted species is a global fisheries problem (Alverson et al. 1994, Lewison et al. 2004, Kelleher 2005, Davies et al. 2009). Circle hooks have been proposed as a conservation measure to reduce bycatch rates or mitigate issues related to incidental hooking of non-targeted species. The scientific literature on circle hooks consists predominantly of studies in which their conservation benefits have been tested in commercial fisheries targeting oceanic pelagic species (Kaplan et al. 2007, Carruthers et al. 2009, Sales et al. 2010, Pacheo et al. 2011), and such studies are well-presented in this volume (Serafy et al. 2012). However, circle hooks also may have significant conservation benefits for reducing the incidental catch of undersized and non-targeted fishes in recreational hook-and-line fisheries (Grover et al. 2002, Prince et al. 2002, Bacheler and Buckel 2004).

Recreational fishing effort has a greater impact on marine fisheries off the southeastern United States than in any other region of the US, both in terms of total landings, as well as landings of stocks estimated to be overfished or undergoing overfishing (Coleman et al. 2004, Hanson and Sauls 2011, Ihde et al. 2011). Increasingly, it is not just the landed catch that is at issue, but also dead discards of undersized, non-targeted, or closed-season fishes that contribute significantly to the total harvest for

several marine species. Red snapper, *Lutjanus campechanus* (Poey, 1860), and gag, *Mycteroperca microlepis* (Goode and Bean, 1879), are two of the more highly targeted marine fishes in the US Gulf of Mexico (GOM), and management of both, as well as the reef fish fishery in general, is greatly affected by bycatch issues (Goodyear 1995, Johnson et al. 1997, Strelcheck and Hood 2007). Recent stock assessments have highlighted the fact that dead discards in the recreational fishery contribute a substantial percentage (i.e., 20%–30%) of the total recreational harvest of red snapper and gag, both of which have a spawning stock biomass estimated to be severely depleted (Porch 2007, SEDAR 2006, 2009a,b).

There are several aspects of the biology of northern GOM reef fishes, as well as their fisheries management, that confound issues related to discarding. Fishery managers have relied mostly on traditional management tools, such as size limits, daily bag limits, and closed seasons, in attempts to limit recreational effort, hence fishing mortality (F). However, the GOM reef fish fishery is diverse, with 42 species in the Gulf of Mexico Fishery Management Council's (GMFMC) reef fish fishery management plan. Catch rates for fishes such as red snapper and gag can be high even during closed seasons given the non-specificity of fishing effort when recreational seasons are open for other reef fishes. Furthermore, many of the snappers and groupers in the northern GOM display ontogenetic movements into deeper waters, being found out toward the shelf edge (approximately 200 m) or deeper as adults (Mitchell et al. 2004, Lindberg et al. 2006, Patterson 2007), where water depth can exacerbate discard mortality. Venting is required for regulatory discards in the GOM reef fish fishery, but acute and chronic barotrauma severely affects physoclistous fishes that experience rapid pressure changes of several atmospheres when brought from depth, which in turn translates into high post-release mortality rates even for fish that successfully return to depth after being released (Gitschlag and Renault 1994, Wilson and Burns 1996, Rummer 2007).

The GMFMC has discussed employing non-traditional management tools, such as tag programs, limits on days-at-sea for for-hire vessels, marine protected areas, and catch shares, to reduce recreational F in the GOM reef fish fishery, partly because the pervasive issue of discard mortality hampers the utility of many of the traditional tools the GMFMC has relied upon. One potential method to reduce catch rates, especially for undersized fishes, is to regulate the selectivity of the hook-and-line gear used to target reef fishes. Circle hooks have been required in the GOM reef fishery since 2007, but the size of hooks that may be used is not currently regulated (GMFMC 2007). The GMFMC considered regulating hook sizes for harvesting reef fishes but opted not to implement hook size restrictions due to limited scientific research pertaining to reef fishes and a lack of standardization in hook sizes among manufacturers (GMFMC 2007). The goal of the present study was to examine the effect of circle hook size on reef fish catch rates, species composition, and size distributions in the GOM recreational reef fish fishery. Our approach was to sample reef sites in the northern GOM with a micro remotely operated vehicle (ROV) to estimate community and size structure of reef fishes present on reefs. Then, we fished the sites with different sized circle hooks to test the effect of hook size on catch rates, species composition, and size distributions. Lastly, we developed a novel method to estimate hook selectivity for red snapper from estimated in situ size distributions and size distributions of hook-specific catches.

METHODS

FIELD SAMPLING OF REEF FISHES.—Sampling occurred at natural ($n = 19$) and artificial reef ($n = 23$) sites located at depths between 20 and 67 m on the northeastern Gulf of Mexico continental shelf (latitude range: 85.92N–88.17N, longitude range: 29.50W–30.20W) between June 2009 and August 2010. Video samples ($n = 69$) of fish communities were obtained with either a VideoRay Pro3 (dimensions: 30 cm long, 24 cm tall, 22 cm wide; mass = 3.8 kg) or Pro4 micro ROV (dimensions: 36 cm long, 28 cm tall, 22 cm wide; mass = 4.8 kg). Both ROVs have a depth rating of 170 m, a wide angle (105° or 116° , respectively) lens on a 570-line forward-looking color camera, and were equipped with a red laser scale (10 cm between lasers) to estimate fish size (Patterson et al. 2009). The ROVs were tethered to the surface where they were controlled by a pilot via an integrated control box containing a 38-cm monitor to observe video captured by the ROV's camera during sampling.

Video sampling was conducted at study reefs either with the point-count method described by Patterson et al. (2009) or a transect method, depending on habitat type and dimensions. The point-count method was used to sample a 15-m wide cylinder around isolated reef habitat, such as single artificial reef modules, while the transect sampling method was utilized for reef habitat that was more broadly distributed, which was characteristic of natural reef habitat examined in the present study. Transects were flown approximately 2 m above the sea floor and the camera angle adjusted such that the field of view was approximately 10 m wide. Orthogonal 25-m long transects were flown from a center point at a given reef site such that approximately 1000 m² of reef habitat were sampled.

Analysis of video samples was performed with a Sony DVCAM DSR-11 digital VCR capable of frame by frame playback and a Sony LMD-170 high resolution LCD monitor. When the point-count method was employed, fish counts were summed among all sampling segments and then divided by the sampling cylinder's area (176.7 m²) to estimate fish density (see Patterson et al. 2009). Fish density was computed by summing taxa-specific fish counts and then dividing by the total area among transects. The mean density of fishery species among all samples was computed, and then the relative proportion of total fishery species density was computed for each species.

Fork length (FL) was estimated for fishes struck by the laser scale during video sampling at study reefs. For a given fish, this was accomplished by multiplying its length measured in a video frame by the known distance between lasers (100 mm), and then dividing that product by the distance measured between lasers in the frame. FL was converted to total length (TL) with regression equations developed from fish captured with hook and line. Bias-correction in fish length estimates then was conducted based on results from a pool experiment in which model fish length was estimated for different angles from perpendicular and distances from the ROV (Patterson et al. 2009). For conditions observed in situ, the mean bias of underestimating fish length was estimated to be 3% with a standard deviation of 0.6%. Therefore, TL estimates were adjusted based on a random probability and normally distributed bias with mean equal to 3% and standard deviation equal to 0.6%.

Red snapper age distribution was estimated from length with an age-length key for laser-scaled fish as well as fish captured with circle hooks. The key was computed from size-at-age data ($n = 1755$) reported in Patterson et al. (2001) for fish from the north central GOM that were aged via analysis of sagittal otolith thin sections. Size-at-age data from additional red snapper samples ($n = 465$) were added to the data set from fish sampled in the north central GOM off northwest Florida and Alabama in 2009–2010 (WF Patterson, unpubl. data). The probability that fish within 10 mm length bins in the combined size at age data set were a given age was computed, and then age was assigned probabilistically to bias-corrected lengths of laser-scaled and hook and line sampled fish.

Fish were captured with hook and line for 30 min by 6–8 anglers at each reef site following video sampling. Two-hook bottom rigs were deployed on each fishing rod and consisted of a 1.5-m leader constructed of 60-lb (approximately 27.2 kg) monofilament which had two

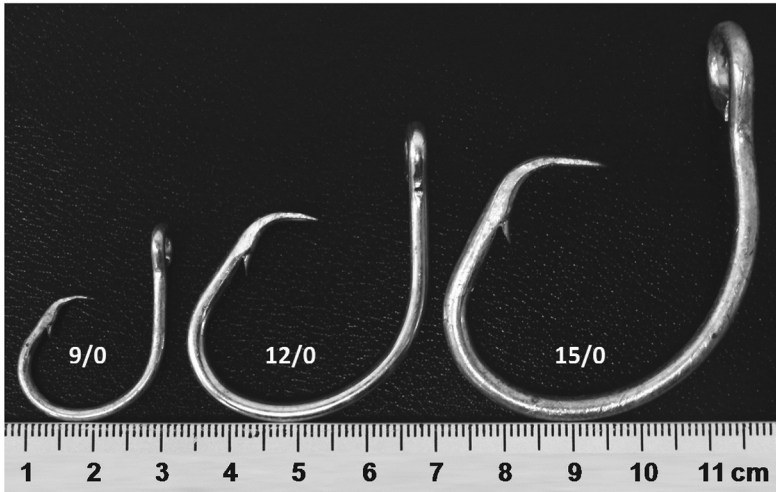


Figure 1. Digital image of 9/0, 12/0, and 15/0 Mustad 39660D circle hooks used to test the effect of hook size on reef fish catch rate and size distribution in the northern Gulf of Mexico recreational reef fish fishery.

shorter leaders extending approximately 0.5 m horizontally from the main leader. Terminal tackle on the ends of the horizontal leaders was either 9/0, 12/0, or 15/0 Mustad 39660D circle hooks (Fig. 1). This range in hook sizes was selected due to the fact that 9/0 Mustad 39660D circle hooks are most similar in size to 3/0 J-hooks traditionally used in the GOM reef fish fishery and 15/0 hooks are the upper limit in hook size typically employed by recreational anglers. Hooks were fished with either cut squid or mackerel scad, *Decapterus macarellus* (Cuvier, 1833), as bait. At a given site, half the anglers fished with one size of circle hooks and the other half fished with another size (combination-1 = 9/0 and 12/0 hooks, combination-2 = 9/0 and 15/0 hooks, and combination-3 = 12/0 and 15/0 hooks), although during 10 sampling events, only one hook size was used. Captured fish were either randomly sampled and retained to provide biological samples for another study, or were returned to the water following length measurement and venting their gas bladders.

STATISTICAL ANALYSIS.—The difference in catch rate among hook sizes was tested with one-way analysis of variance (ANOVA, $\alpha = 0.05$) for all fishes and separately for red snapper. Catch per hook hour was log-transformed to meet the assumption of normality prior to analysis in SAS (SAS, Inc. 1998). Differences among the relative proportion of fishery species estimated among reef sites, and standardized to sample area, and the proportion of those species in the hook-specific catches were tested with a one-way analysis of similarity (ANOSIM, $\alpha = 0.005$) model in the Primer software package (Clark and Gorley 2001). Species-specific proportions were square-root transformed and standardized prior to analysis. The difference in size of fish captured among hook sizes was tested with ANOVA ($\alpha = 0.05$) following log-transformation to meet parametric assumptions.

Red snapper sample sizes were thought to be large enough among laser-scaled individuals and hook-specific catches that selectivity could be estimated directly for this species. In many cases, reef sites were limited in their spatial extent such that it was possible to catch a significant fraction of the local red snapper population. Assuming deaths by natural causes were a negligible source of mortality during the short fishing event, an appropriate model for the catches and ROV observations is:

$$\begin{cases} C_{lhk} = \frac{f_{hk} q_h S_{lh} N_{lk} (1 - e^{-F_{lk}})}{F_l} \\ V_{lk} = edN_{lk} \\ F_{lk} = \sum_h f_{hk} q_h S_{lh} \end{cases} \quad (\text{Eq. 1})$$

where N_{lk} is the number of red snapper of length l at fishing location k , C_{lhk} is the number of red snapper caught by hook type h , and V_{lk} is the number of red snapper measured during the ROV survey. The variable F represents the total fishing mortality rate in the area, which is the sum of the fishing mortality rates associated with each of the two hook types being fished simultaneously. The variables f and e represent the relative effort expended during fishing or the ROV survey. The variables q and d represent the relative fishing power of each hook type and relative detectability of red snapper during the ROV survey. The variable S represents the selection function (see below).

The C and V are observed quantities and the effort parameters are controlled with little error, leaving the q , d , S , and N to be estimated. If the observations C and V were mutually exclusive outcomes, then the estimation could be accomplished using the SELECT model of Millar (1992), which would conveniently eliminate the need to estimate the nuisance parameters (N). However, since the survey was conducted prior to fishing, it is likely that some of the fish surveyed were also caught and retained. Alternatively, if the size distribution of fish in the surveyed area (V) is measured with little error, then the system of equations in (1) may be reformulated as

$$\begin{cases} C_{lhk} = \frac{f_{hk} q_h S_{lh} V_{lk} (1 - e^{-F_{lk}})}{edF_{lk}} \\ F_{lk} = \sum_h f_{hk} q_h S_{lh} \end{cases} \quad (\text{Eq. 2})$$

Assuming the total red snapper catch by each hook type at each location (C_{hk}) has approximately a normal distribution (with variance s^2) and that the proportion of the catch falling in each length category ($p_{lhk} = C_{lhk} / C_{hk}$) has approximately a multinomial distribution, then maximum likelihood estimates of q , d and S may be obtained by minimizing the negative log-likelihood expression

$$L = 0.5 \sum_{h,k} \left(\frac{C_{hk}^{obs} - C_{hk}}{\sigma} \right)^2 - \log_e \sigma^2 + \sum_{h,k} n_{h,k} \sum_l p_{lhk}^{obs} \log_e p_{lhk} \quad (\text{Eq. 3})$$

The superscript *obs* distinguishes the observed data from the value predicted by the model and n indicates the effective sample size (which in some cases might not equal the total catch).

The detectability parameter d in Equation 2 is confounded with the catchability parameters q unless additional information is provided to estimate F , such as might be obtained if a second visual survey were conducted after fishing occurred. In the present study, d was fixed to 0.1 because approximately 10% of the red snapper in each area were able to be measured. The exact value is inconsequential because only the relative fishing power of the gears is of interest here.

The magnitude of the selection vector S_{lh} is similarly confounded with the value of q_{lh} . Moreover, the model can become over-parameterized if unique selection values are estimated for each length category. A common solution to these two problems has been to model selection as a mathematical function of length. Little has been published to guide the choice of hook selection models; however, an inspection of the data indicated the 9/0 hooks caught a lower proportion of large fish than the two larger hook sizes. This implies that the hooks used in our study might exhibit an asymmetric, dome-shaped selection pattern. Two possible candidates that were examined here are the exponential-logistic and double logistic curves:

$$S_l = \begin{cases} \frac{e^{\beta\alpha(\theta-1)}}{1 - \beta(1 - e^{\alpha(\theta-\bar{l})})} & \text{exponential-logistic} \\ \frac{1 - 1/(1 + e^{-\beta(\bar{l}-\theta_2)})}{1 + e^{-\alpha(\bar{l}-\theta_1)}} & \text{double logistic} \end{cases} \quad (\text{Eq. 4})$$

where α , β , q , q_1 , and q_2 are parameters to be estimated and \bar{l} is the midpoint of size interval l . Note that both functions tend toward a flat-topped logistic function as β tends toward zero.

The data were pooled across all locations fished by the same combination of hook types due to the relatively sparse number of video measurements in each unique ROV sample. Thus, there were effectively three locations in terms of Equations 2 and 3, those fished in tandem by 9/0 and 12/0 hooks, 9/0 and 15/0 hooks, or 12/0 and 15/0 hooks. Bias-corrected laser-scaled red snapper TL estimates were binned into 20 length categories defined by the boundaries: 170, 230, 250, 270, 290, 310, 330, 350, 370, 390, 410, 430, 450, 470, 490, 510, 530, 570, 610, 650, and 730 mm. Broader intervals were specified for the smallest and largest categories because of the rarity of fish in those size classes in our samples. The initial model assumed the same parameter values for the selection curves associated with each hook type (i.e., that there was no hook effect) and that the shape of the selection curve was flat-topped (β near zero). Additional parameters were estimated in a stepwise approach to allow for dome-shaped ($\beta > 0$) selection and hook-size effects. Akaike's information criteria for small samples was used to determine the combination of selection parameters that provided the most parsimonious fit to the data (Hurvich and Tsai 1995).

RESULTS

Fish counts from video analysis of ROV samples totaled 18,347 individuals belonging to 108 taxa (94% of individuals were identified to species) among 69 samples. Eleven fishery species accounted for 82% of the total fish count (see Table 1 for names and authorities), with tomtate alone accounting for 34%. There was a distinct shift in the relative proportion of those 11 species in hook-specific catches vs the fish communities observed in video samples. For example, tomtate constituted 58.2% of the total abundance among fishery species, yet was only 6.0% of the 9/0 catch and only one tomtate was captured with a 15/0 hook. Red snapper, on the other hand, constituted only 25.3% of fishery species observed in video samples, yet its percent abundance in catches ranged from 59.1% for 9/0 hooks to nearly 90% for 15/0 hooks.

Catch rates were significantly affected by hook size for all fishes (ANOVA: $F_{2,66} = 15.1$, $P < 0.001$), but not for red snapper alone (ANOVA: $F_{2,66} = 1.57$, $P = 0.215$; Fig. 2). Overall, the size of captured fish was significantly affected by hook size (ANOVA: $F_{3,3061} = 42.1$, $P < 0.001$; Fig. 3). Hook size also significantly affected the size of captured red snapper (ANOVA: $F_{3,1724} = 67.4$, $P < 0.001$), other snappers (ANOVA: $F_{3,402} = 6.65$, $P < 0.001$), and groupers (ANOVA: $F_{3,175} = 18.4$, $P < 0.001$), but was not significant for red porgy (ANOVA: $F_{2,113} = 0.21$, $P = 0.809$) or tomtate (ANOVA: $F_{2,204} = 1.87$, $P = 0.157$). However, sample sizes were low for red porgy and tomtate, both of which had essentially no catch for 15/0 hooks, and most individuals caught of those two species were near the median size observed in video samples regardless of hook size (Fig. 3).

Cumulative frequency distributions of estimated red snapper size and age demonstrate clear shifts between video samples and catches, with increasing trends in both fish size and age with hook size (Fig. 4). Median estimated TL was 373 mm for red

Table 1. Estimates of percent relative abundance of fishery-important reef fish species observed in remotely operated vehicle collected video samples of fish communities at natural and artificial reefs in the northern Gulf of Mexico, as well as percent catch of those species captured with 9/0, 12/0, and 15/0 Mustad circle hooks.

Species	Common name	Abundance among fishery species in video samples (%)			
		9/0 catch (%)	12/0 catch (%)	15/0 catch (%)	
<i>Haemulon aurolineatum</i> (Cuvier, 1830)	Tomiate	58.2	1.8	0.5	
<i>Lutjanus campechanus</i> (Poey, 1860)	Red snapper	25.3	76.8	88.9	
<i>Pagrus pagrus</i> (Linnaeus, 1758)	Red porgy	7.5	9.7	2.3	
<i>Lutjanus griseus</i> (Linnaeus, 1758)	Gray snapper	3.4	0.0	0.5	
<i>Seriola dumerili</i> (Risso, 1810)	Greater amberjack	1.9	1.8	0.5	
<i>Lutjanus synagris</i> (Linnaeus, 1758)	Lane snapper	1.0	0.2	0.0	
<i>Balistes caprisicus</i> (Gmelin, 1789)	Gray triggerfish	0.9	1.2	0.0	
<i>Rhomboplites aurorubens</i> (Cuvier, 1829)	Vermilion snapper	0.8	4.7	1.4	
<i>Mycteroperca phenax</i> (Jordan and Swain, 1884)	Scamp	0.7	2.0	1.9	
<i>Mycteroperca microlepis</i> (Goode and Bean, 1879)	Gag	0.1	1.4	1.9	
<i>Epinephelus morio</i> (Valenciennes, 1828)	Red grouper	0.1	1.1	2.3	



Figure 2. Mean (+ SE) catch rate per hook hour for all fishes and red snapper, *Lutjanus campechanus*, alone that were captured with 9/0, 12/0, and 15/0 circle hooks at reef sites in the northern Gulf of Mexico. * Catch rate of all fishes declined significantly ($P < 0.001$) with increasing hook size.

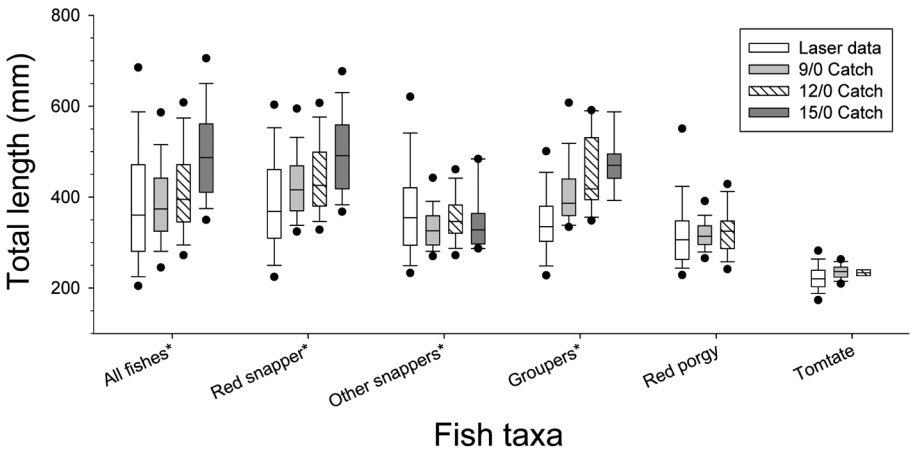


Figure 3. Boxplots of bias-corrected total length (TL) estimates of reef fishes scaled with a red laser scale during remotely operated vehicle sampling of reef fish communities in northern Gulf of Mexico and of measured TL of fishes that were captured with 9/0, 12/0, and 15/0 circle hooks. Midline of each box indicates sample median. Lower and upper sides of each box indicate 25th and 75th distribution percentiles, respectively. Extended bars represent 10th and 90th percentiles, and filled circles indicate 5th and 95th percentiles. * $P < 0.001$.

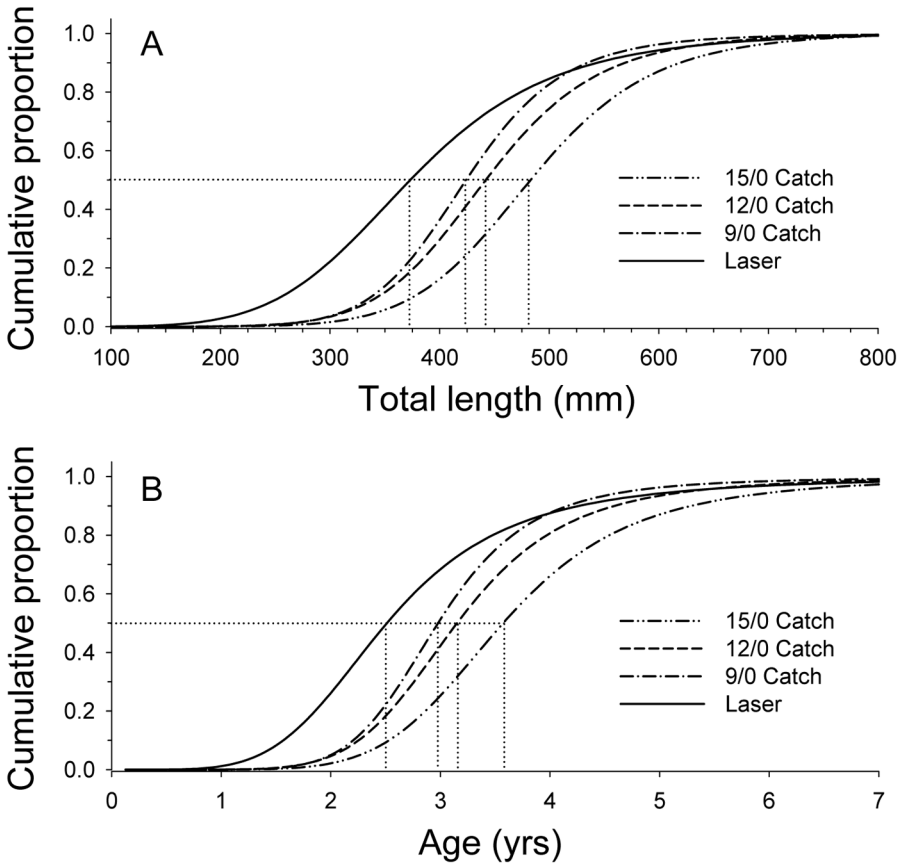


Figure 4. Cumulative frequency distributions of red snapper, *Lutjanus campechanus*, (A) total length and (B) age estimated with an age-length key for fish scaled with a red laser scale ($n = 723$) during remotely operated vehicle (ROV) sampling of reef sites in the northern Gulf of Mexico, as well as fish captured with 9/0 ($n = 430$), 12/0 ($n = 314$), and 15/0 ($n = 174$) circle hooks following ROV sampling. Length estimates for laser-scaled fish were bias-corrected as described in the text.

snapper scaled with the laser scale attached to the ROV, and 424, 443, and 482 mm for fish captured with 9/0, 12/0, and 15/0 hooks, respectively. Median estimated age displayed a similar pattern in that it was 2.5 yrs for fishes scaled with lasers, and was 2.9, 3.2, and 3.6 yrs, respectively, for fishes captured with 9/0, 12/0, and 15/0 hooks. However, the distribution of size or age in the sampled population is as critical as the distribution of the catch when estimating selectivity, and in the present study there were some differences in the size structure estimated among red snapper sampled at sites fished with different hook size combinations (Fig. 5). Therefore, comparisons of the overall size distribution of red snapper to the overall distributions of fishes captured with the three circle hook sizes fished in our study are insufficient to evaluate selectivity differences among hook sizes.

The double logistic model did not provide as good a fit to the data as the exponential logistic, despite having one more parameter, therefore was not explored further.

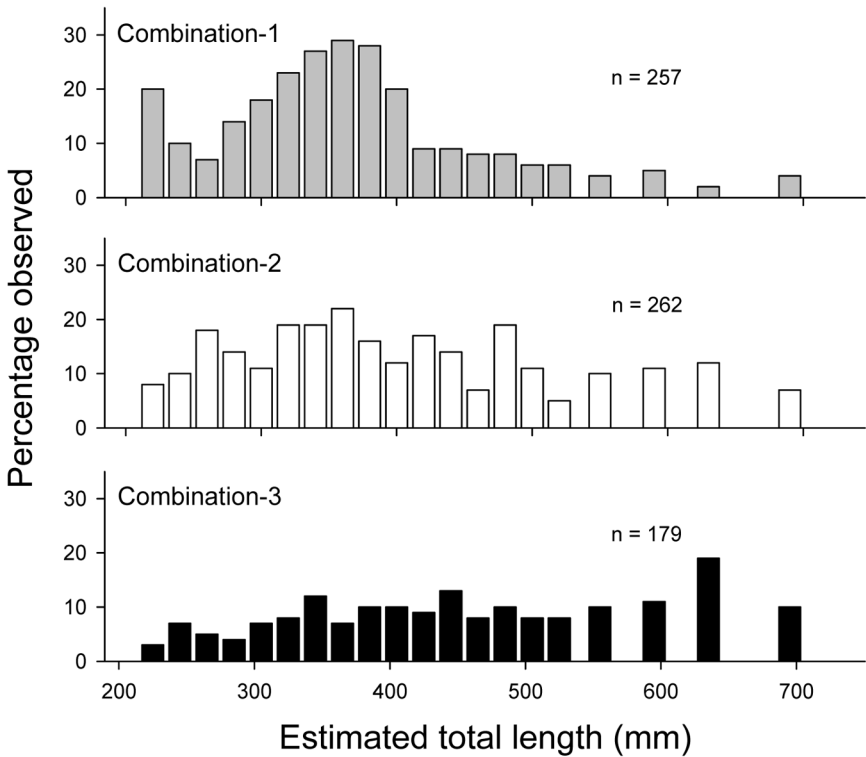


Figure 5. Bias-corrected red snapper, *Lutjanus campechanus*, total length distributions estimated with a red laser scale during remotely operated vehicle video sampling of reef sites in the northern Gulf of Mexico. Combination-1 indicates sites where 9/0 and 12/0 circle hooks were fished. Combination-2 indicates sites where 9/0 and 15/0 hooks were fished, and combination-3 indicates sites where 12/0 and 15/0 hooks were fished.

All of the parameters of the exponential model significantly improved the fit to the data except the β parameter for the 15/0 hook model ($\beta_{15/0} = 0.002$), which did not differ significantly from zero, thus was not included in the final model (Table 2). Resulting selectivity function parameters were highly correlated within hook types, as is typical when a functional relationship is used, but not among hook types (Table 2). The general shapes of the selectivity functions estimated for 9/0 and 12/0 hooks were dome-shaped, while the shape of the function estimated for 15/0 hooks was logistic (Fig. 6). Fits of the exponential-logistic hook-specific selectivity models to the red snapper catch data were reasonably good (Fig. 7). There are some noticeable trends in the residuals of the fits (Fig. 7), but they are not consistent across locations.

DISCUSSION

Our results indicate that circle hook size had a clear effect on reef fish catch rates, species composition, and size distributions. The GMFMC mandated the use of circle hooks in the GOM reef fish fishery in 2008 with Amendment 27 to its Reef Fish Fishery Management Plan (GMFMC 2007), but the only stipulation is that hooks

Table 2. Maximum likelihood estimates (MLE) of parameters, coefficients of variation (CV, standard deviation/MLE), and correlation matrix for the final exponential-logistic model fitted to circle hook catch-at-size data to estimate selectivity. In the table, q = catchability, ω = coefficient of variation of the observed catch, α , β , and θ = exponential-logistic model parameters, and 9/0, 12/0, and 15/0 = circle hook sizes. Note that $\beta_{15/0}$ did not differ significantly from the null hypothesis ($P < 0.001$), thus was not estimated in the final model.

Parameter	MLE	CV	Correlation matrix													
			$q_{9/0}$	$q_{12/0}$	$q_{15/0}$	$\alpha_{9/0}$	$\theta_{9/0}$	$\beta_{9/0}$	$\alpha_{12/0}$	$\theta_{12/0}$	$\beta_{12/0}$	$\alpha_{15/0}$	$\theta_{15/0}$	ω		
$q_{9/0}$	0.163	0.121	1.00													
$q_{12/0}$	0.134	0.131	0.03	1.00												
$q_{15/0}$	0.059	0.106	0.04	0.03	1.00											
$\alpha_{9/0}$	0.034	0.086	0.13	0.00	0.00	1.00										
$\theta_{9/0}$	442.3	0.018	0.09	0.02	0.02	-0.79	1.00									
$\beta_{9/0}$	0.180	0.251	0.33	0.02	0.00	-0.42	0.43	1.00								
$\alpha_{12/0}$	0.026	0.091	0.03	0.30	0.00	0.01	0.00	0.01	1.00							
$q_{12/0}$	486.4	0.028	-0.02	0.22	0.01	-0.03	0.04	0.00	-0.59	1.00						
$\beta_{12/0}$	0.300	0.322	0.00	0.42	0.00	-0.02	0.02	0.01	-0.17	0.64	1.00					
$\alpha_{15/0}$	0.057	0.253	0.01	0.00	-0.18	0.01	-0.01	0.00	0.00	-0.01	0.00	1.00				
$q_{15/0}$	515.3	0.082	0.00	0.00	0.22	-0.01	0.02	0.00	0.00	0.01	0.00	-0.99	1.00			
ω	0.136	0.299	0.01	-0.01	-0.04	0.03	-0.08	0.00	-0.01	-0.12	0.02	0.01	-0.02	1.00		

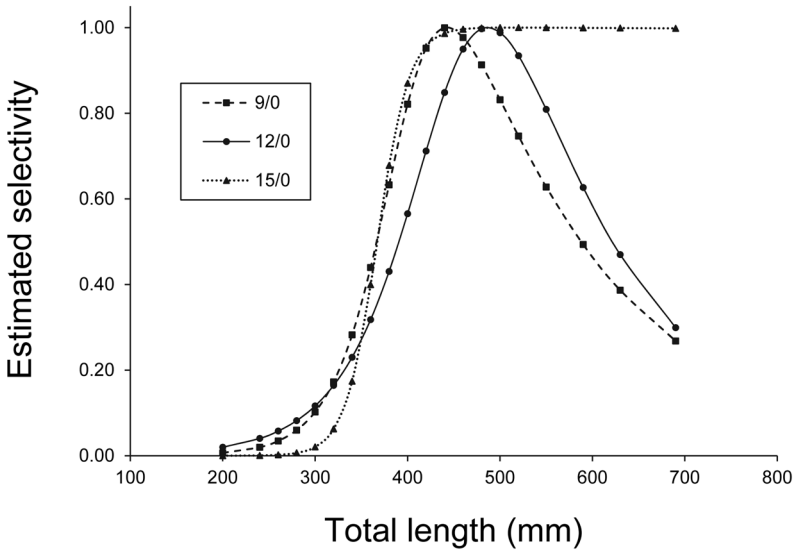


Figure 6. Maximum likelihood selectivity functions estimated for red snapper, *Lutjanus campechanus*, captured with 9/0, 12/0, and 15/0 circle hooks at reef sites in the northern Gulf of Mexico.

cannot be made of stainless steel. Others have examined the conservation benefits of circle vs J-shaped hooks, including in recreational hook and line fisheries, but results from our study indicate that not only hook style but also hook size can have significant effects. One goal of our study was to test whether using larger hooks would reduce the catch of undersized fish, with red snapper (GOM recreational size limit currently 406 mm TL) being a focus given its predominance among northern GOM reefs and the fact that it is perhaps the most targeted fish in the reef fish fishery. Using larger hooks did reduce the percentage of undersized red snapper caught, but species diversity of the catch also decreased substantially as hook size increased, with red snapper constituting nearly 90% of the catch taken with 15/0 circle hooks. Therefore, if a management decision were made to require only larger circle hooks to be used in the GOM recreational reef fish fishery, then a tradeoff for the benefit of minimizing sublegal red snapper discards would be diminished catch rates of other species. Furthermore, during the red snapper closed season, a minimum hook size may actually increase the number of red snapper discards. This would likely occur when fisherman sought other species that constituted a smaller percentage of the total catch when fishing with larger hooks. Therefore, an increasing number of red snapper would be discarded while seeking to fill bag limits for other species.

Beyond the fact that red snapper were a much higher percentage of the catch, even for 9/0 hooks, than their percent abundance in reef fish community data, another apparent trend was a decline of smaller intertivore species with increasing hook size. These smaller species tended to be invertivores, such as red porgy, vermilion snapper, gray triggerfish, and tomtate (Manooch 1977, Grimes 1979, Thomas and Cahoon 1993). Some, such as vermilion snapper and red porgy, constituted a much higher percentage of the 9/0 hook catch than their percent abundance in reef fish community data. For others, like tomtate, and to a lesser extent, gray snapper, their

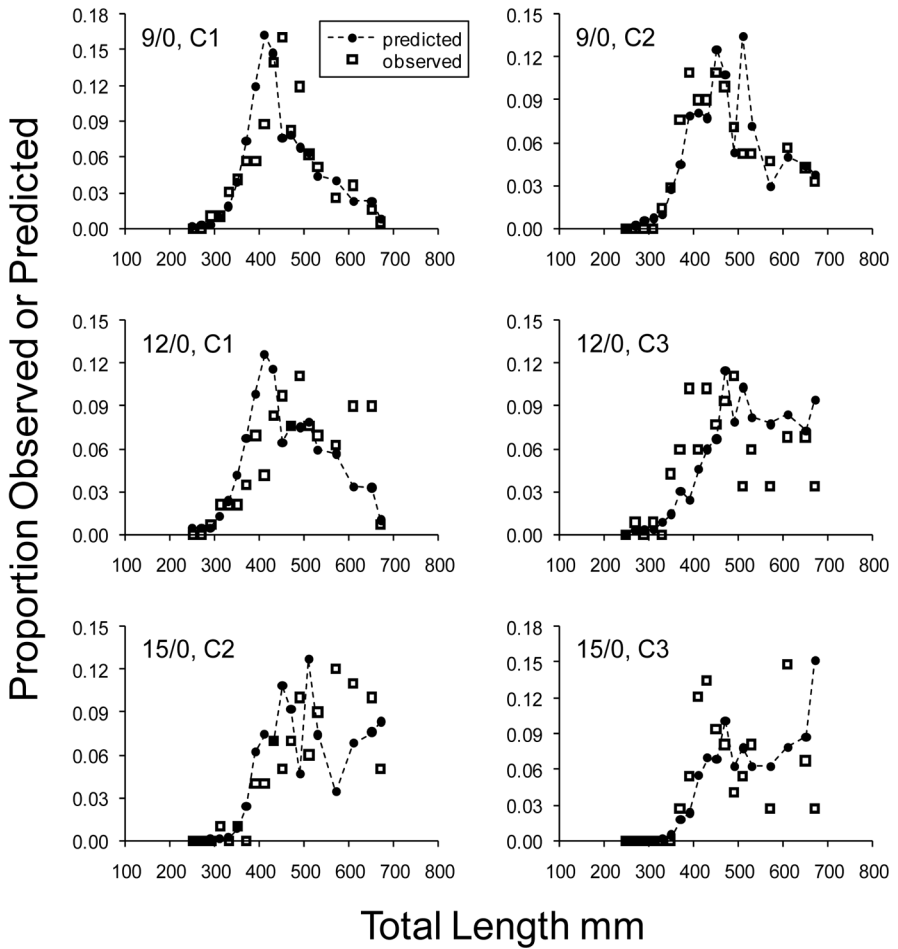


Figure 7. Predicted vs observed (catch) proportion-at-size of red snapper, *Lutjanus campechanus*, captured with 9/0, 12/0, and 15/0 circle hooks at reef sites in the northern Gulf of Mexico. Combination-1 (9/0 and 12/0), combination-2 (9/0 and 15/0), and combination-3 (12/0 and 15/0) are abbreviated on panel labels as C1, C2, and C3, respectively. Predicted proportions at size result from exponential logistic selectivity models fit to observed proportion at size data for each hook comparison combination.

percent abundance even in 9/0 hook catches was just a fraction of their percent abundance in the reef fish community. The decline of the catch of smaller fishery species with increasing hook size, and the percent abundance of the smallest fishery species, tomtate, being an order of magnitude less abundant in 9/0 catches than in the community, is likely largely due to gape limitation (Ralston 1982, Bacheler and Buckel 2004). However, bait selection and fishing technique, which were standardized and not tested as factors in the present study, also may have affected catch rates. Cumulative catch rates among scamp, gag, and red groupers, all of which have large gapes (Weaver 1996), were much greater than their percent abundance in the fish community, which is consistent with the hypothesis that gape limitation explains much of the decline in the catch of smaller species with larger hooks.

Potential effects of regulating hook size on red snapper stock recovery, as well as effects on other co-occurring reef fishes, will remain unclear until results of the present study and follow-up sampling is incorporated into stock assessment model simulations. Given the diversity of fishes targeted and caught in the northern GOM recreational reef fish fishery, and the inverse effect of increasing circle hook size on catches of species other than red snapper, a multispecies assessment approach likely would be required, or at least effects should be evaluated through simulations examined with various single-species assessment models. In the case of red snapper, circle hook size significantly affected the size of fish captured, with an increasing proportion of the catch above the minimum size limit as hook size increased, but there was only a subtle shift in the median size and estimated age of fish captured with 9/0 vs 15/0 hooks. Given the size difference in hooks, a shift in median size from 424 to 482 mm TL and in estimated age from 2.9 to 3.6 yrs is not substantial for a fish that can live to be 60 yrs old (Patterson et al. 2001, Wilson and Nieland 2001), does not reach maximum fecundity until it is 12–15 yrs old (Jackson et al. 2007), and for which maximum yield per recruit occurs at sizes >600 mm TL (Goodyear 1995). However, the fact that red snapper catch rate did not decline with increasing hook size implies that individuals were aggressive to the bait regardless of the size of hooks, which is something that has been reported anecdotally by fishermen attempting to target other species during red snapper closed seasons. Perhaps gape limitation is less of an issue for aggressive species such as red snapper.

Another issue to consider when evaluating the potential conservation gains of establishing a minimum hook size for the GOM recreational reef fish fishery is that during the sampling for our study, we were informed that some charter and private boat recreational anglers target reef fishes with circle hooks smaller than the 9/0 hooks used in our study. One of the difficulties in comparing results among hook studies, or even in understanding fishing practices, is that hook sizes are not standardized among manufacturers, or even within a given manufacturer for different hook types. Therefore, future work should focus on examining catch rates, species composition, and size distributions between hook sizes used in the present study with some of the smaller hooks currently used in the fishery.

Size distributions estimated in situ with the ROV provided a valuable source of information for estimating selectivity functions of the 9/0, 12/0, and 15/0 circle hooks examined. Due to sample sizes, functions were computed only for red snapper, but the procedure developed for estimating hook selectivity from ROV-based estimates of fish size distributions on reefs and hook-specific catches could be applied to other species with sufficient sample sizes. Bacheler et al. (2010) reviewed several methods of estimating gear selectivity, including internally in stock assessment models (Hillborn and Walters 1992, Porch 2007), through comparison of catches between gears (Millar 1992), and with tagging experiments (Schultz 2004, Bacheler et al. 2008). They concluded that tagging methods were the most robust because the size or age composition of the tagged population was known, especially in short-term tagging experiments. The ROV-based method we employed prior to fishing similarly provided an estimate of the size distribution of the targeted population. Furthermore, by controlling hook sizes in fishing trials, we could directly test selectivity for a given hook size and type, and not just estimate overall selectivity for fishery sectors (Bacheler et al. 2010).

Selectivity curves for longline hooks and recreational hook-and-line gear have been assumed to have either logistic shapes typical of trawls or unimodal shapes typical of gillnets (Czerwinski et al. 2010). The shape of the curve is often imposed with some prior knowledge of the size distribution of the catch. In the method presented here, a maximum likelihood framework is used to test the shape of hook-specific selectivity functions given estimates of the size distribution of the fish being targeted and direct measurements of the fish caught. A critical assumption of this approach is that laser-based estimates of fish size are random and unbiased. We applied the slight bias-correction estimated by Patterson et al. (2009), but the issue of whether fish scaled with the lasers were a random sample of the population persists. What is known is that fish tend not to avoid the micro ROVs used in our study (Dance et al. 2011), and no fish were specifically targeted with the lasers. However, a future experiment should be conducted in which reef-associated fish communities are repeatedly sampled on short time scales (e.g., minutes to hours) and estimates of fish size distributions compared. In the present study, if red snapper smaller than those reported here were present but not scaled with the ROV lasers, it likely would have had little effect on selectivity estimates for the hooks tested as the smaller length bins already had zeros for proportion caught. However, if there were fish present that were larger than those scaled with lasers, then the shape of the 15/0 hook selectivity function may have been dome-shaped if the pattern of declining proportional catch with increasing fish size was maintained.

The difference in shapes among hook-specific selectivity functions estimated here is due to the fact the β parameter in Equation 4 did not differ significantly from zero for the 15/0 hook model, thus giving that function a logistic shape. However, when inspecting predicted vs observed size distributions of 15/0 hook catches, a somewhat dome-shaped relationship is apparent in the observed catch at size data, especially for hook combination-2. The divergence from a domed-shape function appears to be driven by the bimodal pattern of catch-at-size observed for 15/0 hooks fished in combination-3. There is a sharp decline in the observed catch at size between 420 and 570 mm TL, but then a spike at 610 mm TL. There was an apparent conflict in attempting to fit that high catch at size for combination-3 data while a different pattern existed for combination-2. The result was a non-significant $\beta_{15/0}$ parameter (i.e., a logistic shape) and large residuals for the fits of the selectivity function to observed catch at size for fish >500 mm TL in both combination-2 and combination-3 scenarios. The logistic fit for 15/0 hooks predicts sizes at median and full selectivity that are similar to those of 9/0 hooks and smaller than those of 12/0 hooks, which is not consistent with patterns observed in the data. It should be noted, however, that the 15/0 hooks had the smallest sample size and perhaps additional field experiments would help clarify the functional form of their selectivity curve.

The exponential-logistic selectivity model also overestimated the proportion of small fishes (<400 mm) caught by 9/0 hooks at reef sites where they were fished with 12/0 hooks (combination-1), but underestimated the proportion of small fishes at sites where 9/0 hooks were fished with 15/0 hooks (combination-2). In principle, the competing mortality model should account for the fact that the two hook sizes are competing for fish of the same size. However, it is possible that the behavior of different fish size classes changes with their relative abundance in a way that affects the apparent selection. For example, larger, more aggressive fish might drive smaller fish away or smaller fish might become emboldened at higher densities. The ROV video

data suggest there were proportionally more large fish among reef sites fished with combination-3 than combination-2, and more at combination-2 sites than combination-1. In general, a comparison of the residual patterns suggests fewer small fish were caught on 9/0 hooks than expected at sites with proportionally fewer small fish. If this trend is real, then it suggests smaller fish actually become more vulnerable to the gear as they decrease in proportion to larger fish. Additional fishing trials, especially single hook size instead of hook combination trials, may help clarify this somewhat counterintuitive result.

In conclusion, results from the present study indicate that varying circle hook size in the GOM reef fish fishery had significant effects on fish catch rates, species composition, and size distributions. It is unclear at this point what the conservation benefits vs detriments would be in requiring a minimum hook size in the fishery, particularly for red snapper. However, it is clear that increasing hook size does increase the size of fish captured while also greatly diminishing the diversity of the catch. Future work should focus on expanding sample sizes in hook trials, increasing the size range of circle hooks tested, and projecting simulated effects of changing hook sizes and their associated selectivity functions on biomass trajectories of exploited GOM reef fishes.

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