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ARTICLE

Assessing the Relative Selectivity of Multiple Sampling Gears for Managed Reef Fishes in the Eastern Gulf of Mexico

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Abstract
Fishery-independent data are important for the effective management of reef fishes in the eastern Gulf of Mexico. Proper characterization of selectivity, or the effectiveness of each type of sampling gear in capturing a species or a size-class, is essential to ensure that assessment models treat various sources of data appropriately. In this study, we analyzed fishery-independent data that was collected using stereo-baited remote underwater video (S-BRUV) arrays, chevron traps (TRAP), and two types of hooked gear (repetitive timed-drop [RTD] and vertical longline [VLL]) to assess gear-related differences of species composition and size selectivity of managed reef fishes in the eastern Gulf of Mexico. Significant differences were detected in the assemblage structures of reef fishes in relation to region, gear type, and depth. Overall, eight managed species were identified as contributing to the top 70% of the assemblage structure for each gear type. Stereo-baited remote underwater video had the highest abundances for most of the species and the highest number of species captured, while VLL had the lowest. Two economically and ecologically important species (Red Grouper *Epinephelus morio* and Red Snapper *Lutjanus campechanus*) were common to all four gear types, and the size selectivity of these two species generally overlapped. However, significant differences among gear types were detected. Unimodal selection curves for hooked gears indicated that size of Red Snapper and Red Grouper increased as hook size increased. These data provide insight on species and size selectivity of multiple gears, which will contribute to future survey design and aid in the management of reef-fish populations.

The Gulf of Mexico supports a multibillion-dollar fishing industry, and reef fishes are a major component of both recreational and commercial fisheries (National Marine Fisheries Service 2016). The management of reef fishes is complicated by diverse life history strategies among species and ontogenetic changes in habitat (Switzer et al. 2015b). Fishery-independent surveys are a valuable method for obtaining long-term data for multiple species and habitats (Gunderson 1993; Suprenand et al. 2015). These methods provide several advantages over fishery-dependent surveys because they have no size limits or seasonal closures and are not influenced by regulatory changes and fisher's behavior; therefore, they usually provide a more accurate representation of population changes through time (Ault et al. 1998; Rotherham et al. 2007; Winner et al. 2014). Fishery-independent surveys can use a stratified random sampling design to provide consistent methods across space and time. Additionally, with appropriate stratification, each stratum is more homogeneous than the total survey, thereby increasing statistical power. Fishery-independent data can also provide details on species distributions while integrating environmental data,

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habitat quality data, and physical oceanographic parameters, making these data especially valuable for stock assessments and long-term monitoring programs (Rotherham et al. 2007; Flaherty et al. 2014; Suprenand et al. 2015).

Multiple sampling gears are often required to characterize the population status and trends of highly diverse fisheries due to species-specific variability in distribution and habitat use that may also vary ontogenetically (Walters and Martell 2004; Winner et al. 2014). Species- and size-selectivity patterns vary among gear types due to gear design and capture method (Huse et al. 2000; Rotherham et al. 2007; Wells et al. 2008). The accurate interpretation of survey data, in particular data indicating low abundance, requires the determination of whether the data are representative of the population of interest or whether the observed data reflect gear-associated selectivity. If size selectivity is undetermined or inappropriately defined, the data that is provided by a specific survey may be biased or imprecise, leading to inaccuracies in the interpretation of abundance trends or size/age composition within stock assessments that can ultimately affect harvest limits (Suprenand et al. 2015). Since no single gear type can effectively target all species and size-classes, estimating selectivity patterns for each gear type is critical to developing long-term monitoring programs and assessments (Hilborn and Walters 1992) while also providing information as to the potential redundancy of types of sampling gear that are used.

The direct size selectivity of a gear type can be determined where the length distribution of a population is known. However, such data are seldom available, so indirect estimates of size selectivity have been developed that compare catch from experimental gear with catch from a control gear (assumed to be nonselective) or a variant of the experimental gear, all of which are fished simultaneously (Millar and Fryer 1999).

Observational techniques, such as stereo-baited remote underwater video systems (S-BRUV), are nonextractive methods that provide details on species composition, individual lengths, and proximate habitat. Stereo-baited remote underwater video systems have been used successfully in reef-fish surveys in multiple habitats; however, the smallest fish may be difficult to identify and measure (Cappo et al. 2007). Specimens are not collected with S-BRUV, so additional capture gears, such as traps or hooked gears, are required to obtain biological samples (e.g., muscles, otolith, or blood). These biological samples are especially critical when conducting age-based or age-structured assessments. However, both traps and hooked gears have multiple factors such as mesh or hook size that may affect both species and size selectivity.

We analyzed the data from a two-year synoptic survey to characterize both species (all of the managed species that were encountered) and size selectivity (the species that were effectively encountered in all gear types) for S-BRUV, chevron traps, and two hooked gears in the eastern Gulf of Mexico. In doing so, we compared the shapes of the size-selectivity curves for the capture gears and S-BRUV for two ecologically and economically important reef fishes, Red Grouper *Epinephelus morio* and Red Snapper *Lutjanus campechanus*. We also investigated the selectivity of three hook sizes (8/0, 11/0, and 15/0) that were used in the hooked-gear surveys. This study measures the relative effectiveness of four sampling methods and provides an evaluation of the most useful methods for providing data inputs for the assessment of managed reef fishes.

METHODS

Study area.— Sampling was conducted during 2014 and 2015 in the eastern Gulf of Mexico (Figure 1). Sampling effort was allocated proportionally based on the available reef habitat within the Florida Panhandle (National Marine Fisheries Service Statistical Zones 9 and 10) and the Florida Peninsula (National Marine Fisheries Service Statistical Zones 4 and 5) and to nearshore (4–37 m) and offshore (38–180 m) depth strata. The specific sampling locations were randomly selected, and a side-scan sonar survey was conducted using a Klein 3900 towfish surveying at 445 kHz to identify specific natural (e.g., potholes, flat hard bottom, or ledge) and artificial reef habitat (e.g., chicken coop, vessels, or construction materials) features that were subsequently sampled (see Keenan et al. 2018 for further details). Due to logistical constraints, all four of the sampling gears were not deployed at all of the locations. For each sampling site, the type of gear and number of gear types that was deployed were predetermined by the number of reef habitat features that were identified.

Sample collection.— The types of sampling gears for reef fish that were used were S-BRUV, chevron trap (TRAP), and two types of standardized hooked gear (repetitive-timed-drop [RTD] and vertical longline [VLL]; Figure 2). At each sampling site, the geographic coordinates, depth, and time of day were recorded. All of the sampling was conducted between one hour after sunrise and one hour before sunset. The S-BRUV and TRAP sampling cruises were conducted on research vessels that were staffed with science personnel from the Fish and Wildlife Research Institute during June–September 2014 and May–September 2015. The hooked-gear sampling cruises were conducted on chartered fishing vessels that were staffed with science personnel from the Fish and Wildlife Research Institute during September and October 2014 and in June and August–October 2015.

Each S-BRUV was equipped with two stereo imaging systems (SIS), each consisting of an underwater housing containing a digital video camera, a pair of stereo still

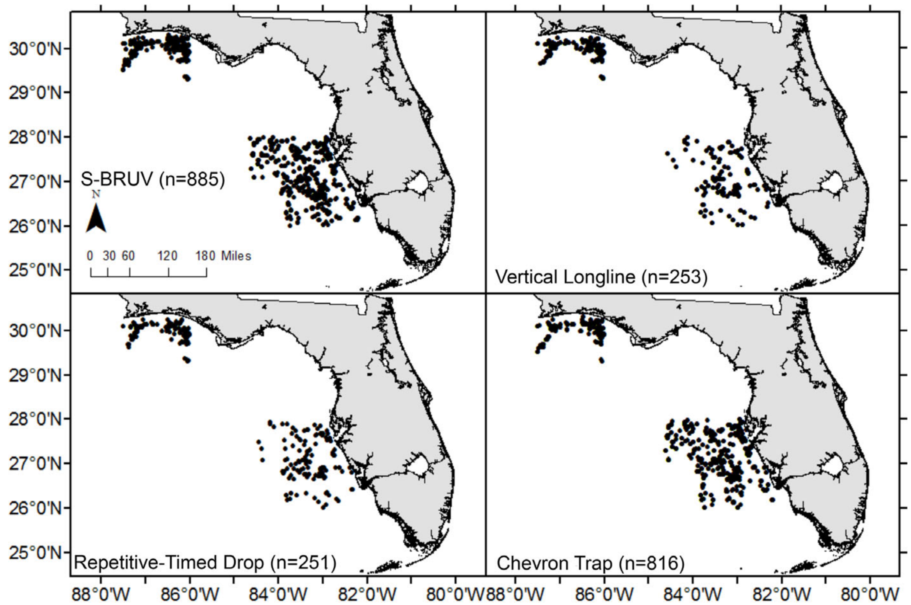

FIGURE 1. Sampling sites on the West Florida Shelf (2014–2015) by gear type: stereo-baited remote underwater video (S-BRUV), vertical longline, repetitive timed-drop, and chevron trap.

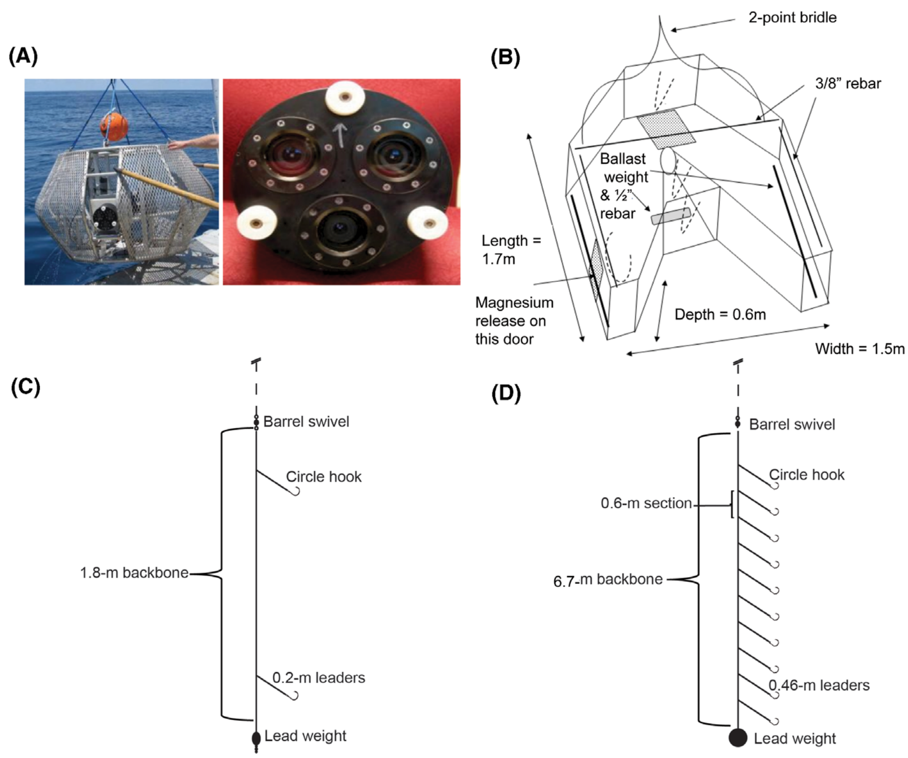

FIGURE 2. Images of **(A)** the stereo-baited underwater remote video system and stereo imaging system. Also shown are the schematics for **(B)** the chevron trap and the terminal tackle configurations for **(C)** the repetitive timed-drop, with mainline attached by a barrel swivel to the backbone and 2 gangions terminating in either 8/0, 11/0, or 15/0 circle hooks, and **(D)** the vertical longline, with mainline attached to the back bone and 10 equally spaced ganagions terminating in either 8/0, 11/0, or 15/0 circle hooks.

cameras (that were used to measure the observed fish and were recording at two frames per second), and a computer that controlled the cameras and recorded the data (Figure 2A). The two SIS units were aimed 180° apart to maximize the likelihood of recording the selected reef habitat. At the beginning and end of each annual sampling season, each SIS unit was calibrated underwater by using SeaGIS CAL software (Seager 2019) and a specialized calibration cube. The calibration files were then created with a correction factor for each camera. Laminated fish cutouts of known length and a calibration bar were recorded (underwater) using each camera and then loaded into and measured with SeaGIS EventMeasure software (SeaGIS; Seager 2019) to check for accuracy against the known lengths. Any S-BRUV with digital estimates that had a margin of error that was greater than 5% compared with the known measurements was not used (less than 1% of all of the cameras). Each S-BRUV was baited with four frozen Atlantic mackerel *Scomber* spp. halves, deployed, and soaked at the bottom for at least 30 min. The TRAPs were a standard chevron shape: 1.7 m long, 1.5 m wide, and 0.6 m deep and constructed of vinyl-clad 3.8-cm-mesh steel with a 28-cm throat diameter (Figure 2B). At each TRAP station, a trap was baited by securing Atlantic mackerel on four bait wires. Two wires are located outside of the trap, serving as teasers to direct fish towards the throat. A third wire is located immediately inside of the throat, each holding one-third of a mackerel. The main bait wire is located inside of the trap and holds four Atlantic mackerel halves. Each trap soaked on the bottom for at least 90 min.

Active hook-and-line fishing using a standardized RTD method was conducted by using powered (12V DC) Electra-mate rigs (model 940XP, Greensboro, North Carolina) that were outfitted with a Penn 115L 9/0 (Senator model) reel that was equipped with 45-kg-test monofilament and mounted on a heavy-duty fiberglass fishing pole. A barrel swivel was attached to the mainline from the reel. Each fishing rig contained two short (~20 cm) gangions that were tied along the length of an approximately 1.8-m section of monofilament leader (36- or 45-kg test, Figure 2C). A hook was looped onto the end of each lead on the monofilament rig. Three hook sizes were used at each sampling station: one angler fished with two 8/0 hooks, another fished with two 11/0 hooks, and a third fished with two 15/0 hooks (Mustad circle hooks, reference number 39960D). The manufacturer's hook number does not represent the actual hook size, so the measurement of hook gape was used to model the size proportions of the hooks (see Supplemental File 1 available separately online; Campbell et al. 2014). A lead weight (225–510 g) was positioned at the end of each rig, and all of the hooks were baited with thawed Atlantic mackerel that was cut proportionally to the hook size. Three anglers simultaneously dropped their rigs (i.e., a team drop) to the bottom and actively fished for no more than 2 min. If an angler hooked a fish before 2 min had elapsed, that angler immediately retrieved, identified, and measured the fish, rebaited, and waited until the next team drop before redeploying. After the two minutes, all of the anglers would retrieve the rigs, rebait, and redeploy simultaneously at the next team drop. Ten team drops were made at each station.

The protocols that were established by the Southeast Area Monitoring and Assessment Program were followed at the stations that were fished with VLL gear (SEAMAP 2016). Each VLL rig consisted of a 6.7-m monofilament (181-kg test) backbone that was equipped with 10 evenly spaced (every 0.6 m) crimped T swivels (Figure 2D). A gangion was attached to each T swivel; each gangion consisted of a snap swivel with 0.46 m of 45-kg-test monofilament and a single Mustad circle hook. Before deployment, the captain evaluated the current sea conditions to determine whether a 4-kg or a 7-kg lead weight (heavier in worse sea conditions) should be attached to the base of the backbone by using a gangion. Two or three VLLs, depending on the vessel size, were fished simultaneously at each sampling site, each rigged with 10 hooks of the same size. For vessels that used two VLLs, two of three hook sizes, 8/0, 11/0, or 15/0 (Mustad circle hooks, reference number 39960D), were randomly selected using a random number that was generated at the first station of the day and rotated by hook size throughout the day to ensure equal sampling effort during a cruise (e.g., at the first station, 8/0 and 11/0, at the second station, 11/0 and 15/0, and at the third station, 8/0 and 15/0). The hooks were baited with thawed Atlantic mackerel that was cut proportionally to the hook size, and the gear was fished passively on the bottom for 5 min before it was retrieved with a bandit reel.

Data processing.— Although each S-BRUV contained two SIS units, video from only one was processed for abundance and size-composition data to avoid potential duplicate counts. If one video was of a higher quality (i.e., the quality of selected habitat, with no significant obstruction of the field of view), then this video was analyzed. If both videos were similar in quality, one was randomly selected. If still images were not available from either SIS unit, measurements were not taken for that video. The videos were read for a total of 20 min (Gledhill 2001), beginning approximately 10 min after the gear reached the bottom to allow for the settlement of any sediment plume. Individuals were identified to the lowest possible taxon. Relative abundance was estimated as MaxN, or the maximum number of fish per species that was observed on a single screen image over the course of 20 min (Ellis and DeMartini 1995). The midline length of each observed fish was estimated (to the nearest mm) through the analysis of the stereo still images by using EventMeasure software. The measurements for each species were taken at one point (i.e., when the maximum number of individuals that can be measured were on screen) to ensure that duplicate measurements were not made. Two frames per second were recorded separately by each (L and R) stereo still camera. Exact frames were isolated that matched the time of occurrence in the corresponding video. To remain consistent with our discussions related to the other sampling methods, we refer to the fish that were observed and measured through video analysis as having been captured.

For both the traps and hooked gear, the individuals that were captured were identified to the lowest possible taxon. Any individuals that could not be identified in the field were brought back to the laboratory for identification. Standard length and fork length were recorded to the nearest millimeter for most of the fish. As image-based length measurements represented FL, the subsequent analyses for all of the gear types used FL data. For some individuals, FL was not recorded in the field. For those cases, species-specific meristic conversion formulas were developed using linear regression analyses of all of the data where multiple measurements were taken and applied to convert SL to FL as necessary.

Statistical analysis.— Our analysis focused on the reef-fish species that are managed under the Gulf of Mexico Fishery Management Council's Reef Fish Fishery Management Plan (i.e., species that are identified to the genus level and nonmanaged species were excluded from this study). The percentage frequency of occurrence (%F) was calculated for each gear type as the percentage of stations in which each species was caught. A station was defined as a single deployment for S-BRUV and TRAP. For RTD, a station was defined as three anglers conducting 10 team drops at a single location and a VLL station included a single simultaneous deployment of two (or three, depending on the vessel size) vertical longline rigs at a single location. To investigate regional differences in species selectivity, the %F was also calculated for each gear type within each region.

To test for differences in the composition of the observed reef-fish assemblages we conducted a series of permutational multivariate analyses of variance (PERMANOVA) using PRIMER v7 with PERMANOVA + software (Anderson et al. 2008) for managed species ($n = 23$) that were captured with at least one type of sampling gear. The species catch data was normalized as a percentage of total catch for each station (Greenwood 2008). The data for artificial and natural reefs were pooled and then averaged within gear types (S-BRUV, TRAP, RTD, or VLL), region (Florida Panhandle or Florida Peninsula), depth (nearshore or offshore), and year (2014 or 2015). The data for each year were treated as replicate samples for the subsequent analyses. The statistical significance and relative importance of gear, region, and depth were investigated using PERMANOVA. The analyses included all of the interaction terms and were conducted using type III sums of squares (which fits every term after accounting for all of the other terms in the full model); p-values were obtained using 9,999 permutations under a reduced model. Pairwise tests were conducted for any significant factors, so we could evaluate which of them contributed to the significance ($\alpha = 0.05$). Community structure by region and gear was visualized via ordination with nonmetric multidimensional scaling based on a Bray–Curtis similarity matrix. We then conducted a similarity percentage (SIMPER) analysis (Buxton and Clarke 1986; Clarke et al. 2014) to determine which species most strongly accounted for fish community differences between gear types across all regions and depths. The above analyses were all conducted in PRIMER v7 (Anderson et al. 2008).

Length-frequency analyses were conducted for two species, Red Grouper and Red Snapper, as they were captured in sufficient numbers in all four gears. The length-frequency data were pooled into 50-mm-FL size-classes for each gear type and species. The length-frequency distributions were compared using kernel density estimates (KDE). This method is sensitive to differences both in the shape and the location of length-frequency distributions (Langlois et al. 2012). To examine differences due to shape, the data were standardized by median and variance ($y = x - \text{median/SD}$; Bowman and Azzalini 1997). Following Langlois et al. (2012), statistical differences were determined by comparing the area between KDEs for each gear type to that of random pairs resulting from permutations of the data (10,000 permutations) using the R package "sm" (Bowman and Azzalini 2010). If the data from both gear types have the same distribution, the KDEs should only differ in minor ways due to within-population variance and sampling effects (Langlois et al. 2012). The "sm.density.compare" function in the "sm" package was used to plot the length-frequency distributions with the mean and standard error, therefore showing the null model of no difference between each pair of KDEs (Bowman and Azzalini 1997).

There were no significant differences in the length-frequency distributions between RTD and VLL for Red Grouper ($P = 0.826$), so the data were combined for the subsequent analyses. For Red Snapper, the analysis was conducted for RTD only, as VLL did not capture enough Red Snapper to determine whether the frequency distributions differed. All of the length data for both species were pooled by hook size into 50-mm-FL size-classes. To examine the shape of the selection curves, exploratory plots of the proportion of catch in TRAPs (Red Grouper or Red Snapper), RTD (Red Snapper), or RTD and VLL combined (Red Grouper) relative to S-BRUV were estimated. The observed proportion of catch was calculated as the catch per length-group in TRAP (or hooked gear) divided by the total catch in each length-group from TRAP (or hooked gear) plus S-BRUV (assuming known selectivity; Millar 1995). Binomial confidence intervals were calculated using the Wilson method in the R package "binom" (Dorai-Raj 2015).

To estimate the selection of the individual hook sizes, indirect selectivity curves were modeled for hooked-gear collection of Red Grouper and Red Snapper by using the methods that are outlined for gill nets and hooked gear (Millar and Fryer 1999; Campbell et al. 2014). Four selectivity models were fit using the Share Each LEngth's Catch Total (SELECT) method (outlined in Millar and Fryer [1999] and Millar and Holst [1997]) and the "gillnetfunctions" package in R (Millar 2003; 2010). Three models (normal, lognormal, and gamma; Table 1) accept Baranov's principle of geometrical similarity, an assumption that implies that the location and spread of the selection curve are both proportional to the hook size (Baranov 1948). The fourth model was run with normal scale and constant spread (i.e., the model did not accept Baranov's principle). The parameters for these four models were estimated by fitting the general log-linear model:

$$\log_{10}(\hat{n}_{ij}) = factor(l_i) + \beta_1 \cdot f_1(m_j, j) + \beta_2 \cdot f_2(m_j, j),$$

where $\hat{n}_{ij}$ is the expected catch of fish of length-class i by hook size j and $f_1(m_j,j)$ and $f_2(m_j,j)$ are the selectivity functions of m_j and j (right hand column of Table 1). Factor (l_i) denotes that a length-class is fitted as a factor in the model. The models were fit to the data twice, once assuming that relative fishing intensity was the same for all hook sizes and once assuming that relative fishing intensity was proportional to hook size (Hamley 1975). Relative fishing intensity is a combined measure of fishing effort and fishing power (Millar and Holst 1997). All of the hooks were fished with the same effort, so in this study, fishing intensity is the same as fishing power. The model with the lowest deviance was chosen as the best fit model. To assess whether the data were overdispersed, the dispersion parameter was calculated as the model deviance divided by the degrees of freedom (Millar and Fryer 1999). When the dispersion parameter was >1 the data were considered to be overdispersed.

RESULTS

Of the 23 species that were analyzed in this study (Table 2), 11 were captured by all gear types, four were captured only by S-BRUV (Goliath Grouper *Epinephelus itajara*, Snowy Grouper *Epinephelus niveatus*, Black Grouper *Mycteroperca bonaci*, and Yellowmouth Grouper *Mycteroperca interstitialis*), and one species was captured solely by TRAPs (Speckled Hind *Epinephelus drummondhayi*). The percentage frequency of occurrence (%*F*) for all of the managed species combined was highest for S-BRUV, followed by RTD, TRAP, and VLL, respectively (Table 2). When investigating individual species, the %*F* varied by species and gear type. For Red Grouper, TRAPs had the highest %*F*, followed by RTD, S-BRUV, and VLL, respectively (Table 2). For Red Snapper, RTD had the highest %*F*, followed by S-BRUV, TRAPs, and VLL, respectively (Table 2). For 6 of the 23 selected species (Black Grouper, Goliath Grouper, Blueline Tilefish *Caulolatilus microps*, Hogfish *Lachnolaimus maximus*, Speckled Hind, and Yellowtail Snapper *Ocyurus chrysurus*) there were no occurrences within the Florida Panhandle for any gear type (Table 3). In the Florida Peninsula region, two species (Snowy Grouper and Yellowmouth Grouper) had zero occurrences (Table 3).

The results from the PERMANOVA indicated that reef-fish assemblage structure differed significantly among gear types, regions, and depths, and the interactions between gear and region as well as those between region and depth were significant (Table 4; Figure 3). Within the Florida Panhandle region, pairwise PERMANOVA comparisons indicated that assemblages differed between all gear comparisons with the exception of RTD and VLL which did not differ (Supplemental File 2). Within the Florida Peninsula region, pairwise PERMANOVA comparisons indicated that S-BRUV was significantly different from the other three gears ($P < 0.05$; Supplemental File 2). The assemblages differed significantly between depth zones for each region. Additionally, within each gear or depth zone the regions were significantly different from each other (Supplemental File 3). There was clear regional separation in the nonmetric multidimensional scaling plot. Within each region, S-BRUV was distinctly separate from the other three gears, while the other three gears had slight overlap (Figure 3).

Eight species were identified by SIMPER as contributing to the top 70% of the observed differences in assemblage structure in the comparison of at least one pair of gear types (Figure 4). In general, most of the species were more abundant in the S-BRUV survey. In contrast, the capture gears (RTD, VLL, and TRAP) were dominated by the catch of Red Grouper, Red Snapper, and Vermilion Snapper *Rhomboplites aurorubens*, with generally low abundances of all of the other species.

The size composition of Red Grouper and Red Snapper generally overlapped among gear types, but the length-frequency distributions between gear types were significantly different (Figures 5, 6). For Red Snapper, the location of the curve was significantly different between VLL and all of the other gears (Figure 5), while both the shape and location of the curves were significantly different for all of the other gear combinations (Figure 5). Both S-BRUV

TABLE 1. Models for normal, gamma, and lognormal selection curves. The model parameters are given in parentheses in the left column. The equations in the right column are the last two terms in the log-linear model.

Model	Selection curve	$\beta_1\cdot f_1(m_j,l_i)+\beta_2\cdot f_2(m_j,l_i)$
Normal: fixed spread (k, σ)	$\exp\left[-\frac{(l_i-k\cdot m_j)^2}{2\sigma^2}\right]$	$\left(\frac{k}{\sigma^2}\right)\cdot(l_i\cdot m_j)+\left(-\frac{k^2}{2\sigma^2}\right)\cdot(m_i^2)$
Normal: spread $\propto m_j$ (k_1, k_2)	$\exp\left[\frac{-(l_i-k_1\cdot m_j)^2}{2k_2\cdot m_j^2}\right]$	$\left(\frac{k_1}{k_2}\right)\cdot\left(\frac{l_i}{m_j}\right)+\left(-\frac{1}{2k_2}\right)\cdot\left(\frac{l_i}{m_j}\right)^2$
Lognormal: spread $\propto m_j$ (μ, σ)	$\frac{1}{l_i}\exp\left\{\mu_1+\log_{10}\left(\frac{m_j}{m_1}\right)-\frac{\sigma^2}{2}-\frac{\left[\log_{10}(l_i)-\mu_1-\log_{10}\left(\frac{m_j}{m_1}\right)\right]^2}{2\sigma^2}\right\}$	$\left(\frac{1}{\sigma^2}\right)\cdot\left[\log_{10}(l_i)\cdot\log_{10}\left(\frac{m_j}{m_1}\right)-\frac{1}{2}\log_{10}{}^2\left(\frac{m_j}{m_1}\right)\right]+\left(1-\frac{\mu_1}{\sigma^2}\right)\cdot\left[\log_{10}\left(\frac{m_j}{m_1}\right)\right]$
Gamma: spread $\propto m_j$ (α, k)	$\left[\frac{l_i}{(\alpha-1)\cdot k\cdot m_j}\right]^{\alpha-1}\cdot\exp\left(\alpha-1-\frac{l_i}{k\cdot m_j}\right)$	$(\alpha-1)\cdot\left[\log_{10}\left(\frac{l_i}{m_j}\right)\right]+\left(-\frac{1}{k}\right)\cdot\left(\frac{l_i}{m_j}\right)$

TABLE 2. Species frequencies by sampling gear type (number of stations per gear type): stereo-baited remote underwater video (S-BRUV), repetitive timed-drop (RTD), vertical longline (VLL), and chevron trap (TRAP). The number of individuals that were captured by each gear type (*n*) and percentage frequency (%*F*) of occurrence across all sets were also calculated.

		S-BRUV (885)		RTD (251)		VLL (253)		TRAP (816)	
Family	Genus species	*n*	%*F*	*n*	%*F*	*n*	%*F*	*n*	%*F*
Balistidae	*Balistes capriscus*	247	19.32	20	4.38	8	1.97	176	10.91
Carangidae	*Seriola dumerili*	291	15.14	9	2.39	2	0.79	10	0.61
	Seriola fasciata	30	1.69	3	0.80	0	0.00	0	0.00
	Seriola rivoliana	78	5.88	4	1.59	2	0.79	5	0.37
	Seriola zonata	19	0.79	18	3.98	0	0.00	27	0.25
Labridae	*Lachnolaimus maximus*	58	4.75	0	0.00	0	0.00	1	0.12
Lutjanidae	*Lutjanus campechanus*	456	27.91	256	28.69	81	13.83	519	15.93
	Lutjanus griseus	668	25.88	14	5.58	1	0.40	9	1.10
	Lutjanus synagris	320	23.05	57	14.34	10	3.16	284	13.36
	Ocyurus chrysurus	17	1.69	4	1.20	0	0.00	1	0.12
	Pristipomoides aquilonaris	21	1.13	4	0.80	1	0.40	4	0.49
	Rhomboplites aurorubens	1,392	31.19	248	33.47	75	18.18	2,889	26.47
Malacanthidae	*Caulolatilus chrysops*	2	0.23	1	0.40	0	0.00	1	0.12
	Caulolatilus microps	1	0.11	1	0.40	1	0.40	46	1.47
Serranidae	*Epinephelus drummondhayi*	0	0.00	0	0.00	0	0.00	3	0.37
	Epinephelus flavolimbatus	1	0.11	3	0.80	0	0.00	1	0.12
	Epinephelus itajara	7	0.68	0	0.00	0	0.00	0	0.00
	Epinephelus morio	286	27.57	355	32.67	48	10.28	719	34.31
	Epinephelus niveatus	1	0.11	0	0.00	0	0.00	0	0.00
	Mycteroperca bonaci	1	0.11	0	0.00	0	0.00	0	0.00
	Mycteroperca interstitialis	1	0.11	0	0.00	0	0.00	0	0.00
	Mycteroperca microlepis	34	3.39	3	1.20	1	0.40	12	0.98
	Mycteroperca phenax	231	15.14	12	3.98	0	0.00	48	4.53
Total individuals captured		4,162	77.7	1,012	68.1	230	39.5	4,755	65.3
Total number of species		22		17		11		18	

TABLE 3. Species frequencies of occurrence by type of sampling gear (number of stations per gear type): stereo-baited remote underwater video (S-BRUV), repetitive timed-drop (RTD), vertical longline (VLL), and chevron trap (TRAP) within region (Pan = Panhandle, Pen = Peninsula).

		S-BRUV (885)		RTD (251)		VLL (253)		TRAP (816)	
Family	Genus species	Pan (296)	Pen (589)	Pan (122)	Pen (129)	Pan (127)	Pen (126)	Pan (221)	Pen (595)
Balistidae	*Balistes capriscus*	31.1	13.4	7.38	1.55	3.94	0.00	20.4	7.39
Carangidae	*Seriola dumerili*	28.7	8.32	1.64	3.1	1.57	0.00	1.36	0.34
	Seriola fasciata	3.04	1.02	1.64	0.00	0.00	0.00	0.00	0.00
	Seriola rivoliana	11.8	2.89	1.64	1.55	0.79	0.79	0.45	0.34
	Seriola zonata	1.01	0.68	7.38	0.78	0.00	0.00	0.00	0.34
Labridae	*Lachnolaimus maximus*	0.00	7.13	0.00	0.00	0.00	0.00	0.00	0.17
Lutjanidae	*Lutjanus campechanus*	56.8	13.4	41.0	17.1	19.7	7.94	32.1	9.92
	Lutjanus griseus	13.5	32.1	0.82	10.1	0.79	0.00	0.00	1.51
	Lutjanus synagris	8.78	30.2	4.1	24	0.79	5.56	4.52	16.6
	Ocyurus chrysurus	0.00	2.55	0.00	2.33	0.00	0.00	0.00	0.17
	Pristipomoides aquilonaris	2.03	0.68	0.82	0.78	0.79	0.00	0.45	0.5
	Rhomboplites aurorubens	27.4	33.1	35.3	31.8	16.5	19.8	17.7	29.8
Malacanthidae	*Caulolatilus chrysops*	0.68	0.51	0.82	0.78	0.00	0.00	0.45	0.00
	Caulolatilus microps	0.00	0.17	0.00	0.78	0.00	0.79	0.00	2.02
Serranidae	*Epinephelus drummondhayi*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
	Epinephelus flavolimbatus	0.00	0.17	1.64	0.00	0.00	0.00	0.00	0.17
	Epinephelus itajara	0.00	1.02	0.00	0.00	0.00	0.00	0.00	0.00
	Epinephelus morio	8.11	37.5	6.56	57.4	0.00	20.6	9.5	43.5
	Epinephelus niveatus	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mycteroperca bonaci	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00
	Mycteroperca interstitialis	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mycteroperca microlepis	5.41	2.38	2.46	0.00	0.00	0.79	0.00	1.34
	Mycteroperca phenax	20.3	12.6	4.92	3.1	0.00	0.00	6.33	4.03

TABLE 4. PERMANOVA results based on Bray–Curtis dissimilarities of the proportion of each species by catch for the 23 species of reef fish that are listed on the Gulf of Mexico Fisheries Management Council managed species list in response to the factors of gear, region, depth, and their interactions. The values in bold are significant.

Source	df	MS	Pseudo-*F*	*P*	Square root (component of variation)	% of variation
Gear	**3**	**2,608.5**	**6.61**	**<0.01**	**16.63**	**13.70**
Region	**1**	**16,847**	**42.66**	**<0.01**	**32.07**	**50.93**
Depth	**1**	**3,287.9**	**8.32**	**<0.01**	**13.45**	**8.96**
Gear × Region	**3**	**1,130.8**	**2.86**	**<0.01**	**13.56**	**9.11**
Region × Depth	**1**	**2,261.6**	**5.73**	**<0.01**	**15.28**	**11.56**
Gear × Depth	3	438.66	1.11	0.37	3.31	0.54
Gear × Region × Depth	3	368.39	0.93	0.52	−3.64	N/A
Residual	16	394.92			19.87	19.56
Total	31					

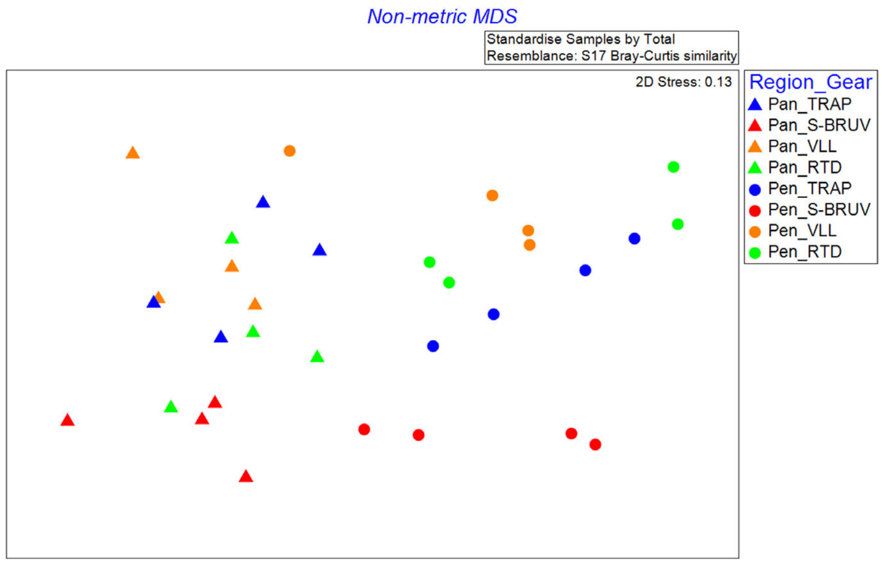

FIGURE 3. Nonmetric multidimensional scaling (MDS) plots based on a Bray–Curtis resemblance for each gear (stereo-baited remote underwater video [S-BRUV], vertical longline [VLL], repetitive timed-drop [RTD], and chevron trap [TRAP]) and region.

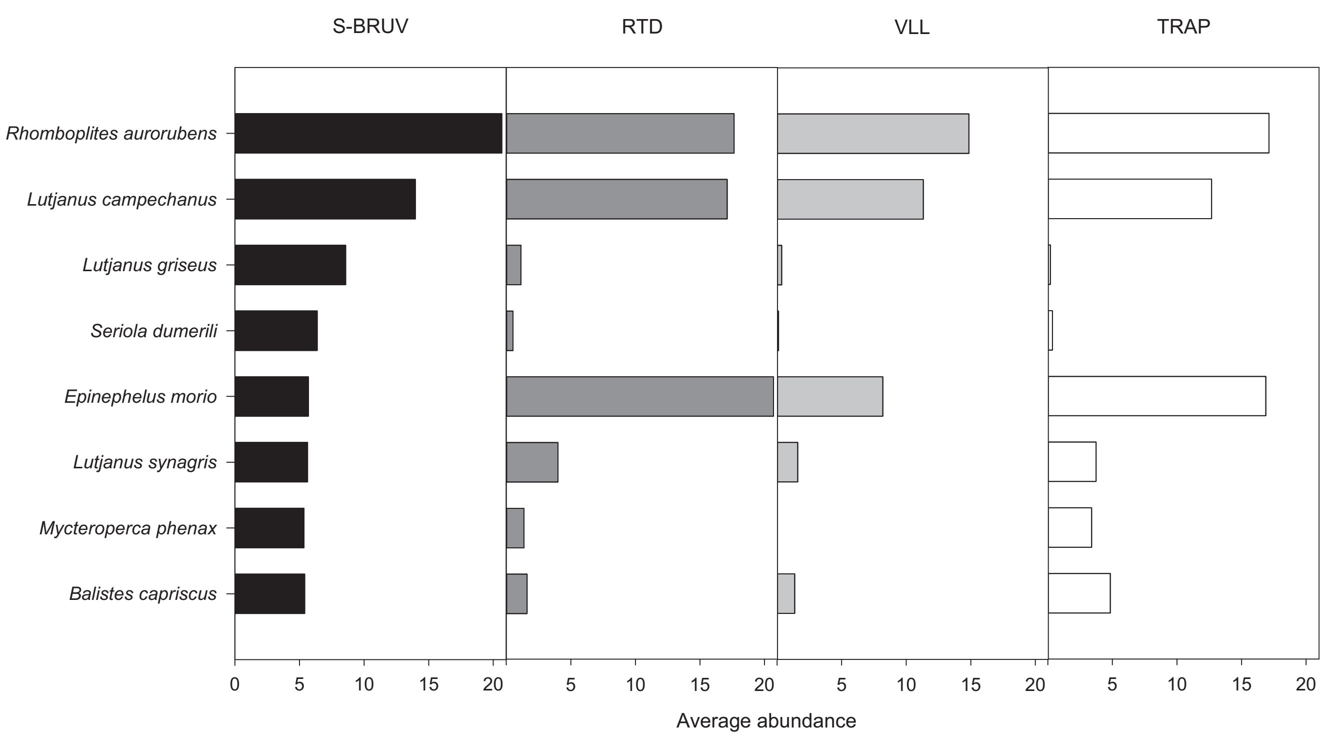

FIGURE 4. Average normalized abundance data for managed species that are listed on the Gulf of Mexico Fisheries Management Council list that were identified by similarity percentage (SIMPER) analysis as contributing to the 70% of the observed differences in the assemblage structure of reef fish that were captured by stereo-baited remote underwater video (S-BRUV), repetitive timed-drop (RTD), vertical longline (VLL), and chevron traps (TRAP).

and RTD had a second peak for larger fish that was not evident for TRAP or VLL, although TRAP had a slight peak in abundance around 250 mm that was not evident in the other gears. For Red Grouper, S-BRUV generally had the widest selection curve and differed significantly from all of the other gears (Figure 6). The location of the curve was significantly different between TRAP and RTD. The length-frequency distributions did not differ

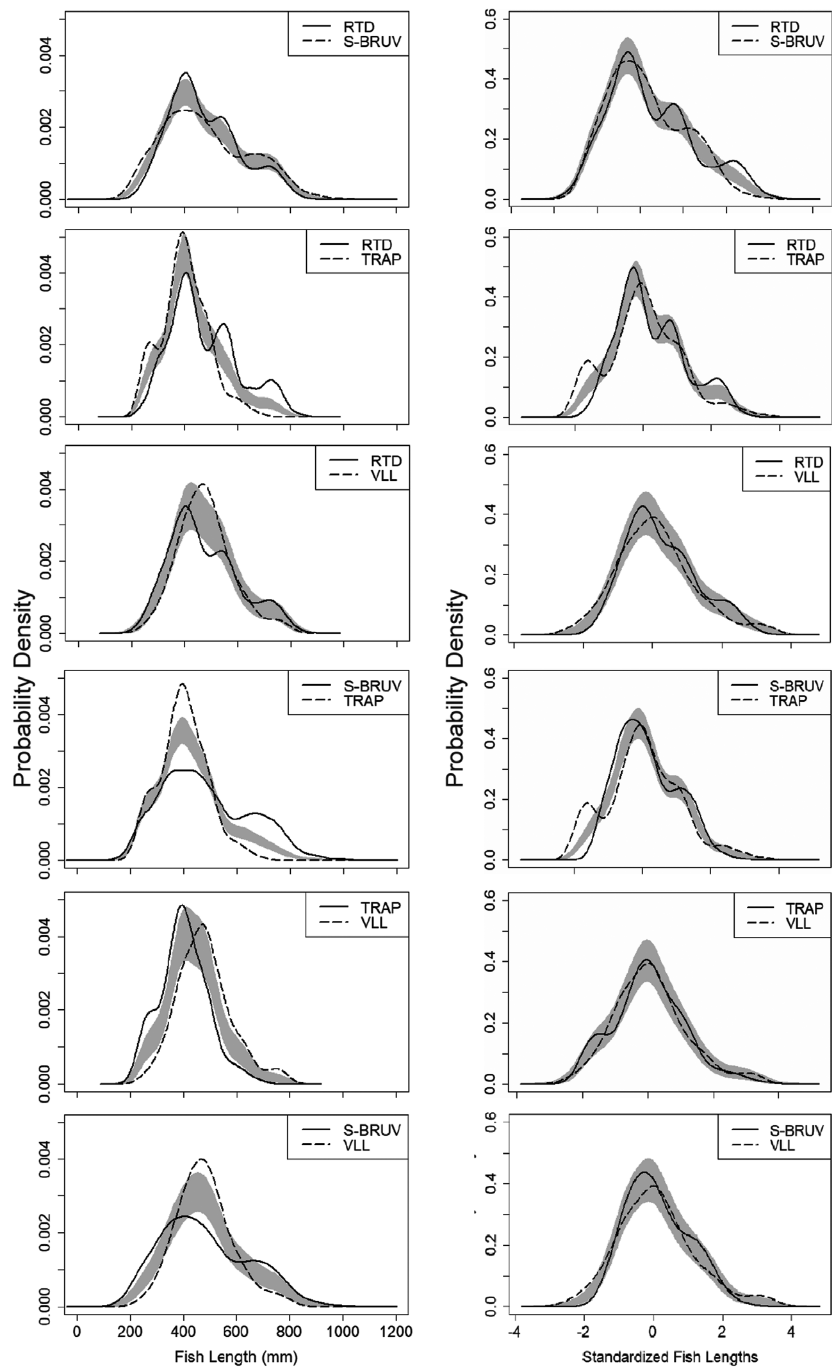

FIGURE 5. Comparison of kernel density estimate probability functions for Red Snapper that were sampled using stereo-baited remote underwater video (S-BRUV), vertical longline (VLL), repetitive timed-drop (RTD), and chevron trap (TRAP). The gray bands represent one standard error on either side of the null model of no difference between the KDEs for each method. The significance tests in the left column are for the raw data, whereas those in the right column are for the standardized data.

significantly between TRAP and VLL or between RTD and VLL for Red Grouper.

The relative selectivity of TRAP and hooked gear to S-BRUV was described by a bell-shaped selection curve (Figure 7) for both Red Grouper and Red Snapper, indicating that the S-BRUV survey captures both smaller and larger individuals at higher relative proportions than does any capture gear. In fact, the proportion of catch by TRAP or hooked gear was zero for the smallest and the largest individuals of both species, except

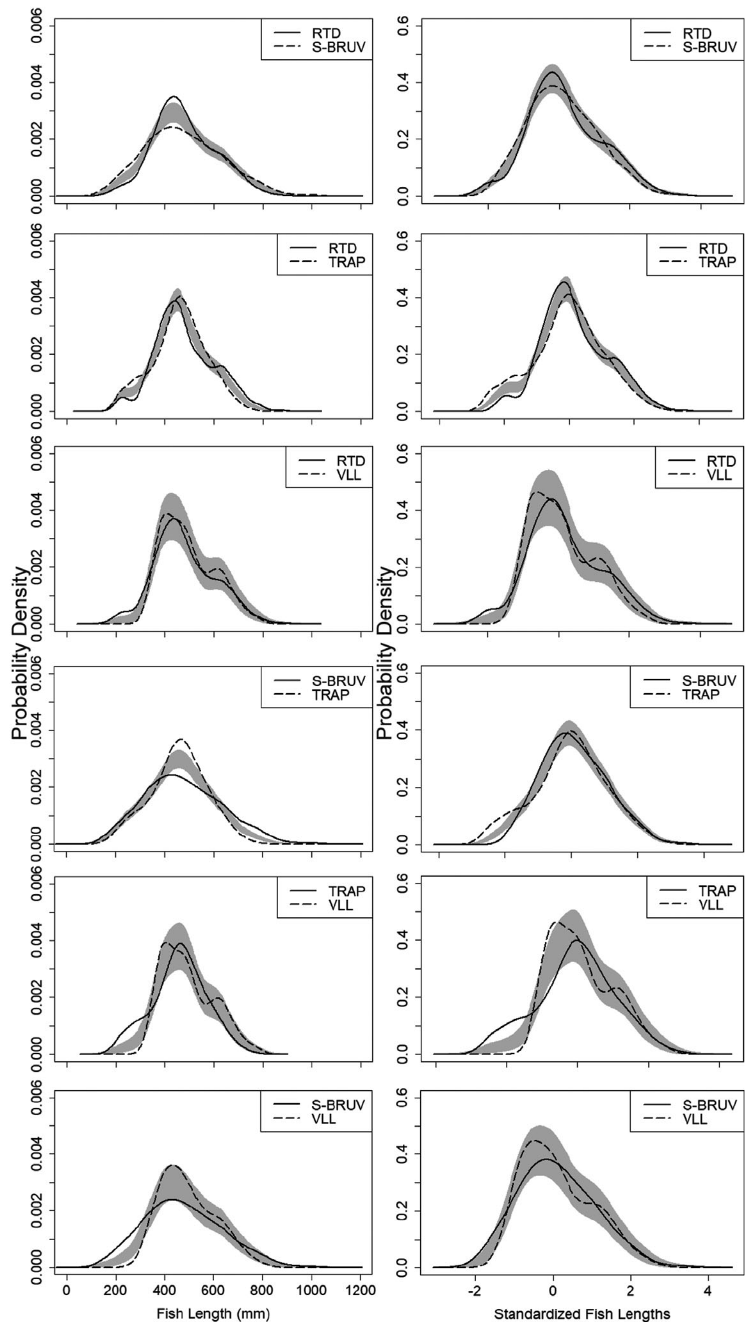

FIGURE 6. Comparison of kernel density estimate probability functions for Red Grouper that were sampled using stereo-baited remote underwater video (S-BRUV), vertical longline (VLL), repetitive timed-drop (RTD), and chevron trap (TRAP). The gray bands represent one standard error on either side of the null model of no difference between the KDEs for each method. The significance tests on the raw data (left column) provide a test of differences in both the location and shape of the length-frequency distributions, whereas tests on the standardized data (right column) provide a test of shape only.

for small Red Groupers that were infrequently captured in TRAPs.

After examining the deviance for each of the models, the lognormal models were determined to provide the best fit for the indirect selectivity curves that were estimated for the three hook sizes for both Red Grouper and Red Snapper (Table 5). The model deviances were not influenced by the fishing intensity assumption and had equal fit under both assumptions for both species (Figures 8, 9). The indirect selectivity curves were broad and unimodal for all of the hook sizes, while median size at full selectivity increased with increasing hook size for both species

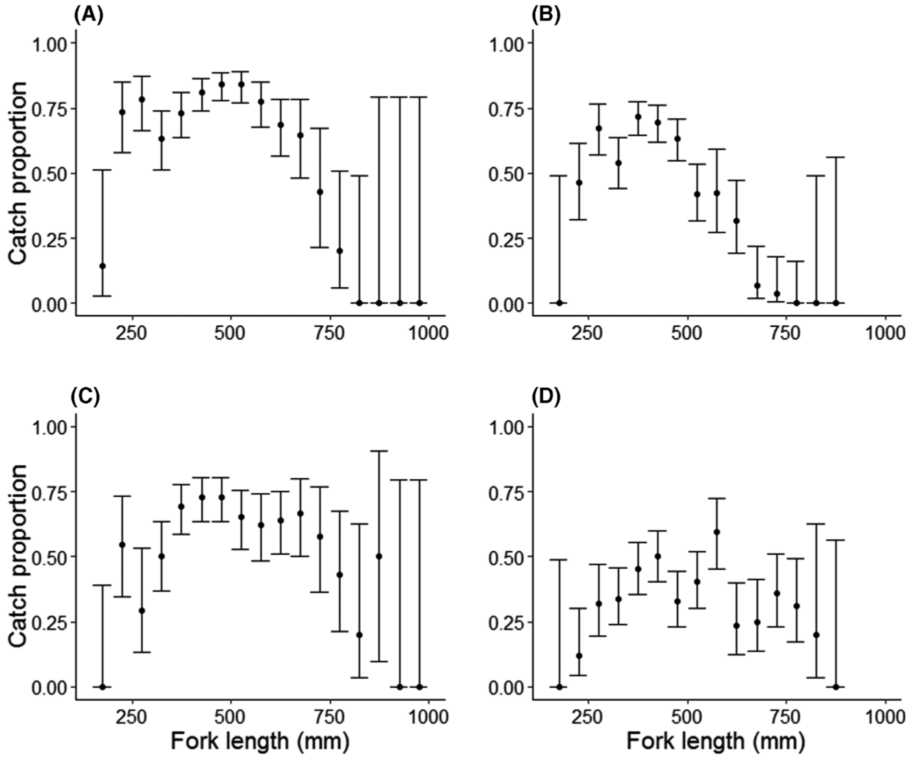

FIGURE 7. Catch proportion for chevron trap relative to stereo-baited remote underwater video (S-BRUV) and hooked gear relative to S-BRUV for **(A, B)** Red Grouper and **(C, D)** Red Snapper. The error bars are 95% confidence intervals.

TABLE 5. Hook selectivity parameters for each model for Red Grouper and Red Snapper. The parameters that are shown in bold indicate the best fit model for each species.

	Equal fishing intensity		Proportional fishing intensity		
Model	Parameters	Model deviance	Parameters	Model deviance	df
		Red Grouper			
Normal: fixed	$(k, \sigma) = (31.98, 253.57)$	59.92	$(k, \sigma) = (42.14, 276.85)$	57.60	26
Normal: proportional	$(k_1, k_2) = (33.27, 872.04)$	67.59	$(k_1, k_2) = (51.66, 600.22)$	73.63	26
Gamma	$(\alpha, k) = (4.09, 11.31)$	54.60	$(\alpha, k) = (5.09, 11.31)$	54.60	26
Lognormal	$\boldsymbol{(\mu, \sigma) = (5.82, 0.51)}$	**47.54**	$\boldsymbol{(\mu, \sigma) = (6.07, 0.51)}$	**47.54**	**26**
		Red Snapper			
Normal: fixed	$(k, \sigma) = (35.78, 186.65)$	28.09	$(k, \sigma) = (41.65, 205.73)$	26.95	24
Normal: proportional	$(k_1, k_2) = (41.99, 352.46)$	44.87	$(k_1, k_2) = (49.58, 292.41)$	49.17	24
Gamma	$(\alpha, k) = (6.99, 6.51)$	26.82	$(\alpha, k) = (7.99, 6.51)$	26.82	24
Lognormal	$\boldsymbol{(\mu, \sigma) = (5.81, 0.39)}$	**20.72**	$\boldsymbol{(\mu, \sigma) = (5.97, 0.39)}$	**20.72**	**24**

and under both assumptions (Figures 8, 9). Under the assumption of equal fishing intensity, the median sizes for both Red Grouper and Red Snapper were smaller than those that were obtained under the assumption that fishing intensity was proportional to hook size (Figures 8, 9). The residual plots revealed that fishing intensity for Red Grouper was greater than that modeled for large Red Grouper that were caught on 8/0 hooks (i.e., positive residuals) and was less than that modeled for both the smallest and largest Red Grouper that were captured on 15/0 hooks (i.e., negative residuals), while the residuals for the 11/0 hooks had no clear trends (Figure 8). For the 8/0 hooks, the variation in residuals was highest for the fish in the 400- to 450-mm size-class, indicating poor fit. Outside of this, size-class variation was relatively low for all of the hook sizes and fish sizes, indicating that model fit was

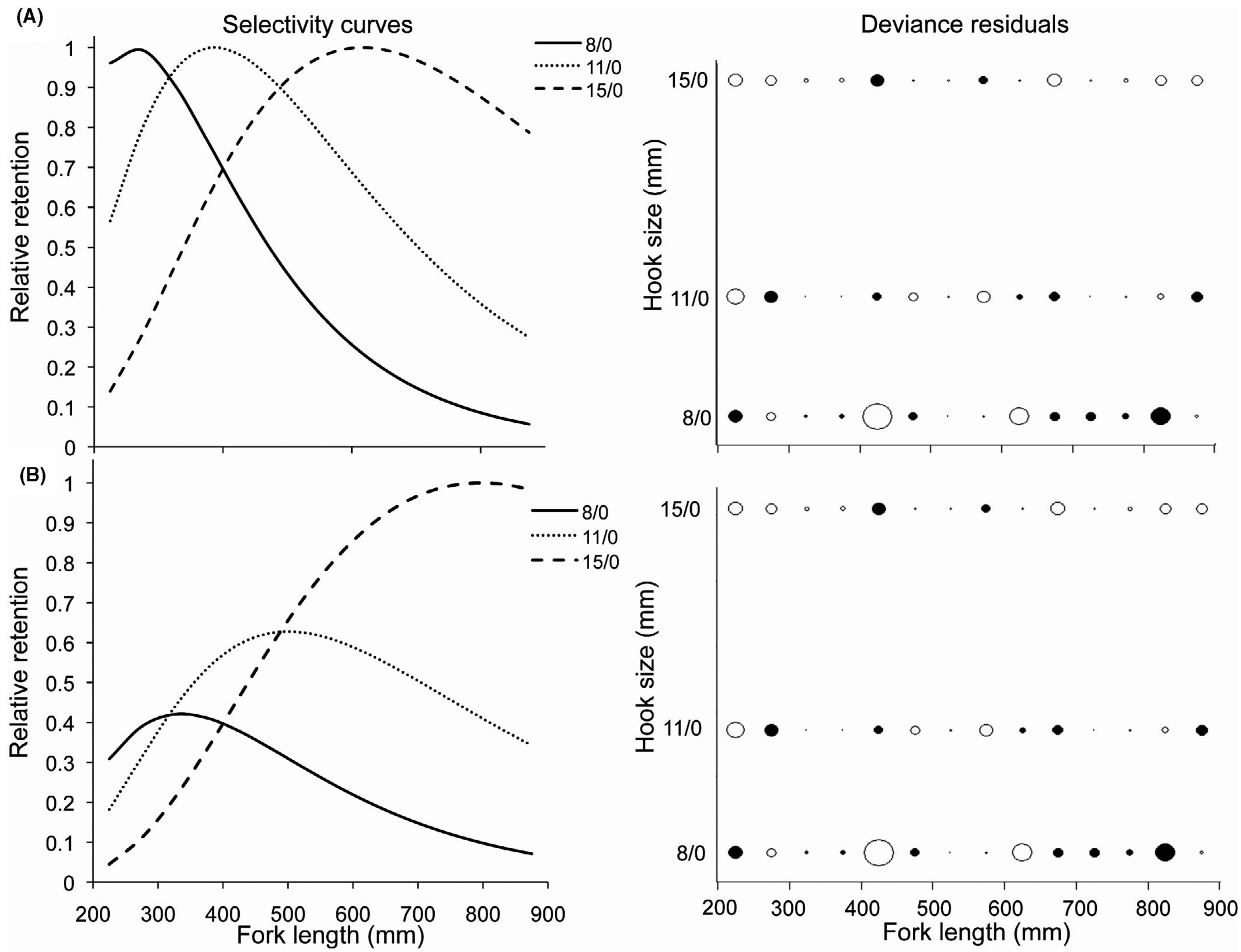

FIGURE 8. Hook selectivity curves for Red Grouper calculated from the lognormal distribution assuming **(A)** equal fishing intensity with increasing hook size and **(B)** fishing intenstiy proportional to hook size. The graphs on right side are the deviance residuals. The closed circles represent positive residuals, and the open circles represent negative residuals. The area of the circle is proportional to the absolute value of the residual.

good. For Red Snapper, no clear trends were evident in positive or negative residuals for any of the three hook sizes (Figure 9). The variation in the size of the deviance residuals generally increased with increasing FL for Red Snapper that were caught on 8/0 hooks. The residuals for the 11/0 and 15/0 hooks had no clear trends and had relatively small variation for all of the sizes of fish that were captured. The data for Red Grouper were marginally overdispersed (1.8), while for Red Snapper, the dispersion parameter was <1.0.

DISCUSSION

We found that both the species-assemblage composition and size structure of managed reef fishes differed significantly by gear type in the eastern Gulf of Mexico. Selectivity studies are often conducted over limited temporal and spatial scales, risking bias in selectivity estimates (Kotwicki et al. 2017). In the present study, four types of sampling gear were used over a broad spatial scale, and differences in species assemblages occurred between gear type, region, and depth range. The use of multiple sampling gear types in this survey allowed for the capture of multiple species across several life history stages (Jones et al. 2010; Switzer et al. 2015a).

The use of multiple hook sizes in the RTD and VLL sampling allowed for the capture of fish with significantly different length-frequency distributions and multiple life history stages. The size of fish that were caught with hooked gears generally increased with increasing hook size, consistent with earlier findings (Erzini and Gonçalves 1996; Patterson et al. 2012; Campbell et al. 2014; Garner

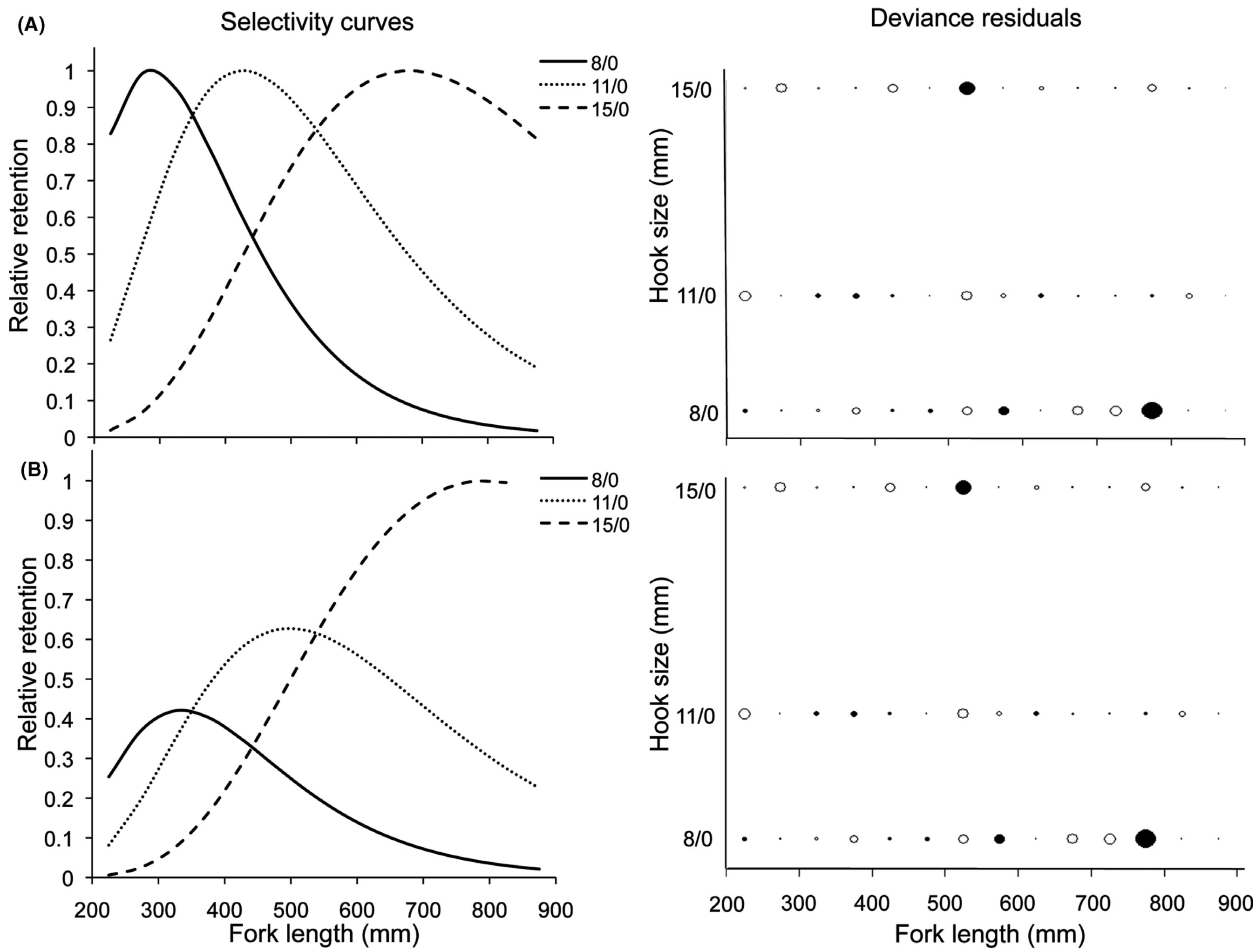

FIGURE 9. Hook selectivity curves for Red Snapper calculated from the lognormal distribution, assuming **(A)** equal fishing intensity with increasing hook size and **(B)** fishing intenstiy proportional to hook size. The graphs of the deviance residuals (right) have closed circles representing positive residuals and open circles representing negative residuals. The area of the circle is proportional to the absolute value of the residual.

et al. 2014), and selectivity was similar between both species that were tested. Although beyond the scope of the current study, additional efforts to examine the influence of hook size on species composition would provide insight as to the best approach for implementing a multispecies hooked-gear survey (Patterson et al. 2012). While the selectivity curves overlapped among hook sizes for Red Snapper and Red Grouper, the catch rate for the species with narrower gapes, like the Gray Triggerfish *Balistes capriscus*, may be reduced if smaller hook sizes are not used (Patterson et al. 2012; Garner et al. 2014). Even when species are capable of taking bait from larger hooks, the effort that is required to catch sufficient individuals for assessing stock status may be untenable (Campbell et al. 2014). These results highlight the importance of using multiple hook sizes to characterize the full size range of the reef fish that are present.

Both assumptions of fishing intensity (i.e., equal or proportional) provided the same fit for the lognormal selection curve of hooked gears because the offset was confounded with other parameters already in the model (Millar and Holst 1997). The data for Red Grouper were slightly overdispersed; this is typically associated with schooling behavior; however, the overdispersion may be an artifact of pooling the data into 50-mm length-classes, which was necessary given the number of individuals that was captured in the current study. Although the presence of overdispersion suggests that the key model assumptions may have been violated, it does not necessarily affect the parameter estimation (Millar and Fryer 1999).

In the current study, the mean size of the Red Snapper that were captured in TRAPs was smaller than that of those that were captured on S-BRUV, which contrasts with the results from a previous study in the northern

Gulf of Mexico where the Red Snapper that were caught in traps were larger than those that were caught in trawls, underwater video, or small fish traps (Wells et al. 2008). However, the largest Red Snapper reported by Wells et al. (2008) was 440 mm FL, while Red Snapper measuring up to ~900 mm FL were captured in the present study. The difference in the overall size composition of Red Snapper between the two studies is likely attributable to the relative scale of each respective study rather than actual differences in size selectivity; Wells et al. (2008) focused effort within a small area and a generally narrow and shallow depth range (25–30 m), whereas the current study encompassed a wide depth range (4–180 m) and two broad study areas in the eastern Gulf of Mexico. These discrepancies highlight the utility of conducting selectivity studies over a wide geographic range and habitats to incorporate all sizes for a species that could be susceptible to that gear type.

Similar to other studies (Harvey et al. 2012; Bacheler et al. 2013; Parker et al. 2016), our results indicate that the S-BRUV survey had the broadest species and size selectivity among all of the gears that were tested, capturing species and length-classes (both smaller and larger) that were not captured with traditional capture gear. Of the four species that were uniquely captured by S-BRUV, Goliath Grouper, Snowy Grouper, and Yellowmouth Grouper are listed as vulnerable on the International Union for Conservation of Nature Red List (IUCN 2019). Expanding S-BRUV surveys throughout the region would likely aid in addressing the critical needs of improved data for the relative abundance and size composition for these species, with the ultimate goal of contributing to formal stock assessments (SEDAR 2016a, 2016b).

Although the S-BRUV captured individuals across a wide range of sizes, important questions remain as to potential biases in the size-composition data that are determined from S-BRUV surveys. Cappo et al. (2009) identified potential biases within the data that are collected within the Great Barrier Reef Marine Park where fish that were measured during the first 15 min of deployment were smaller than those that were observed later in the deployment. To maximize the number of independent fish measurements that were available for analysis, we obtained fish measurements for each species at the time when the most individuals could be measured within a single image frame, not at specific points; accordingly, we do not anticipate that any temporal bias in size composition, if evident, would affect our results. It has also been suggested that larger fish may be more solitary, thus obtaining measurements at a time when the most measurements are possible would bias the resulting size composition towards smaller fish. While this is certainly a concern for the accurate determination of population-level size composition, potential biases towards smaller fish would not negate the results of this study. In fact, the results of this study would only be strengthened with the inclusion of additional measurements of larger individuals. Nevertheless, we recommend further efforts to investigate the potential for species-specific biases in size composition that may arise from the choice of when, during a 20-min video read, individual reef fish measurements are obtained.

In addition to the ultimate effectiveness of a particular sampling gear, survey cost may also be an important consideration when deciding on the most appropriate survey to conduct. The cost of conducting the four surveys that were tested in the present study vary dramatically as a function of several factors including the cost of the sampling gear (e.g., an inexpensive VLL or a more costly S-BRUV array), the size of vessel that is required to conduct the survey, the number of personnel that is required to conduct the survey, and the amount of time that is required to postprocess the survey data (e.g., one video requires 4 to 5 h of trained personnel time). Daily sampling effort may also vary dramatically in relation to the amount of time that is spent during gear preparation and deployment as well as overall soak and retrieval times. It is beyond the scope of the present study to empirically compare the cost effectiveness of the four surveys that were tested; however, the VLL collected the fewest individuals, the fewest species, and had the lowest $\%F$ overall. Nevertheless, the VLL has been shown to be an efficient method for collecting Red Snapper elsewhere in the Gulf of Mexico (Campbell et al. 2014; Karnauskas et al. 2017), indicating that there are additional factors (beyond the scope of this study) that may influence the effectiveness of a sampling gear (e.g., habitat type). Ultimately, researchers must balance survey objectives, gear effectiveness, and cost when determining which approach best fits their needs.

CONCLUSIONS

As fishery-independent surveys are used more widely to meet the increasing need for long-term standardized data in assessing managed species and ecosystem status, knowledge of gear selectivity is vital. These data not only inform proper survey design but also provide insight into the interpretability of collected data. For any sampling gear, the advantages must be balanced with known limitations when determining which gear to use or what type of survey to conduct. In the present study, all four gear types that were tested contributed unique data on the species and size composition of reef fish in the eastern Gulf of Mexico. However, based on the results of this study and the ultimate need for data on multiple managed reef fishes, we recommend the use of S-BRUV as the central component of a regional fisheries-independent survey, as it had the broadest species composition and size selectivity (including species that were not captured by other gears). Repetitive-timed-drop would serve as a valuable supplemental survey to obtain life history data. However, depending on species (e.g., Gray Triggerfish) and regions of interest, TRAP may be more appropriate. Moving forward, additional insight into the statistical power of each sampling gear and how specific habitat types influence the abundance and size composition of managed reef fishes would help facilitate the implementation of a statistically robust fisheries-independent monitoring program that is capable of providing quality data on multiple reef fishes over a wide range of depths, life history stages, and habitats.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.