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Assessing the size selectivity of capture gears for reef fishes using paired stereo-baited remote underwater video

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ABSTRACT

All methods used to sample fish populations exhibit some degree of size selectivity, whether due to the physical properties of the gear, behavioral responses to the gear, or the spatial distribution of the targeted population. In most stock assessments, selectivity functions are assumed and their parameters estimated due to a paucity of empirical data necessary to estimate selectivity. However, incorrect assumptions about selectivity functions can impart significant bias, ultimately affecting assessment outcomes. In 2016, a study was conducted to assess the size selectivity of three fishery-independent survey methods for reef fish in the U.S. South Atlantic: (1) a chevron trap survey, (2) a standardized repetitive timed drop hooked-gear survey, and (3) an unstandardized hooked-gear survey designed to mimic industry fishing practices. Each survey method was paired with a stereo-baited remote underwater video (S-BRUV) camera, which was treated as a comparative reference, considering that it is the least selective of the four gears used. A total of 93 stations were sampled with all gear types, and size data were analyzed for three managed reef fishes: red snapper, *Lutjanus campechanus* (all gears), black sea bass, *Centropristis striata* (all gears), and vermilion snapper, *Rhomboplites aurorubens* (all gears except chevron traps). For red snapper, all three capture gears showed dome-shaped selectivity, the degree of doming being more pronounced for chevron traps as evidenced by a decreasing capture probability for individuals over ~500 mm FL. Despite the largest red snapper (> 800 mm FL) being observed more often on S-BRUV, mean size of red snapper was generally smaller on S-BRUV than for either hooked-gear survey, indicating that hooked-gears capture proportionally fewer smaller red snapper. For black sea bass, there was evidence of flat-topped selectivity for all gear types, but chevron traps captured smaller individuals on average than did hooked gears. For vermilion snapper, both hooked gears exhibited dome-shaped selectivity. Given these results it's clear that improper assessment of selectivity can lead to poor assumptions about the sampled population. Therefore, when the selectivity function of a particular gear type is not explicitly known, studies that directly estimate selectivity should be conducted to reduce assumptions applied to assessments. This study demonstrates the utility of non-destructive video surveys to complement and evaluate the selectivity functions of standard fisheries assessment methods. Furthermore, efforts to broaden the spatial scale of this study's survey methods, expand the species to be examined, validate collected life history data, and determine the potential influence of interannual recruitment variability on observed selectivity patterns are necessary to better understand selectivity processes for all reef fishes assessed in the region.

1. Introduction

All fishery-dependent and fishery-independent gears exhibit some degree of selectivity in which the vulnerability of a population to a gear varies with size or age. The size selectivity of a gear can arise from various processes, including the physical properties of the gear (Pope et al., 1975), behavioral responses to the gear (Hamley, 1975), or the spatial distribution of the targeted population (Løkkeborg and Bjordal, 1992). Size selectivity of fishing gears has been extensively studied in large part due to capture fisheries' efficiency to a size range of the target

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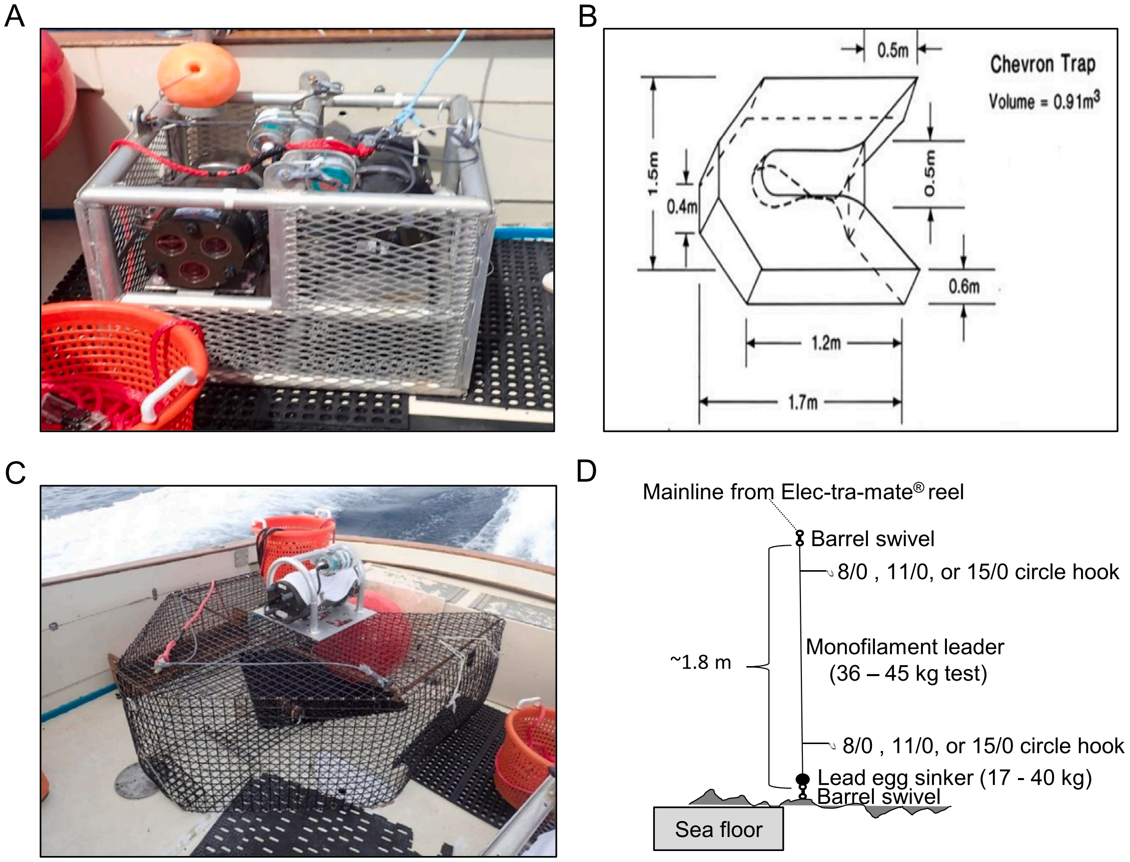

Fig. 1. Sampling gear used during the study. (A) Stereo-baited remote underwater video camera (S-BRUV), deployed prior to repetitive-timed-drop (RTD), and unstandardized hook and line (UHL) sampling. (B) Schematic diagram of chevron trap used during SERFS surveys. (C) Photo of SERFS chevron trap outfitted with an attached stereo imaging system (SIS). (D) Schematic diagram of terminal tackle used during repetitive timed-drop (RTD) hooked-gear sampling.

species (Millar and Fryer, 1999; Walsh et al., 2002). Ideally, size selectivity of a gear should be calculated directly if the population has a known length distribution; however, as population-level size composition is rarely known, this approach is not commonly used (Millar and Fryer, 1999). Instead, indirect size selectivity is estimated by comparing catch from an experimental gear with catch from a control gear (assumed to be nonselective) or a different variant of the experimental gear, which are fished simultaneously (Millar and Fryer, 1999).

For scientific surveys it is often beneficial to use gears that target the widest size range possible to reduce the impact of selectivity on estimating abundance (Kuparinen et al., 2009; Millar and Fryer, 1999; Walsh et al., 2002). Apart from targeted ichthyoplankton surveys (Habtes et al., 2014; Hernandez et al., 2010), most fishes are not vulnerable to a sampling gear until a certain minimum size is reached. For surveys that have flat-topped selectivity, individuals remain susceptible to the sampling gear throughout their lives once fully recruited (Millar and Fryer, 1999); flat-topped selectivity is often evident in trawl surveys as probability of capture increases with fish body length (Millar, 1992). Other surveys or gears such as gillnets exhibit dome-shaped selectivity in which both the smallest and largest individuals are ineffectively sampled (Huse et al., 2000; Kuparinen et al., 2009; Madsen, 2007; Stergiou and Erzini, 2002).

The selectivity function provides information on what portion (age/size) of the population the survey is sampling and accurately defining the selectivity can be critical when fitting an analysis model to survey data. In general, a flat-topped selectivity pattern is commonly assumed unless there is evidence that large-bodied individuals are invulnerable to the fishery or gear being used. This assumption can have important consequences if dome-shaped selectivity were in fact present, as assessment results may incorrectly conclude that the lack of larger or older individuals is a function of high mortality rather than inherent gear selectivity (Butterworth et al., 2014; Hordyk et al., 2015). As was the case for Atlantic menhaden (*Brevoortia tyrannus*) where flat-topped selectivity was assumed and it was determined that the stock was undergoing overfishing; however, with further research it was determined that a dome-shaped selectivity would be more appropriate and the model then indicated the stock was underfished (Butterworth et al., 2014). Alternatively, the effect of the selectivity curve can be somewhat minor relative to the uncertainty due to other variables such as for southern bluefin tuna (*Thunnus maccoyii*) (Butterworth et al., 2014). Unfortunately, empirical estimates of size selectivity are rarely available from scientific surveys, so they must be estimated within the stock assessment model.

In the U.S. South Atlantic, the primary source of fishery-independent data for reef fishes is the South East Reef Fish Survey (SERFS), a collaborative survey consisting of three fishery-independent programs (1) the Marine Resources Monitoring, Assessment, and Prediction (MARMAP) program, (2) the Southeast Monitoring and Assessment Program – South Atlantic (SEAMAP-SA), and (3) the Southeast Fishery Independent Survey (SEFIS; Bacheler and Ballenger, 2015; Smart et al., 2016). Since 1990 either SERFS or one of the independent programs have conducted comparable chevron trap surveys in the U.S. South Atlantic for the purpose of reef fish assessment. In 2010, the survey was expanded both geographically and in sampling volume, additionally underwater video cameras were added to the traps. The underwater videos used in SERFS lack stereo-measurement capabilities and provide abundance data only. Without the ability to derive an empirical selectivity, stock assessments have applied a flat-topped selectivity for the SERFS trap/video survey (SEDAR, 2017a, 2010, 2008). However, a recent stock assessment of red snapper (*Lutjanus campechanus*) indicated

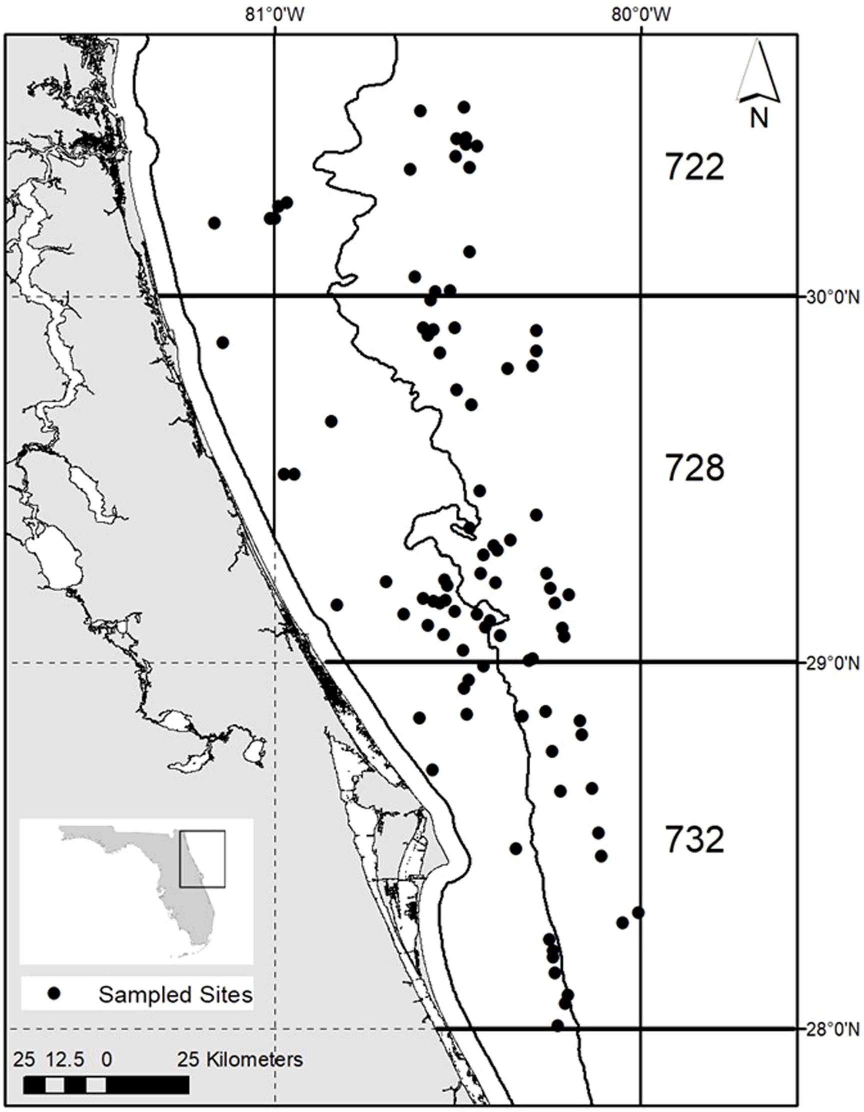

Fig. 2. Map of the study area (sampling bounded by 28° 00′N and 30° 45′N) with latitudinal strata representing NMFS statistical zones 722, 728, and 732. Black circles represent the location of sampled stations (n = 93). Black isobaths indicate 10-, 30-, and 150-m depths.

that, despite increasing total abundance and abundance at age through time, there was a marked truncation of older (and presumably larger) age classes (SEDAR, 2017a). Whether this is primarily attributable to true age truncation in the population or the choice of selectivity function remains unclear.

To investigate the species and size selectivity of reef fish sampling gears in the U.S. South Atlantic, stereo-baited remote underwater video cameras (S-BRUV) were paired with three fishery-independent capture gears: (1) the SERFS chevron traps, (2) a standardized hooked-gear survey recently developed by the Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute (FWC-FWRI) to complement the SERFS chevron trap survey (Guenther et al., 2014), and (3) an unstandardized hooked-gear survey designed to mimic industry fishing practices (Fig. 1). S-BRUVs have been used extensively to collect concurrent abundance and size composition data for reef fishes (Harvey et al., 2012; Switzer et al., 2020; Thompson et al., 2022; Watson et al., 2010) and are generally considered to have a broad selectivity (Cappo et al., 2006). Because S-BRUVs are typically thought to provide data from a broad range of sizes, they can be compared to other sampling gears to infer patterns of size selectivity (Christiansen et al., 2020; Parker et al., 2016; Watson et al., 2010). Indirect selectivity methods were used to estimate the size selectivity of each gear type and determine whether dome-shaped or flat-topped selectivity was evident for three ecologically and economically important reef fishes: red snapper, black sea bass (*Centropristis striata*), and vermilion snapper (*Rhomboplites aurorubens*).

2. Materials and methods

2.1. Study area

A study to assess the size selectivity of various fisheries-independent monitoring sampling gears/methods was conducted on hard-bottom habitats between April–August 2016 in the U.S. South Atlantic from 28° 00′ N to 30° 45′ N (Florida–Georgia state line) in water depths of 10–150 m (Fig. 2). Natural hard-bottom habitats in the U.S. South Atlantic vary, ranging from gently sloping low relief (< 2 m) outcrops to steep high relief ledges (>10 m; Schobernd and Sedberry, 2009).

2.2. Sampling Approach

The study area was subdivided into 0.1-nm longitude × 0.3-nm latitude sampling grids; all sampling grids that intersected with points of presumed natural hard-bottom habitat (e.g., survey points contained within SERFS sampling frame, sites provided by fishers, habitat mapping data from National Marine Fisheries Service (NMFS) and the U.S. Geological Survey, and previous reef fish studies conducted by the FWC-FWRI in the survey area) were included within the sampling frame. To ensure sampling effort was spatially representative, a stratified-random survey design was employed where sampling effort was allocated among three latitudinal strata (NMFS statistical zones 722, 728, and 732) and two depth strata (nearshore 10–30 m and offshore 30–150 m; Fig. 2). The intent was to sample a total of 100 stations during this study; effort was allocated proportionally among spatial strata based on the number of potential sampling grids within each stratum that contained natural hard-bottom habitat. Site selection followed a two-stage approach. One hundred primary sampling sites were selected; then two additional sampling sites were randomly selected within a 2-mile radius of each of the 100 primary sampling sites, resulting in three-site sampling stations. If two additional sites were not available, the primary site was discarded and reselected. The result was a series of 100 three-site sampling stations; the three capture gears (chevron traps, standardized repetitive timed drop hooked-gear [RTD], and unstandardized hook and line [UHL]) were each paired with S-BRUV and then one gear was randomly assigned to each specific sampling site. All gear deployments within the three-site cluster were spaced at least one sampling grid apart (0.1 nm) from any other deployment to preserve the independence of the sampling gear.

2.3. Sampling Gear

2.3.1. Chevron Traps

Chevron traps were constructed and deployed following established protocols developed and currently utilized by SERFS (Collins, 1990; MARMAP, 2009; Mitchell et al., 2014). Chevron traps were arrowhead shaped with a total interior volume of 0.91 m^3. Each trap was constructed of 35 × 35 mm square mesh plastic-coated wire with a single entrance funnel and a release panel to remove the catch. All traps were equipped with a blow-out panel fastened with magnesium releases to minimize the potential of ghost fishing should traps be lost and were attached to an appropriate length (i.e., based on depth and current) of polypropylene line fastened to a surface polyball buoy. Each trap was baited with 24 frozen menhaden (*Brevoortia* spp.) and soaked for a minimum of 90 min prior to retrieval. Traps were retrieved using an onboard commercial-style pot hauler or by other mechanical means depending on the equipment available to each of the contracted commercial/for-hire vessels.

2.3.2. Repetitive Timed Drop Hooked-Gear (RTD)

The RTD survey was conducted using powered (12 V DC) Elec-tra-mate© rigs (model 940XP) similar to methods used by Christiansen et al. (2020). Briefly, the Elec-tra-mate© rig was outfitted with a Penn© 115 L 9/0 (Senator model) reel equipped with 45-kg test monofilament. The entire rig was mounted onto a heavy-duty fiberglass fishing pole (~ 2.4 m). Terminal tackle for all Elec-tra-mate© rigs was standardized. A barrel swivel was attached to the mainline from the reel. Starting from the swivel, a 1.8-m section of 45-kg test monofilament leader was attached. Two short leads (~ 0.2 m long) were tied along the length of this leader (i.e., "dropper loops"); one was located near the top of the rig and the other near the bottom. A specific hook size (either 8/0, 11/0, and 15/0 Mustad non-offset circle hooks [Ref 39960D]) was assigned to both the top and bottom leads for each rig. A lead sinker (size depending on prevailing current conditions, ranging from 0.17 kg to 0.40 kg, heavier with stronger currents) was inserted at the bottom of the leader.

RTD sampling employed a standardized system of active fishing involving three fishers who deployed a series of 10 repetitive team drops. Each fisher was assigned a two-hook rig consisting of a pair of either 8/0, 11/0, or 15/0 circle hooks; all three hook sizes were fished at each sampling site. All hooks were baited with frozen Atlantic mackerel (*Scomber* spp.) cut proportional to hook size. For each team drop, all three fishers simultaneously dropped their rigs to the bottom and allowed their rig to soak for no more than 2 min. Fishers soaked their rigs in contact with the bottom and reeled in their rig as soon as a fish was hooked and then waited until the next team drop to redeploy. After the 2-min time period elapsed, all remaining rigs were retrieved and rebaited prior to subsequent team drops. Fishers rotated hook sizes fished at subsequent sites to remove any potential fisher-associated bias.

2.3.3. Unstandardized Hook and Line (UHL)

At each selected UHL sampling site, the specific gear, tackle, and bait used were dictated by the captain of the vessel who was instructed to fish these sites using methods during a typical charter or commercial trip. For each UHL fishing site, three anglers actively fished for 30 min, counting how many times that they retrieved and deployed their respective baits at each sampling site to provide a measure of effort comparable to that of the RTD survey. The start and end time of sampling was recorded and any breaks in individual fisher sampling were documented. Field staff also documented the specific gear (conventional, electric, bandit, spinning), tackle (leader strength, leader type), hooks (size, number), bait (live, dead, cut, etc.), and any other pertinent metrics observed to facilitate comparison to standardized RTD methods.

2.3.4. Stereo-Baited Remote Underwater Video (S-BRUV)

At all sampling sites, a stereo-baited remote underwater video (S-BRUV) camera system was deployed either concurrent to (chevron traps) or immediately preceding (RTD, UHL) capture gear deployment. For chevron traps, the S-BRUV was a single stereo imaging system (SIS), consisting of an underwater housing containing a digital video camera, a pair of stereo-still cameras, and a computer that controlled the cameras and recorded data. The S-BRUV was mounted onto the trap facing outward above the throat, identical to current SERFS camera-mounting protocols (Bacheler et al., 2014). For stations sampled via RTD and UHL, a stand-alone S-BRUV array, consisting of two SIS units positioned at an angle of 180° from one another, was deployed prior to conducting sampling (for further details see Switzer et al., 2020). Each array was baited with cut Atlantic mackerel (*Scomber* spp.) and soaked for 30 min to allow for 20 min of continuous recording time.

2.4. Sample Processing

Depth (m), geographic coordinates, times of gear deployment and retrieval, bottom water temperatures (°C), and other pertinent physical parameters were recorded at each sampling site. All fish collected were identified, enumerated, and measured (mm) as standard length (SL), fork length (FL), and total length (TL) unless individuals were partially preyed upon prior to landing. Any individuals that were not positively identified in the field were brought back to the laboratory for confirmation of identification. For RTD and UHL surveys, deployment (e.g., fisher information, number of hooks, size of hooks used, number of drops) and catch data (e.g., species captured, length) were recorded at each sampling site.

One S-BRUV recording from each sampling site was analyzed for fish abundance and size composition; for the RTD and UHL sites, the video analyzed was randomly selected unless either (1) only one video observed reef habitat, or (2) only one video was of readable quality (e.g., the other video was out of focus, had a severely obstructed view, or had a short recording). All video analysis for fish abundance was conducted using Luxriot® software. During analysis, viewers recorded the maximum number of individuals (MaxN) observed on a single video frame for each species identified during a continuous 20-min analysis. To ensure accurate length measurements each SIS unit was calibrated following Christiansen et al. (2020) at the beginning and end of the sampling season. Briefly, a calibration cube and calibration bar containing several hundred points of known lengths were recorded and measurements were obtained using stereo still images and SeaGIS® software (Seager, 2019). Any SIS unit with digital estimates that had a

Table 1
Number of individual fish measurements analyzed for each species and gear type. For S-BRUV, numbers within parentheses represent the total number of each species observed (not all individuals could be measured).

Species	Trap	S-BRUV (Trap)	RTD	S-BRUV (RTD)	UHL	S-BRUV (UHL)
Red Snapper	187	157 (320)	240	138 (262)	264	163 (341)
Black Sea Bass	310	24 (64)	147	45 (84)	116	53 (111)
Vermilion Snapper	8	349 (1193)	66	196 (1730)	31	273 (1313)

margin of error that was greater than 5% compared with the known measurements was not used. When video conditions allowed, observed individuals were measured to the nearest mm FL using SeaGIS® software. As with MaxN, measurements were taken only of individuals observed on a single video frame to avoid duplicate measurements; measurements were typically taken at the time of MaxN, unless more measurements were possible at another point during the 20-min read.

2.5. Statistical Analysis

For three species common to all gears (red snapper, black sea bass, and vermilion snapper), analyses were conducted to compare data from each capture gear (chevron trap, RTD, or UHL) with the corresponding S-BRUV deployed in association with that gear. Separate analyses were conducted for each capture gear; data were pooled over all stations for each sampling gear type.

Kernel density estimates (KDE) were used to test for differences both in the shape and location of length-frequency distributions. Length-frequency data were first standardized by median and variance ($y = x - \text{median}/\text{stdev}$) to examine differences due to shape (Bowman and Azzalini, 1997). Following Langlois et al. (2012), statistical differences were then tested by comparing the area between KDEs for each method to that of random pairs resulting from permutations of the data (10,000 permutations) using the R package 'sm' (Bowman and Azzalini, 2010; R Core Team, 2017). The 'sm.density.compare' function in the 'sm' package was used to plot the length-frequency distributions with a gray band centered on the mean KDE and extending one standard error above and below the mean; this interval represented the null model of no difference between the pair of KDEs (Bowman and Azzalini, 1997). If

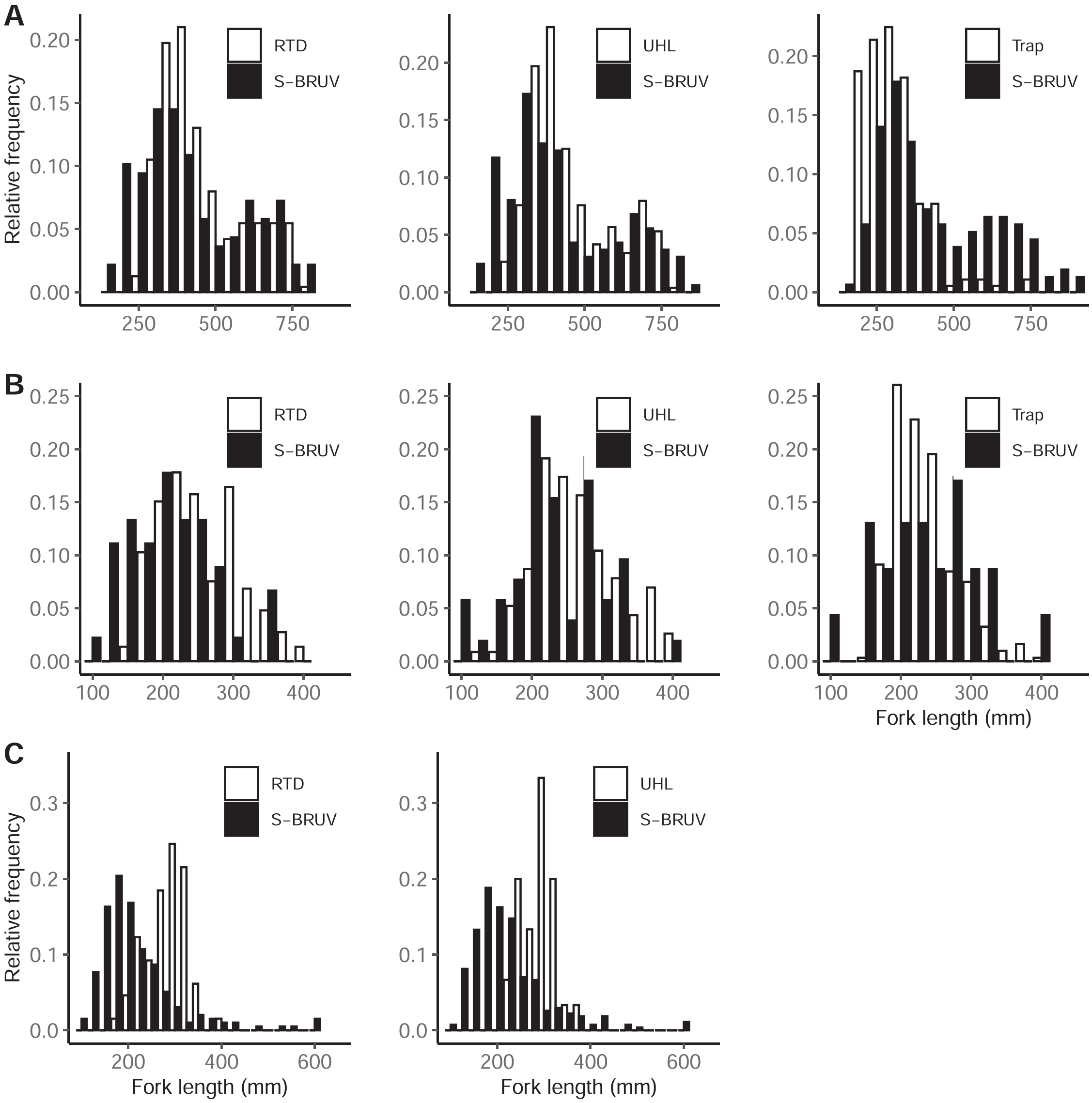

Fig. 3. Length frequency distributions for A) red snapper, B) black sea bass, and C) vermilion snapper between capture gear (repetitive timed drop (RTD), unstandardized hook and line (UHL) and chevron trap (trap)) and corresponding S-BRUV.

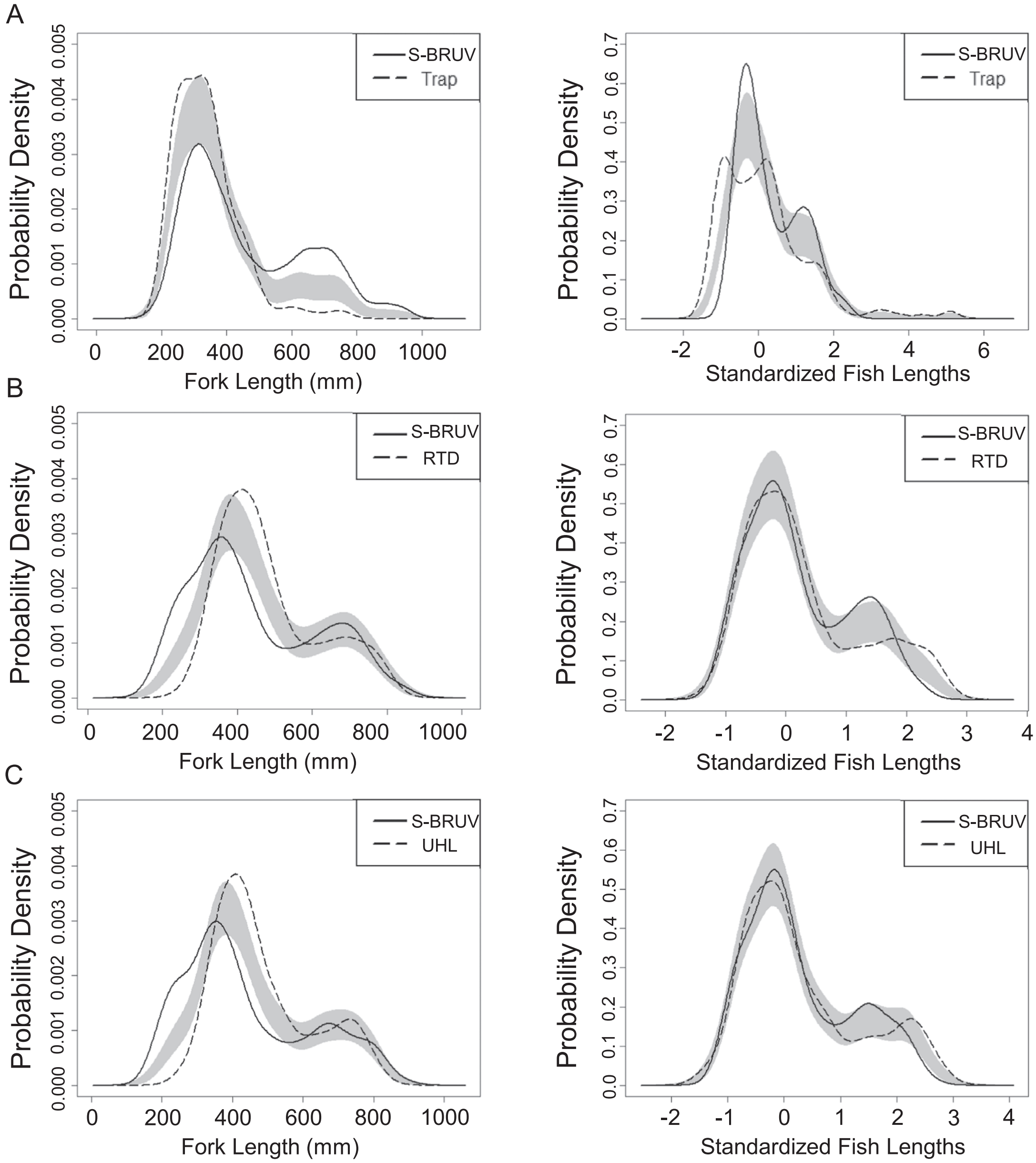

Fig. 4. Comparison of kernel density estimate (KDE) probability density functions for red snapper sampled using A) chevron trap (trap), B) repetitive timed-drop (RTD), or C) unstandardized hook and line (UHL) with stereo-baited underwater remote video cameras (S-BRUV). Grey bands represent ± 1 SE about the null model. Analyses of raw data (left column) provide a test of differences in both location and shape of the length-frequency distributions, whereas analyses of standardized data (right column) provide a test of shape only. An asterisk indicates significant differences between the two distributions ($p < 0.05$).

the data from both methods have the same distribution, the KDEs should only differ in minor ways because of within-population variance and sampling effects (Langlois et al., 2012).

For indirect selectivity analyses, length-frequency data were pooled into 25-mm (black sea bass and vermilion snapper) or 50-mm (red snapper) FL size bins for each gear type and species. To estimate the shape of the selectivity curves, exploratory plots of the observed proportion of catch were calculated as the relative catch per length group in each capture gear divided by the sum of the relative catch in each length group from each capture gear and its associated S-BRUV (Millar, 1995). Binomial confidence intervals were calculated using the Wilson method in the R package "binom" (Dorai-Raj, 2015).

For RTD collections of red snapper and black sea bass (vermilion snapper had too few individuals captured per individual hook size), indirect selectivity curves were modeled using the SELECT (Share Each Length's Catch Total) method (outlined in Millar and Fryer, 1999) and the "gillnetfunctions" package in R (Millar, 2010, 2003). Log-linear models were fit to four families of distributions (gamma, lognormal, normal-proportional spread following Baranov's principle of geometric similarity, and normal-constant spread [Baranov, 1948]). All models were fit twice; first, assuming relative fishing intensity was equal for all hook sizes and then again assuming relative fishing intensity was proportional to hook size. Relative fishing intensity is a combined measure of fishing effort and fishing power. Each hook was fished with equal effort and hence fishing power is the same as fishing intensity in this study (Millar and Holst, 1997). Manufacturer's hook number does not represent the actual measurement of hook size; therefore, the measurement of hook gape (mm) was used to model the relative size proportions of the hooks (Campbell et al., 2014). The best-fitting model was selected based on model deviance and Akaike's information criterion (AIC).

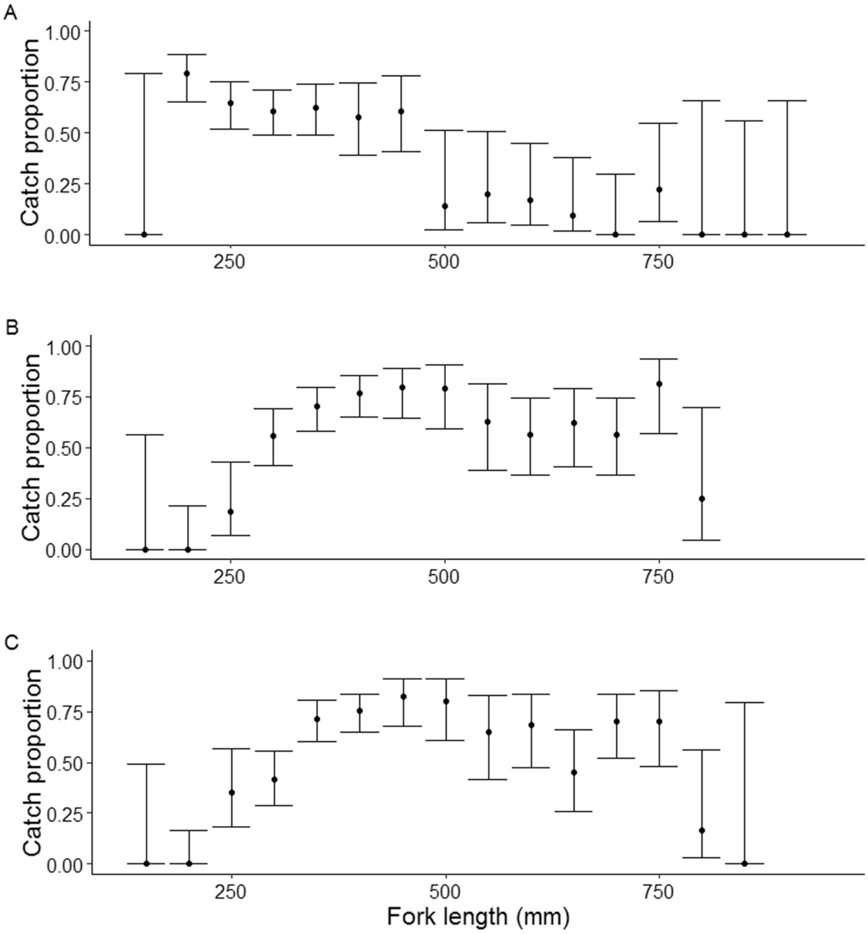

Fig. 5. Relative selectivity for red snapper of A) chevron traps, B) repetitive timed-drop, and C) unstandardized hook and line, each relative to their corresponding S-BRUV. Error bars represent 90% confidence intervals.

3. Results

3.1. Red snapper

Red snapper were frequently caught by all three capture gears and observed on corresponding S-BRUVs (Table 1; Fig. 3A.). Comparisons of KDE probability density functions identified significant differences (KDE function of each sampling method falls outside the standard error band around the model of no difference) in both location and shape (raw data) as well as shape only (standardized data) between the size of red snapper captured within chevron traps and those observed on corresponding S-BRUVs (Fig. 4A). On average, red snapper captured within chevron traps were smaller than those observed on video, likely due to individuals 600–800 mm FL that were frequently observed on video but rarely captured within traps. For hooked gear, no significant differences were detected in relation to shape only, indicating that the significant differences found in the tests of shape and location were due to location only, where both RTD and UHL captured larger red snapper on average than were observed on video (Fig. 4B, C). For both hooked gears the differences in length frequency distributions were driven by small individuals observed by the S-BRUV that were not caught by the hooked gears.

An examination of relative catch proportions of red snapper between traps and S-BRUV (i.e., relative selectivity) indicated that as individual size increased, proportionally more individuals were observed on S-BRUV except for the smallest size class (Fig. 5A). In contrast, for both RTD and UHL, proportionally more individuals were captured than observed on S-BRUV with increasing size (Fig. 5B, C), although the largest individuals were observed by S-BRUV for all gears.

In terms of hook-specific selectivity, the normal model with proportional scale and spread under the assumption that fishing intensity was proportional to hook size was the best fit model for indirect selectivity of the three hook sizes used in RTD (Fig. 6A). The indirect selectivity curves were broad for all hook sizes and the median size of red snapper at full selectivity increased with increasing hook size. The deviance residuals were generally small with no obvious patterns in positive or negative residuals.

3.2. Black sea bass

Black sea bass were captured by all three capture gears and observed on corresponding S-BRUVS (Table 1, Fig. 3B), although the number of individuals observed by S-BRUV was lower than captured in the corresponding sampling gear. For S-BRUVs deployed with traps, the number of black sea bass measured by S-BRUV was low (n = 24), so comparisons between gears should be interpreted with caution. No significant difference was evident between the shape of the length-frequency distributions sampled with S-BRUV and any of the three sampling gears (Fig. 7), indicating that subsequent tests of both shape and location were essentially tests of location (mean length) only. These tests for location were significant for all three sampling gears compared with S-BRUV; on average, black sea bass observed by S-BRUV were larger than those captured in traps (Fig. 7A), whereas the mean length of black sea bass captured by both RTD and UHL was larger than observed by S-BRUV (Fig. 7B, C).

For both the smallest and largest size classes of black sea bass,

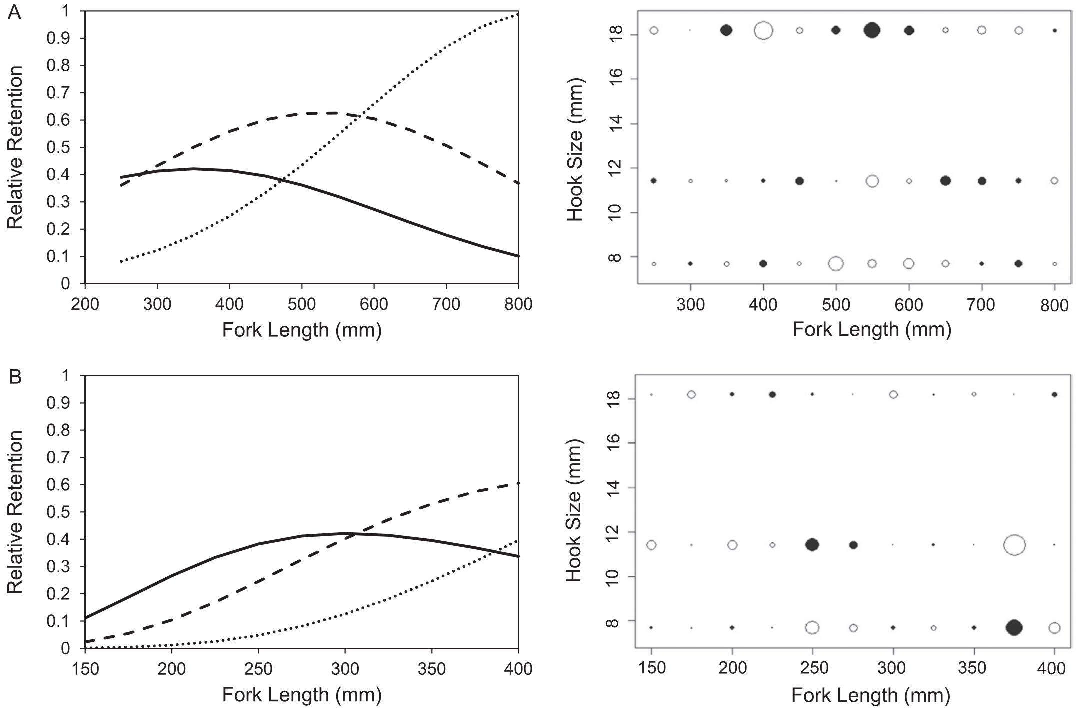

Fig. 6. Hook selectivity curves (left panels) from repetitive timed-drop sampling for A) red snapper calculated from the normal distribution assuming fishing intensity proportional to hook size and B) black sea bass calculated from the lognormal distribution assuming fishing intensity proportional to hook size. Solid lines represent 8/0 hooks, dashed lines represent 11/0 hooks, and dotted lines represent 15/0 hooks. The right panels are the deviance residuals, where closed circles represent positive residuals and open circles represent negative residuals. The size of each circle is proportional to the absolute value of the residual.

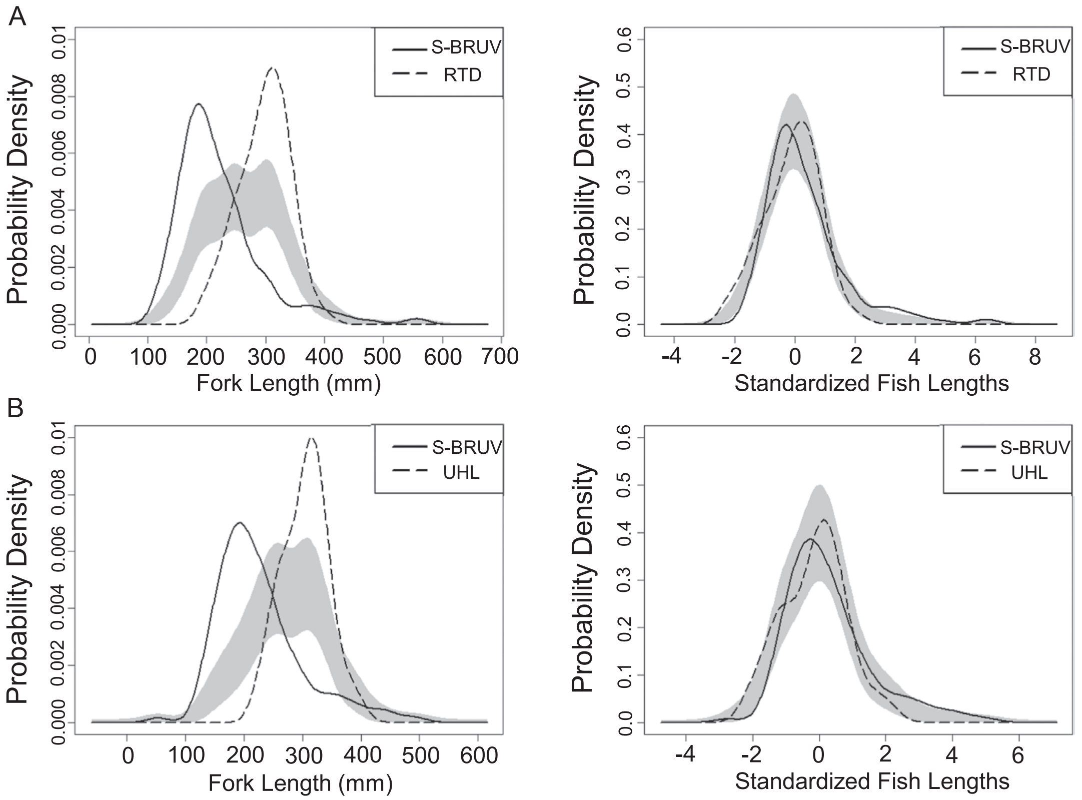

Fig. 7. Comparison of kernel density estimate (KDE) probability density functions for black sea bass sampled using A) chevron trap (trap), B) repetitive timed-drop (RTD), or C) unstandardized hook and line (UHL) with stereo-baited underwater remote video cameras (S-BRUV). Grey bands represent ± 1 SE about the null model. Analysis of raw data (left column) provide a test of differences in both location and shape of the length-frequency distributions, whereas analyses on standardized data (right column) provide a test of shape only. An asterisk indicates significant differences between the two distributions ($p < 0.05$).

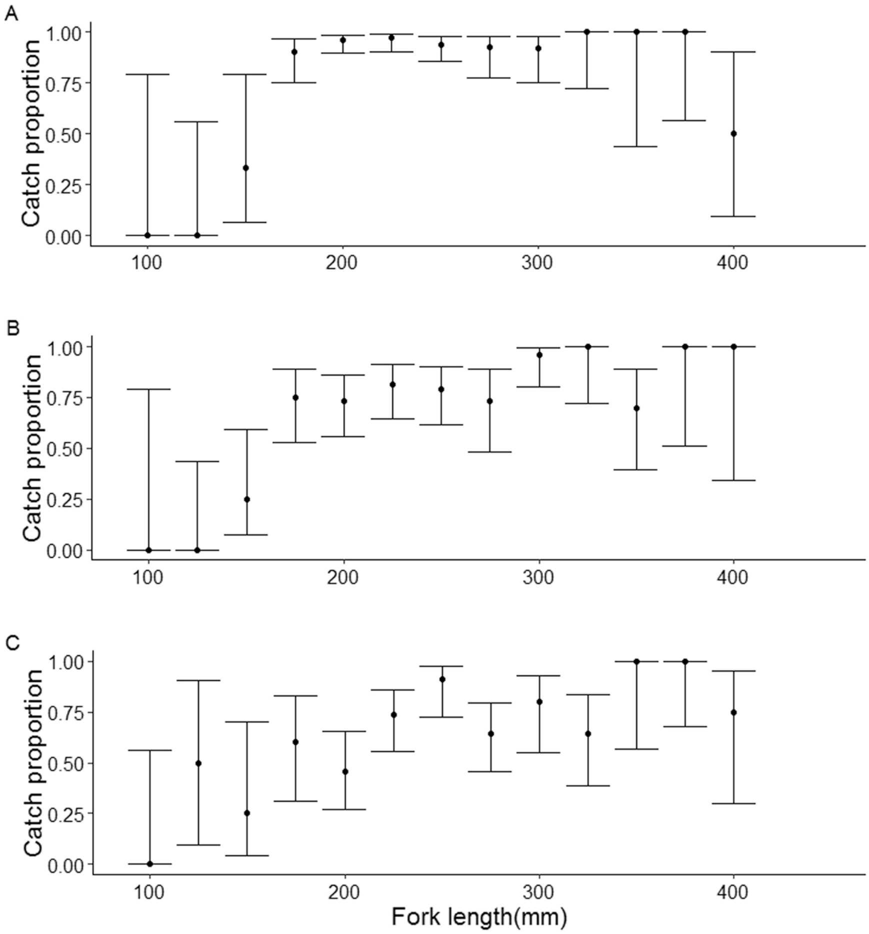

Fig. 8. Relative selectivity for black sea bass of A) chevron trap, B) repetitive timed-drop, and C) unstandardized hook and line, each relative to their corresponding S-BRUV. Error bars are 90% confidence intervals.

proportionally more individuals were observed by S-BRUV than captured in traps (Fig. 8A). The curve of catch proportions for both hooked gears indicated as length increased, proportionally more black sea bass were caught by the hooked gears than were observed by S-BRUV (Fig. 8B, C).

The lognormal model provided the best fit for both the assumption of equal fishing intensity among all hook sizes as well as fishing intensity proportional to hook size (Fig. 6B); however, a best fit could not be distinguished between these two models, and results are only presented for the model with fishing intensity proportional to hook size. The selection curves were broad with increasing median size of black sea bass at full selectivity with increasing hook size. Overall, the residuals were small for all hook sizes with no patterns in positive or negative residuals.

3.3. *Vermilion snapper*

The numbers of vermilion snapper caught by the capture gears were much lower than observed by S-BRUV (Table 1, Fig. 3C), especially in traps. Therefore, the size selectivity analysis was not conducted between traps and S-BRUVs. Additionally, the sample size was too low to conduct an indirect selectivity analysis for either hooked gear. The KDE analysis found no significant difference between the shape of the length-frequency distributions sampled with S-BRUV and those of RTD or UHL, which indicates that the tests for both shape and location were essentially tests of location (mean length) only (Fig. 9A, B). The tests for location indicated that the mean length of vermilion snapper sampled by both RTD and UHL was larger than observed by S-BRUV.

The plots of catch proportion indicated that for both the smallest and largest size classes, proportionally more vermilion snapper were observed by S-BRUV than with either hooked gear. For intermediate-sized individuals (200–400 mm FL), proportionally more individuals were captured by RTD and UHL than observed on video (Fig. 10A, B).

4. Discussion

In this study, the shape of the size selectivity curves was empirically estimated for several fishery-independent reef fish capture gears by comparing them relative to S-BRUV surveys. Results of these analyses indicate that observed patterns of size selectivity were both gear and species-specific. For red snapper and vermilion snapper, the size selectivity of chevron traps and hooked gears was dome-shaped, although the degree of doming was much more pronounced for chevron traps than for hooked gears. In contrast, the size selectivity of all capture gears was flat-topped for black sea bass. These results indicate that, in some instances, the standard application of flat-topped selectivity for data from the SERFS chevron trap survey may not be appropriate. Incorrect assumptions of size selectivity can have tremendous implications toward the determination of stock status; accordingly, increased efforts to empirically test assumptions of gear and species-specific size selectivity for fishery-independent surveys is warranted. Additionally, further research is required to examine the effect of poorly estimated selectivity on a stock assessment.

This study was undertaken to explore the uncertainty in the choice of flat-topped selectivity of the SERFS trap survey for red snapper (SEDAR, 2017, 2010, 2008). As the SERFS trap/video survey is the most reliable continuing fishery-independent index, it has a particularly important

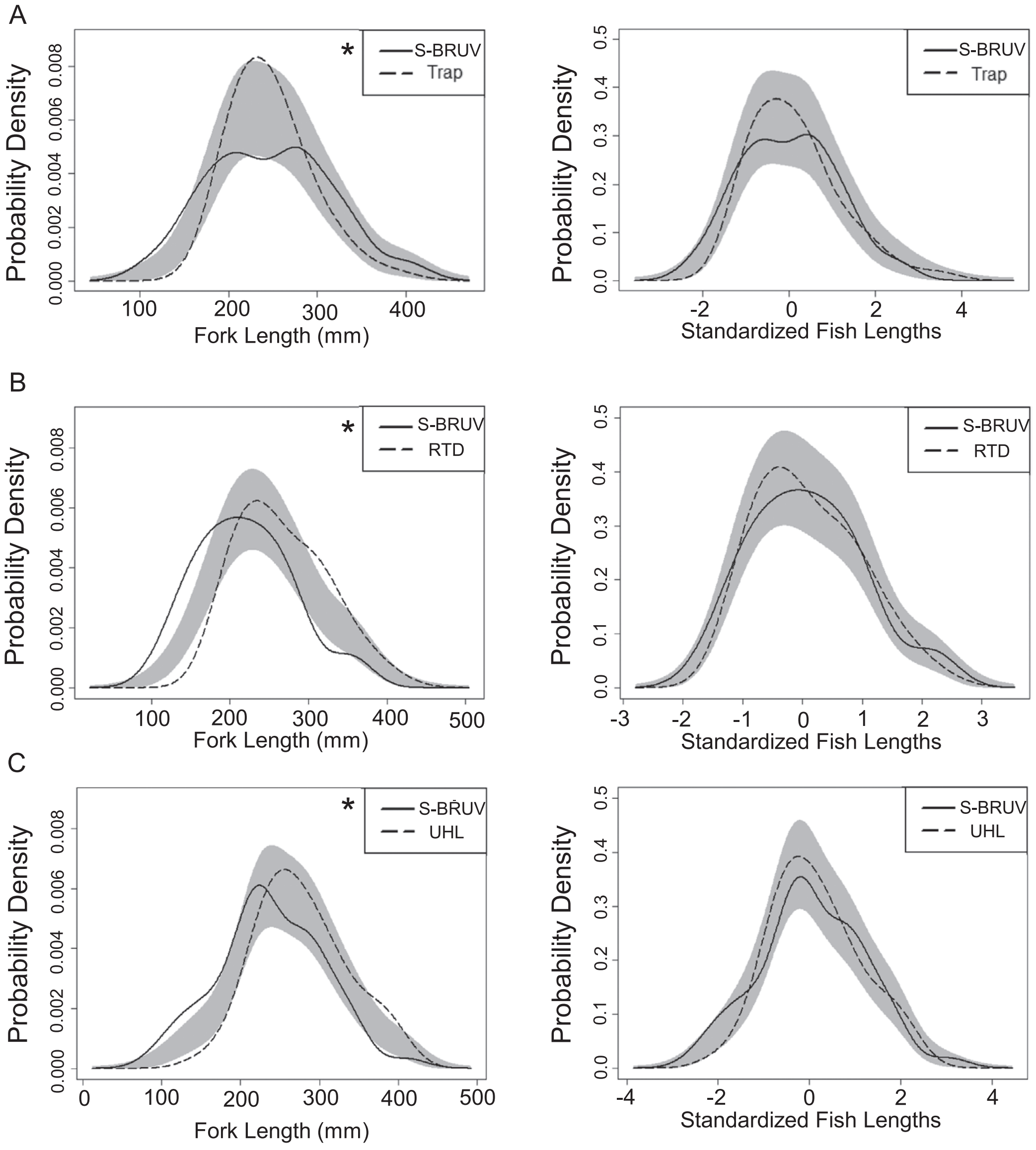

Fig. 9. Comparison of kernel density estimate (KDE) probability density functions for vermilion snapper sampled using A) repetitive timed-drop (RTD), or B) unstandardized hook and line (UHL) with stereo-baited underwater remote video cameras (S-BRUV). Grey bands represent ± 1 SE about the null model. Analyses of raw data (left column) provide a test of differences in both location and shape of the length-frequency distributions, whereas analyses of standardized data (right column) provide a test of shape only. An asterisk indicates significant differences between the two distributions ($p < 0.05$).

contribution to the assessment. Because of the potential implications of the selectivity function implemented, a special workgroup (South Atlantic Fisheries Management Council) was convened in advance of the recent red snapper assessment and charged with examining issues pertaining to selectivity in the South Atlantic (South Atlantic Selectivity Workgroup, 2020). Based on results of this study and ancillary information, it was recommended by the workgroup to modify the selectivity function for the chevron trap survey from flat topped to dome shaped in the assessment; however, further research is required to determine the degree of doming (South Atlantic Selectivity Workgroup, 2020). The evidence for dome-shaped selectivity for both red snapper and vermilion snapper in the current study is consistent with results of similar gears used in a wide range of habitats and depth strata in the Gulf of Mexico (Christiansen et al., 2020). Conversely, in a comparison of standard otter trawls, small fish traps, chevron traps, and stationary four-camera underwater video arrays collected over low-relief reef habitats Wells et al. (2008) found the largest red snapper were captured in chevron traps (150–440 mm TL), although Wells et al. (2008) were focused primarily on subadults (a size that our results indicated were in fact fully selected for). Differences in the size range captured by individual gears between these two studies likely reflect the availability of the fish and habitats sampled rather than differences in selectivity of similar gears. These results highlight the importance of regional, multi-habitat, and gear specific selectivity studies to accurately reflect trends for each stock.

Tests of location of the length distributions were significantly different for all three reef fish species sampled by chevron traps, RTD, and UHL when compared to S-BRUV in this study, similar to the differences described between sampling gears in the length distribution of several reef fish species off the coast of north western Australia (Langlois et al., 2015). However, in the current study, patterns in the shape of the selectivity curve differed among species; black sea bass exhibited more of a flat-topped selectivity pattern for all three capture gears tested, while dome-shaped selectivity patterns were observed for red snapper and vermilion snapper. For several species (e.g., red snapper, vermilion snapper, red grouper (*Epinephelus morio*), the trap/video data are combined into one index for stock assessments based on the assumption of a shared flat-topped selectivity (SEDAR, 2020, 2018a, 2018b, 2017b, 2010). If the shape of the selectivity curve for an individual survey differs, as in the case of red snapper, it may no longer be appropriate to combine the two surveys into one index (SEDAR, 2021). Because of these factors, efforts to further evaluate selectivity for other reef fish species (e.g., scamp, red grouper, gag, red porgy) and gears are critical.

Based on these observed patterns of selectivity, it appears that standardized fishery-independent hooked-gear surveys developed by

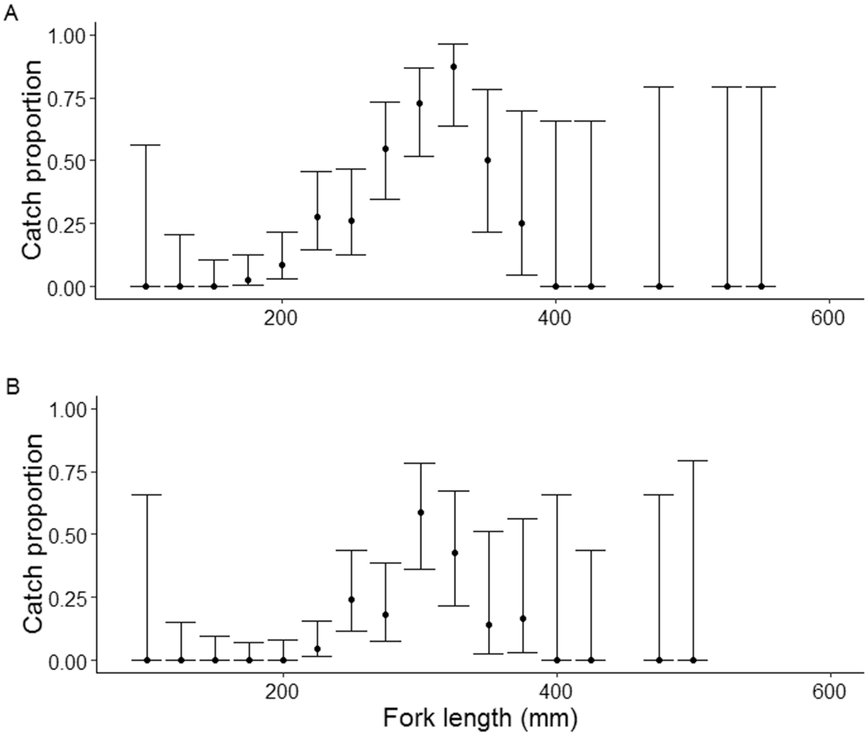

Fig. 10. Relative selectivity for vermilion snapper of A) repetitive timed-drop, and B) unstandardized hook and line, each relative to S-BRUV. Error bars are 90% confidence intervals.

the FWC-FWRI may complement the SERFS chevron trap survey by providing data for larger, older individuals, especially for red snapper. Red snapper caught by hooked gears had the largest mean FL, indicating the potential of standardized hooked gears to effectively sample larger potentially older fish than chevron traps which have traditionally been used to assess reef fish populations in the U.S. South Atlantic. This similar pattern of hooked gears capturing larger fish on average compared to other fishery- independent gears has previously been described for vermilion snapper and red snapper caught in the Gulf of Mexico (Campbell et al., 2014; Christiansen et al., 2020; Garner et al., 2014). Multiple hook sizes used in these studies and the current study allowed for a broad size range of red snapper to be collected as the median size at full selectivity of red snapper increased with increasing hook size. The mean length of vermilion snapper was largest when captured using hooked gears; however, there were not enough individual vermilion snapper captured by either hooked gear to analyze the catch of each hook size separately. Previous studies have shown there may be mouth gape limitations for vermilion snapper when larger hooks are used (Campbell et al., 2014; Patterson et al., 2012). The low number of vermilion snapper captured by hooked gears in the current study may therefore be related to the size of hook used, as both the RTD and UHL surveys were designed to maximize catches of red snapper, which is a generally larger species. Further research is required to examine the potential effects of hook size on catch rates of the different commercially important reef fish in the U.S. South Atlantic.

Although KDEs probability density function estimates account for differences in sample size (Bowman and Azzalini, 1997), results of analyses with exceptionally low sample sizes (black sea bass observed on S-BRUV, vermilion snapper captured in traps) should be interpreted cautiously, as they will have reduced sensitivity to differences in the shape of length distributions (Bowman and Azzalini, 1997; Langlois et al., 2015). Similar to the current study, Bacheler et al. (2013) found that black sea bass had the highest rates of occurrence in traps while not being observed by the corresponding S-BRUV, whereas vermilion snapper had the second highest rate of being absent in traps but present on the S-BRUV. Incidents of low sample size do not appear to be artifacts of the current study but rather aspects of how species-specific swimming and foraging behavior appear to influence the susceptibility of a species to a gear. The S-BRUV records only a portion of the trap deployment so fish may potentially enter the trap outside of the video recording period (Watson et al., 2010). While general characteristics of each species are known, further research is recommended to investigate species-specific behaviors when encountering a gear. Additionally, environmental conditions such as current directions, water temperatures, attached biota, and water clarity have also been shown to affect the detectability of black sea bass and vermilion snapper (Bacheler et al., 2014). Although environmental variables were not explicitly examined in this study, some of these variables, such as visibility, were measured and all videos were within an acceptable range, indicating there was likely a minimal effect of visibility on detectability.

In the present study, we acknowledge there may be some selectivity occurring for the S-BRUVs, however it was assumed that this was the least selective gear type deployed in this study and that for inter-gear comparison sake the fish measured at each station by the S-BRUVs were representative of all size classes present at that station. Due to the calibration protocols each S-BRUV unit undergoes both pre- and post-sampling season there is high confidence in the accuracy of the measurements obtained. Previously, a size bias due to time of measurement was found in the Great Barrier Reef Marine Park, where fish measured in the first 15 min of deployment were found to be smaller than later in the deployment (Cappo et al., 2009). In the current study, measurements were obtained when the highest number of measurable fish were on screen, not at a specific time period in the video; therefore, it is unlikely that there was a bias due to time of measurement. Additionally, the S-BRUVs recorded the largest individuals in this study, showing the utility of this sampling gear to obtain the full-size range present at time of recording. If there is a bias present due to the time the measurement was recorded it would indicate that the S-BRUVs could potentially be underestimating the true mean length as the largest potentially solitary fish would not be included in the measurements. Although S-BRUVs have the potential to be a valuable long term reef fish assessment tool, this study demonstrates the utility of this gear to complement and evaluate the selectivity functions of standard fisheries assessment methods.

In summary, fishery-independent surveys allowed for the comparison of catch between multiple sampling gears to estimate the shape of the size selectivity curve. Understanding the selectivity curve of individual gear types provides important insight into the effectiveness of each gear type in describing the population. In this study, the size selectivity of reef fish varies with sampling gear and species. In general, S-BRUV had the widest sampling ranges, sampling the smallest and largest individuals for all three species and gear comparisons. Traps on average had a smaller mean sampling length, while hooked gears generally had a higher mean sampling length than S-BRUV. Using multiple gears allowed for the estimation of the shape of the selectivity curve, providing valuable information to be used in stock assessments. Making an incorrect assumption on the shape of the selectivity curve can have unintended consequences for a population and its fisheries recovery. This study reveals that the selectivity of traps, S-BRUV, and hooked gears differs for three economically and ecologically important reef fish, indicating that incorporating a multiple sampling gear approach would be valuable to the assessment of reef fishes in the U.S. South Atlantic.

CRediT authorship contribution statement

Heather Christiansen: Methodology, Formal analysis, Writing – original draft. **Justin Solomon:** Conceptualization, Funding acquisition, Investigation, Writing – original draft. **Theodore Switzer:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision. **Russell Brodie:** Project administration, Conceptualization, Funding acquisition, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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