Fisheries Research 196 (2017) 117–125

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Research Paper

Minimizing bycatch and improving efficiency in the commercial bottom longline fishery in the Eastern Gulf of Mexico

Daniel G. Foster[a,*], Jeffrey R. Pulver[b], Elizabeth Scott-Denton[b], Charles Bergmann[a]

[a] National Marine Fisheries Service, Mississippi Laboratories, 3209 Frederic St., Pascagoula, MS 39567, USA
[b] National Marine Fisheries Service, 4700 Avenue U, Galveston, TX 77551, USA

ARTICLE INFO

Handled by George A. Rose

Keywords:
Bottom longline
Red grouper
Shark
Hook timers
Capture times

ABSTRACT

We investigated the effects of hook soak time on targeted reef species and shark bycatch in the reef fish bottom longline fishery in the Gulf of Mexico. Beginning in 2010, capture time and catch per unit effort (CPUE) for the primary target species red grouper (*Epinephelus morio*) in the fishery were evaluated using hook timers. Findings indicated that typical duration of hook soak times is longer than necessary to efficiently harvest red grouper and a reduction in gear soak times to less than one hour would result in minimal or no reduction in red grouper CPUE. The mean capture time of sharks and red grouper differed significantly, suggesting that a reduction in soak time would likely reduce the bycatch of sharks in the fishery. The study also revealed barometric pressure, lunar phase, and fish size were significant covariates with red grouper capture times and that different bait types significantly affected CPUE. Implementing shorter hook soak times would likely improve fishery profitability and potentially reduce discards of unwanted species in the fishery.

1. Introduction

Bottom longlines have been the primary method of harvesting grouper in the Gulf of Mexico (GoM) since the early 1980's with a peak in total grouper landings of 5670 t in 1982 (Goodyear and Schirripa, 1993). The primary species targeted inshore of the 91 m (50 fathom) contour is red grouper (*Epinephelus morio*) but the incidental capture of other important reef fish species also occurs. Currently, there are approximately 62 permit holders with a reef fish bottom longline endorsement operating in the eastern Gulf of Mexico (SERO, 2016). In 2014, the GoM bottom longline fishery landed 1785 t of red grouper valued at 12.6 million dollars. The eastern GoM is not only an important fishing ground, but also critical habitat and foraging area for sea turtles (Schmid and Barichivich, 2005; Foley et al., 2014).

The management of the reef fish fishery has been regulated by area closures, quota systems, and size limits to enhance fish stock strength and reduce bycatch. The effectiveness of these measures has long been debated (Coleman et al., 2000; Nieland et al., 2007; Stephen and Harris, 2010). The management system for many of the species currently targeted in the fishery has shifted from a “derby” fleet-wide quota to an individual fishing quota within the past ten years. The individual fishing quota system annually distributes a transferrable allocation of the quota for each species category to shareholders in the fishery. The shareholders can then assign a portion or all of the allocated allowable catch to a fishing vessel in their fleet. Once a vessel's quota for a particular species is reached, another finfish species may become the target. The current management system does allow some flexibility between species categories to reduce discards if a vessel lacks the necessary allocation.

In 2006, the National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center (SEFSC) implemented a mandatory observer program to gain a greater understanding of catch rates, bycatch composition, and discard mortality associated with the U.S. Gulf of Mexico commercial reef fish fishery (Scott-Denton et al., 2011). Before the mandatory observer program, industry self-reporting through logbook and discard supplementary data submission was used to estimate landings and bycatch (inclusive of protected species).

The bycatch of both unwanted and undersized species, notably red grouper is of particular concern. The minimum size limit for red grouper was 50.8 cm in total length (TL); in 2009, the limit was reduced to 46 cm TL. Based on surface observations of discarded species in the bottom longline fishery (Scott-Denton et al., 2011), the majority of discards were released alive; however, 42% of the individuals displayed visual signs of barotrauma stress (air bladder expansion and/or eyes protruding). Of the individuals released alive, undersized red grouper, Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), smooth dogfish shark (*Mustelus canis*), and red snapper (*Lutjanus campechanus*), accounted for 83%.

* Corresponding author.
E-mail address: Daniel.G.Foster@noaa.gov (D.G. Foster).

http://dx.doi.org/10.1016/j.fishres.2017.08.007
Received 13 July 2016; Received in revised form 23 July 2017; Accepted 13 August 2017
0165-7836/ Published by Elsevier B.V.

Based on the documented takes of loggerhead sea turtles (*Caretta caretta*) during the first two years of the observer program, the estimated take in the fishery exceeded the authorized take level promulgated in the 2005 biological opinion and led to regulatory action. In May 2009, an emergency rule to protect sea turtles went into effect prohibiting the use of bottom longline gear east of Cape San Blas, Fla., shoreward of the 91 m (50 fathom) contour (US Department of Commerce, 2009a). These time and area closures were intended to reduce the spatial and temporal overlap of fishing effort and sea turtles when turtles were on the summer foraging grounds.

Subsequent regulations in 2010 restricted bottom longline gear east of Cape San Blas, Fla., shoreward of the 64 m (35 fathom) contour from June through August, limited the number of hooks onboard to 1000, of which only 750 could be rigged for fishing, and reduced the number of vessels through an endorsement system based on documentation of an average annual landing of at least 18.14 t during 1999 through 2007 (US Department of Commerce, 2010). The hook number restriction was intended to minimize the amount of time needed to set and haul the gear, thus limiting the mean hook soak time and decreasing the likelihood that sea turtles will drown if captured. However, little is known about the capture process of the targeted reef fish or bycatch species and what potential affect the reduced soak times may have had.

As with many reef fish species, groupers are sedentary, opportunistic feeders that lie in wait and ambush their prey (Thompson and Munro, 1978). In contrast, sharks are roving foragers with large home ranges. While exhibiting varying degrees of philopatry, foraging ranges commonly include areas of hundreds of square kilometers (Hueter et al., 2005). In addition, the fishing power or catch efficiency of bottom longline gear changes over time due to several factors including bait loss and target or bycatch species occupying hooks (Shomura, 1955; Shepard et al., 1975; Skud and Hamley, 1978; Løkkeborg, 1994; He, 1996). These studies indicate that the rate of bait loss over time is influenced by bait type and baiting technique, with firm bait such as squid (*Loliginidae*) being less likely to be torn or fall from hooks compared to soft fish baits such as mackerel (*Scomber spp*.). Bait is often removed by scavengers such as smaller fish that occasionally become hooked and in turn, become bait themselves.

The objective of this study was to use hook timers to characterize the time it takes for target and bycatch species to become hooked after the gear reaches the bottom. In this study, capture times were compared for animals with differing foraging strategies to assess the potential effects of reducing hook soak times on CPUE. The effects of environmental parameters and bait type on red grouper catch rates and capture times were also evaluated.

2. Materials and methods

2.1. Data collected in the study

Beginning in September 2010, experimental data were collected by fishery observers on contracted commercial bottom longline vessels equipped with hook timers (Table 1). Data were collected in two fishing periods from September to December 2010 and January to May 2013 to distribute effort across the calendar year. Summer months (June to August) were excluded due to seasonal restrictions in place to limit sea turtle interaction in the fishery. Fishery observers collected data consistent with the mandatory reef fish observer program in addition to specific supplementary hook timer experimental information (NMFS, 2015). Scott-Denton et al. (2011) and Scott-Denton and Williams (2013) provide detailed descriptions of the protocol on data collection for the reef fish observer program. Prior to the initiation of the experiment, the variables of interest that may affect capture times were determined with input from industry and collaboration with other researchers. Table 2 provides a summary and brief description of the covariates examined for their influence on capture times for both phases of the study.

Table 1
Summary information including the number of unique vessels, fishing trips, fishing sets, total number of hooks, and total number of hook timers deployed for each fishing period of the study.

Fishing Period	September–December 2010	January–May 2013
Number of Vessels	3	1
Fishing Trips	9	5
Fishing Sets Observed	216	147
Total Number of Hooks Set	145,674	96,016
Total Number of Hook Timers Deployed	28,608	19,106

Sets were deployed between dawn and dusk. Prior to each set, the barometric pressure and pressure trend were recorded from a Cole-Palmer, model WU-90080-02 barometer (accuracy ± 12 mbar). The barometer displayed pressure readings from the previous 12 h as a histogram. The pressure trend was interpreted by the observer as Falling, Rising, or Stable. During set deployment, hook timers (HT 600, Lindgrin Pittman Inc.) were distributed evenly across the set on every fifth or sixth hook (Fig. 1). Section markers were placed on the mainline every tenth hook timer to demarcate the gear into sections. Up to four Temperature/Depth Recorders (TDR) (LAT 1400, Lotek Wireless Inc.) were randomly placed along the line to record temperature and depth at one-minute intervals and provide an estimate of the average time needed for the gear to reach the bottom (sink time). Deployment times (time of day) were recorded for each section marker. Due to the rapid deployment rate of hooks, all hook timers within a section were assigned the mean deployment time for that section, i.e. the mean deployment time of the two adjacent section markers. Section deployments took up to four minutes; therefore using the mean section deployment time as an estimate for individual hook deployment times was accurate to +/− two minutes.

When fish were boarded on gangions with hook timers, the observer recorded the boarding time (time of day) and elapsed time from the hook timer. The capture time was calculated as follows;

$$\text{Capture Time} = \text{Boarding Time} - \text{Elapsed Time} - \text{Sink Time} - \text{Mean Section Deployment Time} \quad (1)$$

Because of using the mean section deployment time (instead of individual hook deployment times) in the capture time calculation, results were on occasion slightly negative when fish activated the timer immediately upon reaching the bottom. When the negative capture times occurred, the times were rounded up to zero min. Approximately 7% of the fish were either too small to activate hook timers or activated timers during haulback (i.e. elapsed times < 5 min) and therefore were not included in the capture time analyses. The fork length of red grouper was measured and converted to total length using the regression: TL = 1.05 * FL – 5.95, where TL is total length and FL is fork length, both in cm (SEDAR, 2009).

2.2. Statistical analyses

Analyses concentrated on drawing inferences for the two different metrics of capture times as a quantile or mean and catch per unit effort (CPUE) for evaluating efficiency in the fishery. For each major species group and the common individual species, 95% confidence intervals of the quantiles (0.5, 0.9, and 0.95) for capture times were generated by bootstrapping with 10,000 iterations. Bootstrapping was used because the capture times were not distributed normally and many subsets of the data had a limited amount of observations available. Different potential management scenarios for reducing soak time could then be compared by evaluating these results. Next, the available covariates were examined for their influence on mean capture times for red grouper and sharks. The final set of analyses examined the CPUE of red

Table 2
Summary information for each variable with a brief description including either the range and mean during the study for continuous variables or the number of hook timer captures observed for each categorical variable level.

Variables	Description	Observations
Capture Time	Time between gear reaching bottom and the fish biting the hook	Range: 0–134 min, Mean: 21.3 min
Fishing Period	Period 1: September–December 2010, Period II: January–May 2013	Period I: 1897, Period II 1284
Depth	Bottom Depth (m)	Range: 36.6–52.3 m, Mean: 44.4 m
Temperature	Bottom Temperature (C°)	Range: 17.6–26.1C°, Mean: 20.4C°
Barometric Pressure	Barometric pressure at the start of the fishing set (mb)	Range: 1007–1031 mb, Mean: 1022 mb
Barometric Trend	12-h barometric trend F, R, S (Falling, Rising, Stable)	F: 575, R: 546, S: 2060
Length	Fork or total length in mm depending on species	Range: 270–1445 mm, Mean: 499 mm
Lunar Phase	Lunar Phase: New, Waxing, Full, Waning	New: 1105, Waxing: 777 Full: 735 Waning: 564

grouper, number of fish per hook set, for potential influences on catch rates. Basic summary information such as histograms, cumulative distribution plots, and tables of mean capture times were assembled for each of the species and groups. All statistical analyses in the study were performed in R version 3.2.2 (R Development Core Team, 2015).

2.2.1. Capture times

In the first analysis, the available covariates recorded during the project were examined for their influence on mean red grouper capture time. Initial data exploration using histograms indicated a right-skewed distribution of capture times suggesting a gamma distribution. Therefore, a generalized linear model (GLM) with a gamma distribution and log link was used to assess the covariates for significance. One minute was added to the capture times to fit the model because the gamma distribution requires only positive values in the response and then the predicted fits were corrected to the actual capture time by subtracting one minute. The model fitting process used stepwise backwards regression testing for significance ($P < 0.05$) with a type II ANOVA with the χ^2 distribution to remove the least significant variable at each iteration. The assumptions of normality and homoscedasticity were examined by plotting the deviance residuals from the model and included as supplementary data. Model significance was determined using the difference in deviances and degrees of freedom between the final and an intercept-only model to calculate the probability under a right-tailed χ^2 distribution.

The next analysis determined if a significant difference between the mean capture times of red grouper and shark species was present while controlling for the significant covariates. All shark species captured in the experiment were aggregated into a grouped shark category due to the limited number of captures observed. As with the previous analysis, one minute was added to capture times for both groups to meet the gamma distributional requirements and a GLM was fit comparing the two groups using the same previous covariates except length. The model fitting process, a test of model significance, and assumptions were performed in a similar manner as the previous model. The predicted capture times for both GLMs were fit using the most common factor for categorical variables and the median for continuous variables.

2.2.2. CPUE

The final set of analyses examined other factors present that may affect the CPUE of red grouper. To evaluate the influence of hook timers on catch rates, the number of red grouper captured per hook with or without timers was used to calculate CPUE for individual fishing sets. A one-way ANOVA was used to test for significance ($P < 0.05$) and modeled using different variances for each factor level to correct for heteroscedasticity indicated by diagnostic plots. Model improvement was confirmed using the corrected Akaike Information Criterion (AICc; Burnham and Anderson, 2002) and by visually diagnosing the plots for improvements in homoscedasticity of residuals. The final analyses examined the four different bait types commonly used in the fishery, squid (*Loliginidae*), herring (*Clupeidae*), skate (*Rajidae*), and ladyfish (*Elops saurus*) heads, for their influence on catch rates. Bait type information was only collected for the second phase of the experiment beginning in January 2013 at industry's request. Industry representatives believed that catch rates for red grouper could be affected by bait type potentially reducing bycatch of undersized target species. For both undersized and legal red grouper, a one-way ANOVA was used to test for significant ($P < 0.05$) differences in CPUE and modeled

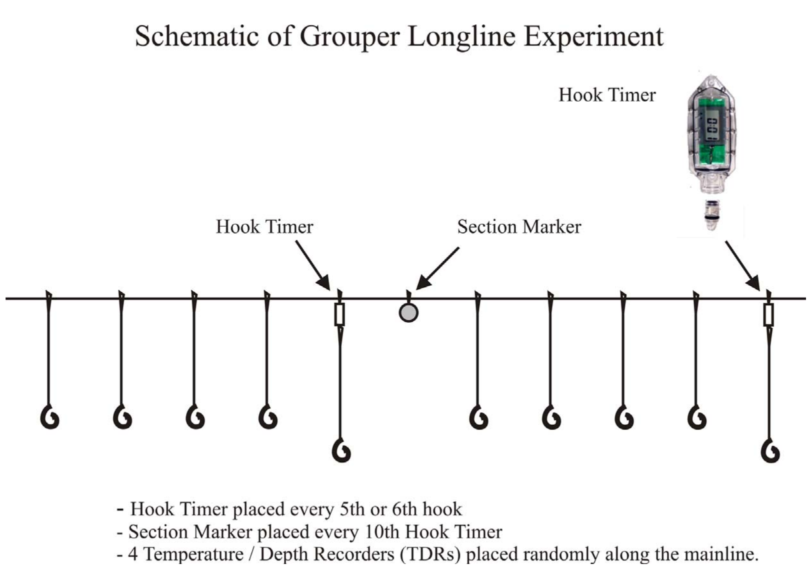

Fig. 1. Schematic of grouper bottom longline hook timer experiment.

using different variances for each factor level to correct for heteroscedasticity indicated by diagnostic plots. Model improvement was confirmed using AICc and by visually diagnosing the plots for improvements in homoscedasticity of residuals. Unplanned pairwise comparisons between the bait types for each ANOVA were tested using Westfall's stepwise extension of the Tukey test to correct for multiple testing (Westfall, 1997).

3. Results

During the study, three commercial longline vessels conducted 363 sets, deploying an average of 665 circle hooks per set (size range = 12/0–14/0). Vessels typically deployed four fishing sets per day, weather permitting, but not all sets were sampled for this project due to time constraints placed on the observers. Vessels deployed hooks at an average of 15 hooks per minute with an overall mean of 44.8 min deployment time. At the depth range of the study (37–52 m), it took approximately two minutes for the gear to sink to the bottom. After deployment, gear soaked for an average of 34.8 min before hauling commenced. The gear was hauled at an average rate of 10.2 hooks per minute, taking an average of 66.5 min to haul. The entire process took an average of 146 min to complete, with a mean hook soak time of 90.5 min. On approximately 50% of the sets, gear was hauled in the reverse order from which it was set, i.e. the last hook deployed was the first hook hauled. For reverse hauls, the first hooks deployed soaked during the entire set and hauling process, with the maximum hook soak time averaging 134 min. For standard hauls, the first hook set was the first hook retrieved; the maximum hook soak time averaged 93.4 min.

For the 47,714 hooks deployed with hook timers, 3181 captures were observed with red grouper being the most common species (90%), accounting for 2865 of the captures (Table 3). Four loggerhead turtles were caught and released alive during the study, but none were caught on hooks with timers. A total of 115 individual sharks were captured on hook timers with Atlantic sharpnose shark being the most common species observed (64%), with 74 captures. In addition to red grouper and shark species, 23 other non-target species were observed captured on hook timers in the study. The majority (77%) were other grouper (*Mycteroperca* spp.) or snapper (*Lutjanus spp*.). These species had a similar mean capture time of 24.3 min with a standard error of the mean (SEM) of 1.69 when compared to red grouper with a mean time of 20.4 min (SEM = 0.37). The red grouper mean capture was 47% less than the aggregated shark mean capture time of 38.6 min (SEM = 2.22). The frequency distribution of red grouper and red snapper capture times were both positively skewed to the left while shark capture times were more evenly distributed (Fig. 2). Greater than 60% of the total number of captured red grouper occurred within 20 min while only approximately 20% of the total shark captures occurred with the first 20 min (Fig. 3). Shark capture rate exhibited a more linear relationship, evident in the subplot of Fig. 3 that has the capture times truncated at 63 min to represent when > 95% of the red grouper were captured. By comparing bootstrapped confidence intervals, larger legal-sized red grouper had longer capture times compared to undersized red grouper for each quantile with only a slight overlap of confidence intervals (Table 4). For the two most common reef fish species, similar capture times were observed with 90% of the red grouper captured in ≤46 min and 90% of red snapper, captured in ≤56 min. For shark capture times, 90% of captures observed were ≤68 min, and Atlantic sharpnose sharks had shorter capture times than blacknose sharks (*Carcharhinus acronotus*) at each quantile. A comparison of the quantiles for capture times indicates that soak times

Table 3
Total number captured, hook timer captures used in the analysis, and mean capture time for each species with at least one capture on gangions with hook timers.

Group	Common Name	Scientific Name	Frequency Observed	Hook Timer Frequency Analyzed	Mean Capture Time (min)
Red Grouper	Red Grouper	*Epinephelus morio*	13,305	2865	20.4
Sharks	Atlantic Sharpnose Shark	*Rhizoprionodon terraenovae*	321	74	35.6
	Blacknose Shark	*Carcharhinus acronotus*	104	25	43.6
	Tiger Shark	*Galeocerdo cuvier*	32	5	71.8
	Spinner Shark	*Carcharhinus brevipinna*	8	3	48.3
	Grouped Sharks	General sharks	32	2	19.5
	Scalloped Hammerhead Shark	*Sphyrna lewini*	4	2	41.5
	Silky Shark	*Carcharhinus falciformis*	5	1	0.0
	Blacktip Shark	*Carcharhinus limbatus*	17	1	40.0
	Nurse Shark	*Ginglymostoma cirratum*	5	1	28.0
	Bonnethead Shark	*Sphyrna tiburo*	11	1	6.0
		Group Total	**539**	**115**	**38.6**
Misc. Species	Red Snapper	*Lutjanus campechanus*	478	129	23.2
	Lane Snapper	*Lutjanus synagris*	28	8	12.5
	Gag Grouper	*Mycteroperca microlepis*	48	7	23.9
	Gray Snapper	*Lutjanus griseus*	19	6	30.3
	Clearnose Skate	*Raja eglanteria*	14	6	15.0
	Inshore Lizardfish	*Synodus foetens*	16	6	19.5
	Jolthead Porgy	*Calamus bajonado*	15	4	15.5
	Sharksucker	*Echeneis naucrates*	32	4	50.3
	Cobia	*Rachycentron canadum*	15	4	37.5
	Great Barracuda	*Sphyraena barracuda*	24	4	32.0
	Sand Diver	*Synodus internedius*	30	4	42.3
	Scamp Grouper	*Mycteroperca phenax*	13	3	14.3
	Banded Rudderfish	*Seriola zonata*	24	3	10.7
	Mutton Snapper	*Lutjanus analis*	5	2	22.5
	Red Porgy	*Pagrus pagrus*	7	2	50.5
	Greater Amberjack	*Seriola dumerili*	9	2	67.0
	Knobbed Porgy	*Calamus nodosus*	2	1	47.0
	Littlehead Porgy	*Calamus proridens*	3	1	3.0
	Bank Seabass	*Centropristis ocyurus*	5	1	6.0
	Southern Stingray	*Dasyatis americana*	1	1	95.0
	Little Tunny	*Euthynnus alletteratus*	13	1	12.0
	Leopard Toadfish	*Opsanus pardus*	13	1	0.0
	King Mackerel	*Scomberomorus cavalla*	3	1	8.0
		Group Total	**817**	**201**	**24.3**

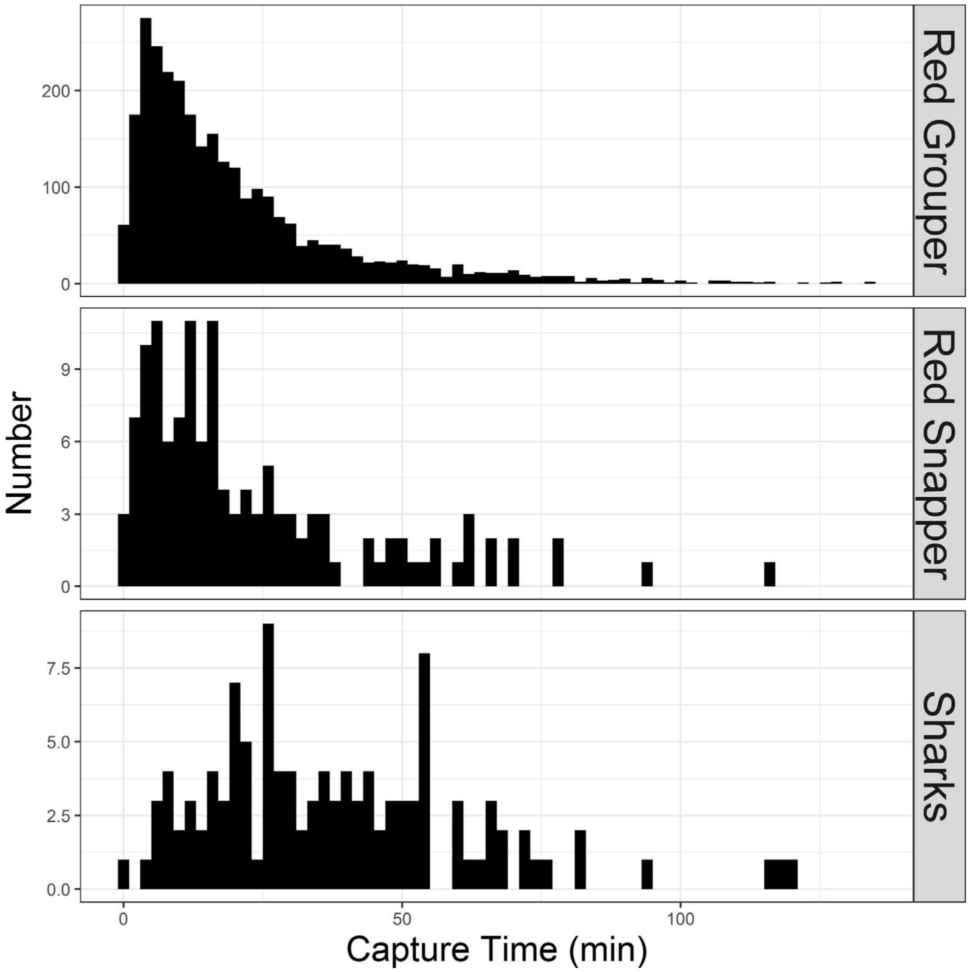

Fig. 2. Histograms of the observed frequency (number) of capture times for the three major species groups observed in the study.

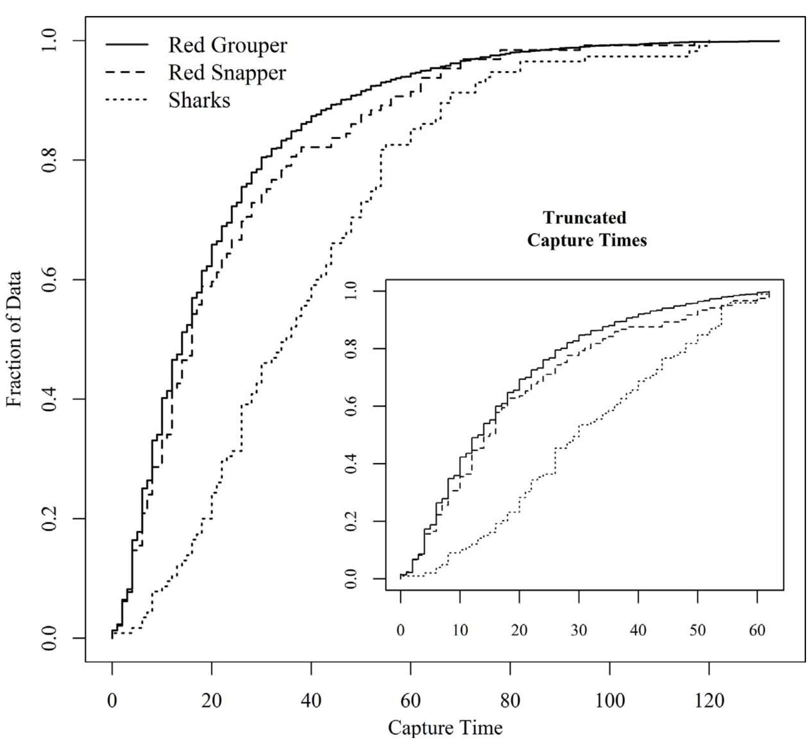

Fig. 3. The empirical cumulative distribution function of capture times with a subplot for truncated capture times at 63 min for the three species groups in the study.

Table 4
Quantiles of capture times in minutes for major species groups captured in the study with 95% bootstrapped confidence intervals in parentheses.

Species Group	Min	≤50%	≤90%	≤95%	Max
All Red Grouper	0	14 (14–15)	46 (44–50)	63 (60–67)	134.
Red Grouper < 46 cm TL	0	12 (12–14)	42 (38–46)	57 (51.3–62.6)	134
Red Grouper ≥46 cm TL	0	16 (14–16)	50 (46–52)	66 (61.5–70)	134
Red Snapper	0	16 (12–18)	56 (44.8–66)	66 (56–78)	117
Aggregated Sharks	0	35.5 (28–40)	67.4 (58–76)	78.1 (66.6–116)	120
Atlantic Sharpnose Shark	6	30 (26–40)	64.1 (54–73)	73 (60.7–82)	95
Blacknose Shark	8	39 (26–50)	75.6 (50–118.4)	109.2 (54–120)	120

Table 5
The type II ANOVA results for variables with the likelihood ratio (LR) test-statistic, degrees of freedom (Df), and p-value based on the χ^2 distribution reported. Significant variables are denoted by an asterisk and insignificant variables are numbered in the order they were removed using stepwise backwards regression.

Significant Variables	LR statistic	Df	*P*-value
Barometric Pressure	4.8508	1	0.0276*
Length	21.6266	1	< 0.0001*
Lunar Phase	22.2261	3	< 0.0001*
1. Fishing Period	0.0471	1	0.8281
2. Temperature	0.6029	1	0.4375
3. Depth	0.5055	1	0.4771
4. Barometric Trend	1.8804	2	0.3905

≤46 min would have captured 90% of the red grouper while only capturing 67% of the sharks observed in this study.

The first GLM analysis comparing all the variables recorded in the experiment on red grouper capture times revealed that fish length, barometric pressure, and lunar phase were the only significant variables remaining in the final model after stepwise backwards regression removed variables (Table 5). The effect of length and lunar phase on capture time were highly significant ($P < 0.0001$), and barometric pressure was significant with a *P*-value = 0.0276. The diagnostic plots indicated an acceptable fit and overall the model was significant (Figure A.1 in Supplementary materials). Positive increases in capture times were predicted by the GLM corresponding with higher barometric pressure and increases in red grouper fork length (Fig. 4). The contrasts for lunar phase were fixed using the new moon phase as the reference level. The shortest capture times were predicted to occur during the new and full moon lunar phases with significantly longer capture times for the waxing and waning lunar phases compared to the new moon (Table 6). The final model comparing red grouper and shark capture times revealed significant differences between the groups controlling for barometric pressure and lunar phase as significant covariates (Table A.1 in Supplementary materials). The model comparing red grouper and shark capture times also had an acceptable fit and was overall highly significant (Figure A.2 in Supplementary materials). Barometric pressure was significant with a p-value of 0.0137, followed by lunar phase at 0.0003, and the mean difference between red grouper and sharks with a p-value < 0.0001 (Table A.1 in Supplementary materials). Both groups showed the same previous trends with longer capture times predicted from higher barometric pressure and a similar pattern in lunar phase capture times (Fig. 4). Based on the GLM regression coefficient comparing the groups, sharks had a mean capture time approximately 1.8 times longer than red grouper. Despite the large difference in observations between the groups, the significantly longer mean capture time predicted for aggregated shark species was evident when comparing the different confidence intervals (Fig. 4).

The presence of hook timers on the gear had a marginally significant ($P = 0.0424$) positive influence on red grouper CPUE increasing the estimate by 0.0054 fish per hook (Table A.2 in Supplementary materials; Fig. 5). The estimate equates to an overall mean CPUE increase of 9.8% for hooks equipped with timers versus those without timers. The CPUEs for hooks without timers had a standard deviation ~38% smaller than hooks with timers, which may be because there were five to six times more hooks set without timers. However, the model still detected a positive influence on catch rates for hook timers despite the different variances. For the second phase of the experiment, significant differences in red grouper CPUE were detected between the majorities of bait types (Tables A.3–A.4 in Supplementary materials; Fig. 5). For the undersized red grouper, squid had significantly higher CPUE compared to the other three bait types and herring had significantly higher CPUE compared to skate and ladyfish heads. For legal-sized red grouper, the three bait types of squid, herring, and ladyfish heads all had significantly higher CPUE than skate, but there was no significant difference between the three types.

4. Discussion

During this study, the average hook soak time of 90 min was almost double the amount of time needed to harvest red grouper, with 90% taking the hooks within 46 min of being deployed. The fact that the majority of reef fish species are sedentary with distinct territories suggests that they are most likely to be susceptible to capture when the home ranges are transected by the bottom longline. When a baited hook falls into the groupers home range, grouper can quickly detect the presence of the bait. The quick detection of bait is evident by the short capture times of red grouper, with the majority of captures occurring within the first 16 min after the bait reached the bottom.

The rate of hook occupation is influenced by fish densities, distribution, and foraging behavior. Factors that affect the home range of reef fish include resource availability, competitor density, and body size (Hixon, 1987; Grant, 1997). Smaller fish have smaller home ranges and the reduced ranges may explain the results of this research relating to grouper length and capture times. In this study, small red grouper exhibited significantly shorter capture times than did larger specimens. It is expected that reef fish with smaller home ranges (i.e. smaller fish) will likely locate the baited hook more quickly after the gear reaches the bottom, and therefore have shorter capture times.

With large roving foragers such as sharks, the likelihood of encountering the baited hooks or the bait scent plume is more a matter of chance. In these cases, longlines set perpendicular to current may have increased catch rates due to the scent plume being dispersed over a larger area (Løkkeborg and Pina, 1997). As expected, the distribution of capture times for sharks was less skewed (i.e. more linear) as compared to reef fish capture times suggesting a linear relationship between soak time and shark catches. Morgan and Carlson (2010) demonstrated that bottom longline gear will continue to catch sharks for a much longer duration than is typically deployed in the reef fish fishery. They found that the highest shark catch rates were observed between 5 and 12 h after the gear was deployed. The differing distributions between sharks and red grouper suggest that shorter soak times could potentially reduce shark captures at a higher proportion than red grouper.

Results from our study show that environmental factors can affect how quickly red grouper locate the bait and become hooked. The model for red grouper was able to detect a positive correlation between barometric pressures and capture times. The model also detected a significant lunar effect, with the shortest capture times predicted to occur during the new and full moon lunar phases. It is not clear how environmental factors affect capture times, but these factors may affect how aggressively red grouper patrol their home ranges. Guy et al. (1992) reported that activity level in black crappie (*Pomoxis nigromaculatus*) was positively correlated with barometric pressure and

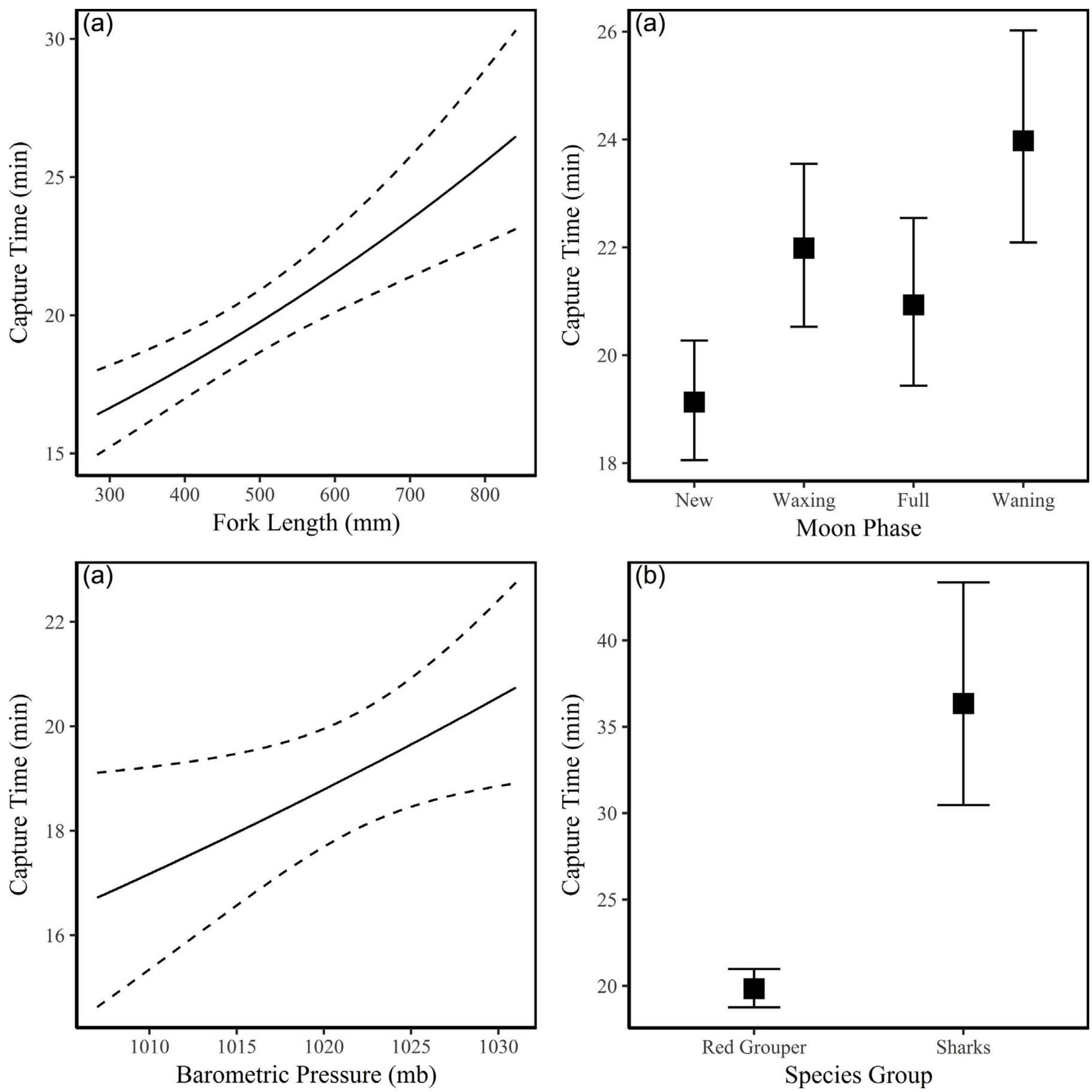

Fig. 4. The predicted mean capture times with 95% confidence intervals from the generalized linear model for (a) significant variables that influenced red grouper, and (b) the difference between red grouper and sharks. All predicted capture times use the median for continuous variables and the most common factor for categorical variables for reference.

Table 6
The output for the final generalized linear model for the covariates affecting red grouper capture times. The final model had a *P*-value of < 0.0001 using the χ^2 distribution with on the difference between the null deviance of 2177.0 with 2845 Df and a residual deviance of 2138.5 with 2840 Df.

Parameter	Estimate	Standard Error	T-value	*P*-value
(Intercept)	−6.6290	4.1833	−1.5846	0.1132
Barometric Pressure (mb)	0.0090	0.0041	2.1915	0.0285
Length (mm)	0.0009	0.0002	4.7655	< 0.0001
Lunar Waxing	0.1390	0.0454	3.0609	0.0022
Lunar Full	0.0900	0.0479	1.8780	0.0605
Lunar Waning	0.2257	0.0508	4.4458	< 0.0001

not water temperature, water transparency, cloud cover, wind direction, wind speed or precipitation. We were unable to determine if the effect we observed was a product of barometric pressure changes or other environmental factors that are associated with pressure changes, such as changes in cloud cover (i.e. changes in illumination), wind or turbulence. There have been no controlled feeding ecology experiments conducted to distinguish the effects of these concurrent factors (Stoner, 2004). The effect of lunar phase is in agreement with a study conducted by Vinson and Angradi (2014) who concluded that catch rates of Muskellunge (*Esox masquinongy*) were highest during full and new moons. While the current study differed in that capture times were evaluated rather than catch rates, it is reasonable to expect that periods of increased catch rates would also correspond to more aggressive feeding and would result in reduced capture times.

Another byproduct of this research is the analysis of the effect of bait type on the catch of legal and undersize red grouper. The effects of bait type on catch size are valuable for increasing the efficiency of fishers by potentially reducing bycatch of undersized target species. Of the bait types included in this study, ladyfish heads represent the best opportunity to minimize the bycatch of undersized red grouper while still maintaining high CPUE for legal size red grouper. Conversely, skate as a bait type had the lowest levels of CPUE observed for both undersized and legal red grouper; thus, fishers may benefit by reducing the use of skate in the fishery. The ladyfish heads were comparable in size to the other baits used during the study. However, in comparison to the other bait types, fish heads are composed of a hard bony structure that may offer resistance while being ingested. Johannes (1981) suggested that after ingesting the bait and hooks, circle hooks engage in the side

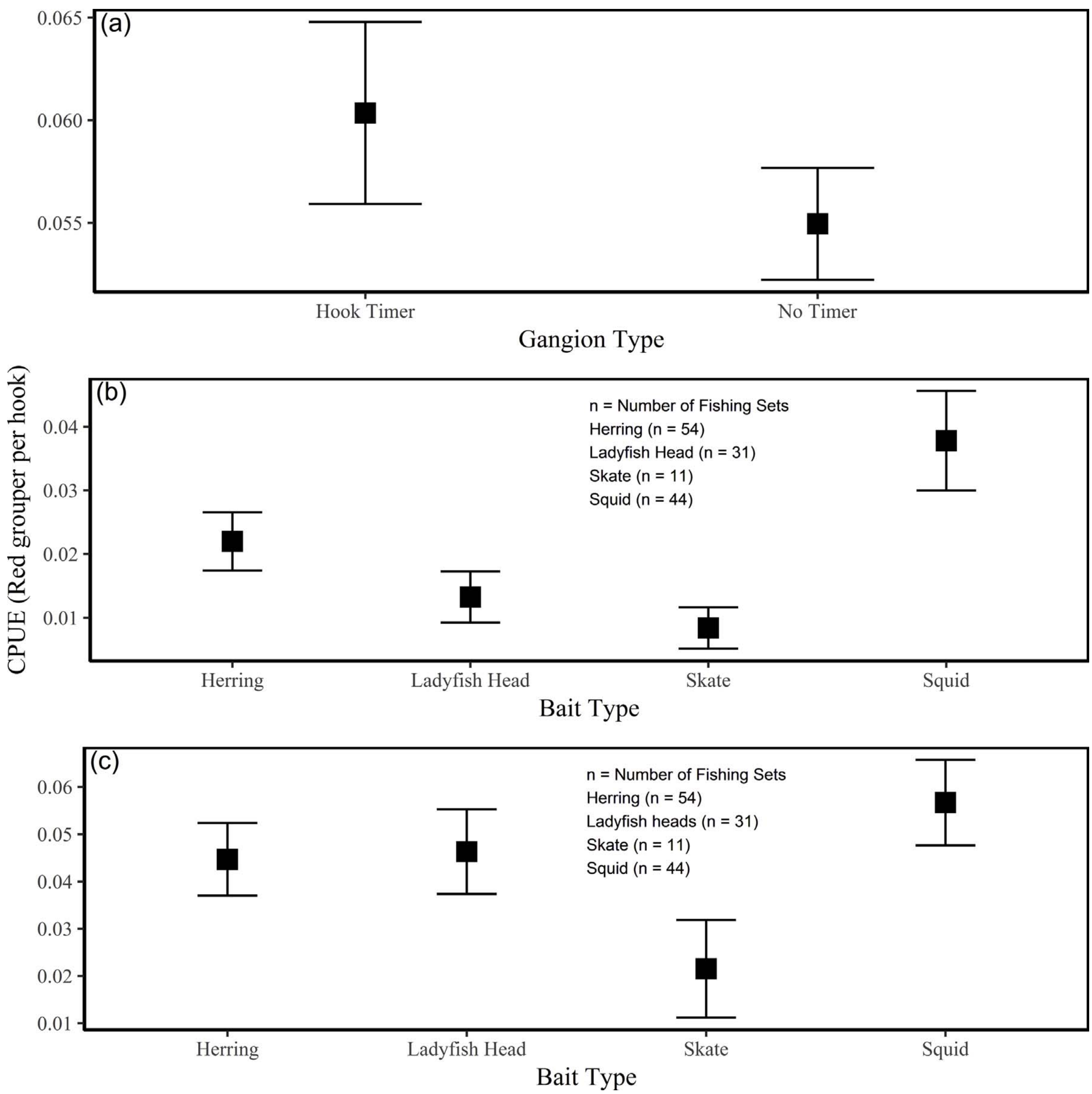

Fig. 5. The predicted mean CPUE with 95% confidence intervals comparing (a) gangions with and without hook timers, (b) four different bait types for undersized size red grouper, and (c) four different bait types for legal sized red grouper.

of the mouth as the fish swims away and pressure pulls the hook to the side of the mouth. It is possible that small red grouper have difficulty swallowing the hard bait and expel the bait prior to the hook becoming engaged in the jaw. One bait type suggested for future studies not included in this research is Atlantic mackerel (*Scomber scombrus*). Driggers et al. (2016) found almost all shark species encountered with bottom longline gear in the northern GoM preferred Atlantic mackerel compared to squid. In addition to the potential benefits of limiting soak time, eliminating the use of Atlantic mackerel in the fishery could minimize the bycatch of shark species.

One variable not standardized for this study that may have influenced catch length is hook size. Future research should include hook size since it could have had a confounding effect, especially on capture length. Brulé et al. (2015) comparing 11/0–13/0 hooks for red grouper caught off Mexico found no difference in mean catch rates, but the largest hook size (13/0) did catch larger sized fish than the smaller hooks. In addition, a significantly higher catch rate of red grouper on gangions with hook timers was observed as compared to ones without hook timers. It is possible that the size and reflectivity of the hook timers serve as a lure attracting fish towards the baited hooks. Another plausible explanation is that the addition of the hook timer increased the length of the gangion by approximately 50 cm.

In the bottom longline fishery, gear is commonly deployed in a semi-circular or U-shaped pattern in order to quickly traverse back to the beginning of the set for the start of the haul. Based on observer coverage, many fishers allow the gear to soak for additional time before hauling due to the misconception that the increased soak time will increase the catch rate. Results of this study show that in the time it takes to deploy the last hook of the set (mean = 45 min), the potential catch for the first part of the gear has already been realized with minimal gains in catch after the deployment ends. Therefore, there was little or no benefit when the gear soaked longer than the time needed to steam back to the beginning of the set and start the haul. For fishing sets hauled in reverse order, it is necessary to allow the last hooks to soak before hauling the gear to optimize the catch on the last part of the gear deployed. The reverse haul configuration results in excessive soaking for the first hooks deployed, which in our study averaged 134 min. Therefore, a reverse hauling practice should be avoided when possible.

Our findings suggest that it is unlikely that the regulatory maximum of 750 hooks placed on the fishery in 2010 has had a negative impact on the productivity of the fishery. On the contrary, a result of the rule is that fishers on average have been able to increase the number of sets deployed in a given day. Additional improvements in efficiency could be achieved by using standard hauling practice, as opposed to reverse hauling, which would eliminate the need to soak the gear between deployment and retrieval. The soak time reductions, in turn, will allow fishers to make additional sets per day, thus increasing the harvest of the target catch. The increase in efficiency should not threaten the health of red grouper stocks due to overfishing since the fishery operates with fixed allocations under an individual fishing quota system (US Department of Commerce, 2009b).

In conclusion, the results from this study present several scenarios that should be of interest to both fishers and managers in the region as well as other reef fish longline fisheries worldwide. A reduction in gear soak times to less than one hour would realize minimal, or no loss in red grouper CPUE based on this study but have the potential to significantly reduce shark bycatch in the fishery. A reduction in soak time could be accomplished by minimizing the time between hauling and setting the gear as well as minimizing the use of a reverse haul configuration. Since the fishery has fixed quota allocations, an increase in efficiency using these tactics, in addition to the results from the bait study, should improve fishery profitability and reduce the number of discarded sharks and undersized red grouper.

Acknowledgements

Funding for this project was provided by the National Marine Fisheries Service, Bycatch Reduction Engineering Program (BREP). We are grateful for the efforts of the owners, captains, and crews of the vessels participating in the experiment. We thank the NOAA Reef Fish Observer Program, especially Matt Duffy, Michael Hourihan, Sara Hutton, Andria Schurman, Brendan Turley, and Andrew Whatley. Additionally, we thank Glenn Parsons, John Mitchell, Chris Gledhill and Alex Chester for reviewing the manuscript. The National Marine Fisheries Service does not approve, recommend, or endorse any proprietary product or material mentioned in this publication.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2017.08.007.

References

Brulé, T., Montero-Munoz, J., Morales-Lopez, N., Mena-Loria, A., 2015. Influence of circle hook size on catch rate and size of red grouper in shallow waters of the Southern Gulf of Mexico. N. Am. J. Fish. Manag. 35, 1196–1208. http://dx.doi.org/10.1080/02755947.2015.1091409.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Interference: A Practical Information-theoretic Approach, 2nd ed. Springer-Verlag.

Coleman, F.C., Koenig, C.C., Huntsman, G.R., Musick, J.A., Eklund, A.M., McGovern, J.C., Sedberry, G.R., Chapman, R.W., Grimes, C.B., 2000. Long-lived reef fishes: the grouper-snapper complex. Fish 25, 14–21. http://dx.doi.org/10.1577/1548-8446(2000)025 < 0014:LRF > 2.0.

Driggers, W.B.I.I., Campbell, M.D., Hannan, K.M., Hoffmayer, E.R., Jones, C.M., Jones, L.M., Pollack, A.G., 2016. Influence of bait type on catch rates of predatory fish species on bottom longline gear in the northern Gulf of Mexico. Fish. Bull. 115, 50–59.

Foley, A.M., Schroeder, B.A., Hardy, R., MacPherson, S.L., Nicholas, M., 2014. Long-term behavior at foraging areas of adult female loggerhead sea turtles (Caretta caretta) from three Florida rookeries. Mar. Biol. 161, 1251–1262. http://dx.doi.org/10.1007/s00227-014-2415-9. (PMID:24882883).

Goodyear, C.P., Schirripa, M.J., 1993. The Red Grouper Fishery in the Gulf of Mexico. National Marine Fisheries Service, Southeast Fisheries Science Center, Miami Laboratory. Contribution No. MIA-92/93-75 (122 pp.).

Grant, J.W.A., 1997. Territoriality. In: Godin, J.-G.J. (Ed.), Behavioural Ecology of Teleost Fishes. Oxford University Press, Oxford, pp. 81–103.

Guy, C.S., Neumann, R.M., Willis, D.W., 1992. Movement patterns of adult black crappie, Pomoxis nigromaculatus, in Brant Lake, South Dakota. J. Freshw. Ecol. 7, 137–147. http://dx.doi.org/10.1080/02705060.1992.9664679.

He, P., 1996.. Bait loss from bottom-set longlines as determined by underwater observations and comparative fishing trials. Fish. Res. 27, 29–36. http://dx.doi.org/10.1016/0165-7836(96)00477-8.

Hixon, M.A., 1987. Territory area as a determinant of mating systems. Am. Zool. 27, 229–247. http://dx.doi.org/10.1093/icb/27.2.229.

Hueter, R.E., Heupel, M.R., Heist, E.J., Keeney, D.B., 2005. Evidence of philopatry in sharks and implications for the management of shark fisheries. J. Northwest Atl. Fish. Sci. 35, 239–247.

Johannes, R.E., 1981. Words of the Lagoon: Fishing and Marine Lore in the Palau District of Micronesia. Univ of California Press.

Løkkeborg, S., Pina, T., 1997. Effects of setting time, setting direction and soak time on long-line catch rates. Fish. Res. 32, 213–222. http://dx.doi.org/10.1016/S0165-7836(97)00070-2.

Løkkeborg, S., 1994. Fish behaviour and longlining. In: Ferno, A., Olsen, S. (Eds.), Marine Fish Behaviour in Capture and Abundance Estimation. Fishing News Books, Oxford, UK, pp. 9–27.

Morgan, A., Carlson, J.K., 2010. Capture time, size and hooking mortality of bottom longline-caught sharks. Fish. Res. 101, 32–37. http://dx.doi.org/10.1016/j.fishres.2009.09.004.

NMFS, 2015. Characterization of the U.S. Gulf of Mexico and southeastern Atlantic otter trawl and bottom reef fish fisheries. Observer Training Manual. NMFS, Southeast Fisheries Science Center, Galveston Laboratory, Galveston, Texas. http://www.galvestonlab.sefsc.noaa.gov/forms/observer/obs_training_manual_12_2015.pdf (Accessed 30 January 2017).

Nieland, D.L., Fisher, A.J., Baker Jr., M.S., Wilson III, C.A., 2007. Red snapper in the northern Gulf of Mexico: age and size composition of the commercial harvest and mortality of regulatory discards. In: In: Patterson, W.F., Cowan, J.H., Fitzhugh, G.R., Nieland, D.L. (Eds.), Red Snapper Ecology and Fisheries in the U.S. Gulf of Mexico, vol. 60. pp. 301–310 (Am. Fish. Soc. Symp Bethesda, MD).

R Development Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria (ISBN 3-900051-07-0).

SEDAR, 2009. Stock assessment of red grouper in the Gulf of Mexico. 2009 Update, SEDAR 12 Gulf of Mexico Red Grouper. . http://sedarweb.org/docs/suar/Red_Grouper_2009_Assessment_Update_Report.pdf (Accessed 30 January 2017).

SERO, 2016. Limited Access Commercial Permits: Eastern Gulf Reef Fish Bottom Longline Endorsement. Southeast Reg. Off., Natl. Mar. Fish. Serv. NOAA, St. Petersburg, Fla. http://sero.nmfs.noaa.gov/operations_management_information_services/constituency_services_branch/freedom_of_information_act/common_foia/index.html (Accessed 30 January 2017).

Schmid, J.R., Barichivich, W.J., 2005. Developmental biology and ecology of the Kemp's ridley turtle Lepidochelys kempii, in the eastern Gulf of Mexico. Chelonian Conserv. Biol. 4, 828–834.

Scott-Denton, E., Williams, J.A., 2013. Observer Coverage of the 2010- Gulf of Mexico Reef Fish. NOAA Technical Memorandum (NMFS-SEFSC-646, 65 pp.).

Scott-Denton, E., Cryer, P.F., Gocke, J.P., Harrelson, M.R., Kinsella, D.J., Pulver, J.R., Smith, R.C., Williams, J.A., 2011. Descriptions of the U.S. Gulf of Mexico reef fish bottom longline and vertical line fisheries based on observer data. Mar. Fish. Rev. 73, 1–26.

Shepard, M.P., Roberts, R.F.A., Aro, K.V., Turner, C.E., 1975. Effect of bait loss on catching power of floating longline gear. Int. N. Pac. Fish. Commun. Bull. 32, 71–77.

Shomura, R.S., 1955. A comparative study of longline baits. Special Scientific Report: Fisheries No. 151. U.S. Fish and Wildlife Service, Washington (34 pp.).

Skud, B.E., Hamley, J.M., 1978. Factors affecting longline catch and effort: I. General review, II. Hook spacing, III. Bait loss and competition. Int. Pac. Halibut Commun. Sci. Rep. 64, 66.

Stephen, J.A., Harris, P.J., 2010. Commercial catch composition with discard and immediate release mortality proportions off the southeastern coast of the United States. Fish. Res. 103, 18–24. http://dx.doi.org/10.1016/j.fishres.2010.01.007.

Stoner, W., 2004. Effects of environmental variables on fish feeding ecology: implications for the performance of baited fishing gear and stock assessment. J. Fish Biol. 65, 1445–1471. http://dx.doi.org/10.1111/j.0022-1112.2004.00593.

Thompson, R., Munro, J.L., 1978. Aspects of the biology and ecology of Caribbean reef fishes: serranidae (hinds and groupers). J. Fish. Biol. 12, 115–146. http://dx.doi.org/10.1111/j.1095-8649.1978.tb04158.x.

US Department of Commerce, 2009a. Fisheries of the Caribbean, Gulf of Mexico, and South Atlantic; reef fish fishery of the Gulf of Mexico; Gulf reef fish longline restriction. Fed. Regist. 74, 20229–20230.

US Department of Commerce, 2009b. Fisheries of the Caribbean, Gulf of Mexico, and South Atlantic; reef fish fishery of the Gulf of Mexico; amendment 29. Fed. Regist. 74, 44732–44750.

US Department of Commerce, 2010. Fisheries of the Caribbean, Gulf of Mexico, and South Atlantic; reef fish fishery of the Gulf of Mexico; amendment 31. Fed. Regist. 75, 21512–21520.

Vinson, M.R., Angradi, T.R., 2014. Muskie Lunacy: does the lunar cycle influence angler catch of muskellunge (Esox masquinongy). PLoS One 9, e98046. http://dx.doi.org/10.1371/journal.pone.0098046.

Westfall, P.H., 1997. Multiple testing of general contrasts using logical constraints and correlations. J. Am. Stat. Assoc. 92, 299–306. http://dx.doi.org/10.1080/01621459.1997.10473627.