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A R T I C L E I N F O

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A B S T R A C T

Recreational fishers discard millions of red snapper (*Lutjanus campechanus*) annually in the northern Gulf of Mexico (nGOM), resulting in significant foregone yield. We conducted simulation modeling to evaluate the potential for hook-size regulations to improve efficiency in the recreational red snapper fishery. First, we imposed a suite of candidate parameter sets, informed by recent empirical studies, within the 2015 red snapper assessment model to estimate contact-selectivity of recreational fleets in the northeastern or northwestern GOM. We then evaluated potential hook-size regulations by imposing a suite of candidate parameter sets on future contact-selectivity of each recreational fleet, conditional on likelihood-based estimates from the first simulation exercise. In the assessment model, maximum likelihood values improved when strongly domed contact-selectivity curves with peak size approximating the current minimum length limit were imposed in either the eastern or western recreational fleet. Simulation results indicate mandating large hook sizes could modestly increase retained catch for the eastern recreational fleet while dramatically reducing the number of red snapper discarded by either fleet. Realized benefits of hook-size regulations will depend upon future fisher retention behavior, such as the intensity of live high-grading, discard mortality reduction practices, such as venting and the use of descender devices, and changes to current management regulations.

1. Introduction

Fisheries discards are a pervasive global problem that negatively impact ecosystem function and resilience, ecosystem food availability, trophic transfer through food webs, and fisheries economics (Jennings, 2001; Harrington et al., 2005; Kelleher, 2005; Zeller and Pauly, 2005; Matsuoka, 2008; Sethi et al., 2010). Discards, or fish that are caught and returned to the sea (alive or dead), can result in substantial foregone yield, stock depletion, and reduced fishing opportunities when release-survival rates are low. Global capture fisheries production remains stagnant at approximately 90 million tons (Pauly et al., 2005; FAO, 2018), emphasizing the need to increase harvest efficiency to help satisfy the ever-increasing demand for seafood products. As most stocks are managed to maximize yield, mandates to reduce discards can put management objectives in direct conflict. Hook-size regulations present a possible technological solution to opposing management objectives by shifting catch and subsequent mortality away from unfavorable stock demographics (e.g., undersized individuals) towards maximum yield-per-recruit (Goodyear, 1996; Cerdà et al., 2010).

Gear type can have a dramatic effect on catch and size composition with hook size playing an important role in hook-and-line fisheries. Results of multiple studies have indicated increases in mean length of fish captured with increasing hook size for a variety of species (Ralston, 1990; Grixti et al., 2007; Alós et al., 2008; Cerdà et al., 2010). Physical sorting of fish by hook size depends upon hook dimensions relative to fish mouth diameter and is strongest when relative hook size nears extremes (Cooke et al., 2005). Selectivity refers to the probability that a particular stock demographic is vulnerable to capture in a fishery and is influenced by fish behavior, the degree of spatial overlap between fishing fleets and stock demographics, and changes in management regulations affecting the areas or gears used by a fishery (Pope, 1975; Millar and Fryer, 1999; Sampson and Scott, 2012). Selectivity in stock assessment models is commonly estimated as an age-specific function and can be separated into component parts as availability (i.e., the fraction of the population encountering the gear) and contact selectivity (i.e., the probability of a fish being captured having encountered the gear). Selectivity can be modeled with a variety of functional forms depending upon the ecology of the fish and the flexibility of the selectivity function. The probability of capture in most hook-and-line fisheries ascends rapidly from zero towards full selectivity at a

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relatively young age, and then declines with increasing age with variable intensity (Pope, 1975; Millar and Fryer, 1999; Erzini et al., 1996; Campbell et al., 2014a, b). Rapidly growing recruits interact with fishing gears to determine the rate of the ascending limb towards full selectivity, after which behavioral or ontogenetic diet shifts may reduce contact selectivity with the gear (Huse and Soldal, 2000; Garner et al., 2016a,b) or seasonal shifts in habitat use may affect the availability of fish to different fleets if they move farther from shore or migrate (Hurtado-Ferro et al., 2014; Okamura et al., 2014; Waterhouse et al., 2014).

Selectivity specification is a central issue in modern, integrated, age-structured stock assessments (see volume 158 of Fisheries Research and papers therein) due to its influence on estimates of survival, productivity, and yield, as well as being potentially confounded with important vital rates such as recruitment, growth, or natural mortality (Goodyear, 1996; Maunder, 2002; Punt et al., 2014; Sampson, 2014). In age-based stock assessment models, selectivity functions allow the partitioning of fishing mortality from an apical estimate (i.e., the estimate for the fully selected ages) into age-specific values to maximize parsimony between selectivity information and the number of estimable parameters. Results of recent simulation studies highlight the potential sensitivity of biological reference points to selectivity misspecification (Scott and Sampson, 2011; Crone and Valero, 2014; Ichinokawa et al., 2014; Sampson, 2014). Assessment modelers may need to make strong assumptions regarding certain processes underlying stock population dynamics due to insufficient length composition data or empirical selectivity estimates, even for data-rich species (Maunder and Punt, 2013; Ichinokawa et al., 2014; Maunder and Piner, 2015). Incorrectly specifying the functional form (i.e., domed versus asymptotic) or constancy (i.e., time-variant versus time-invariant) of the selectivity function may cause overharvest and rapid depletion of older age-classes, possibly leading to recruitment failure and stock collapse (Sampson, 1993; Myers and Quinn, 2002; Ichinokawa et al., 2014; Stewart and Martell, 2014).

Red snapper, *Lutjanus campechanus*, are long-lived (to 60 yr), large demersal reef fish that experience intense discarding rates in northern Gulf of Mexico (nGOM) recreational fisheries (SEDAR, 2015). Despite being a data-rich species, strong assumptions regarding selectivity processes have been made in previous stock assessments due to a lack of empirical information. In 2015, stock assessment biologists estimated that selectivity shifted to older age classes after 2008, in part due to regulatory changes enacted in the Reauthorized Magnuson-Stevens Act (MSRA, 2007) that mandated circle hooks be used in place of traditional J-hooks by recreational fishers when targeting red snapper and other reef fishes. Circle hooks are generally circular in shape with a hook point that curves back towards the shank while J-hooks resemble the letter j and have a hook point that is parallel to the shank. It was reasonable to expect that the circle hook regulation enacted by the Gulf of Mexico Fishery Management Council (GMFMC) in Amendment 27 to the Reef Fish Management Plan (RFMP; GMFMC, 2007) altered selectivity patterns because different hook shapes function differently during the hook-setting process (Cooke et al., 2005). However, recently collected empirical data indicate no difference in contact selectivity patterns between circle and J-hooks across the full range of hook sizes typically used by recreational fishers (Patterson et al., 2012; Campbell et al., 2014a, b; Garner et al., 2014, 2017). The empirical estimates provide an opportunity to examine the red snapper stock assessment model's sensitivity to alternative selectivity parameterizations and the potential for hook-size regulations to increase harvest efficiency by decreasing annual discards, a management alternative previously considered by the GMFMC.

The objectives of this study were to 1) evaluate assessment model sensitivity to alternative selectivity parameterizations informed by empirically derived contact-selectivity estimates and 2) assess the potential for minimum hook-size regulations to improve recreational fishery efficiency. Specifically, we informed the assessment model with empirical contact-selectivity estimates by inputting a suite of fixed parameter values for size-selectivity of directed recreational fleets (i.e., simulation set 1). Given each set of fixed size-selectivity parameters, age selectivity was re-estimated from the observed catch-at-age data. Results from simulation set 1 were evaluated to identify plausible contact-selectivity curves during the period since Amendment 27 was adopted into law (hereafter referred to as the recent past, 2008–2014). Using the likelihood-based estimates of contact-selectivity derived from the assessment model in simulation set 1, we then imposed a suite of corresponding size- and age-selectivity curves on recreational fleets during the projected period to evaluate effects from imposing potential hook-size regulations on catch metrics (i.e. retained catch or discards).

2. Material and methods

We briefly describe the assessment model used to conduct simulation exercises below. For a full description of the red snapper fishery (S1.1) and stock assessment model (S1.2) see supplementary information. A more detailed description of the model structure is available on the SEDAR website (http://sedarweb.org/sedar-31).

2.1. Assessment model description

Red snapper is managed as a single stock and biological reference points are calculated for the entire nGOM, but stock dynamics and fleet-specific variables are modeled separately for eastern and western areas. The red snapper stock assessment model (SEDAR, 2015), hereafter referred to as the 2015 model, was parameterized and computed in the integrated stock assessment framework Stock Synthesis (SS) version 3.24U (Methot and Wetzel, 2013). The optimal parameter set was informed by maximum likelihood estimates calculated as the negative log of the likelihood value for the parameter set that maximized the probability of observing the data given the parameter estimates (hereafter referred to as likelihood). The final likelihood value was calculated as the weighted sum of the individual likelihood components estimated for each dataset for each fleet or index of abundance included in the model (Methot and Wetzel, 2013).

The 2015 model included time-varying age selectivity to account for the switch from J-hook to circle hook gear in 2008. Age-specific selectivity was estimated separately for the eastern or western private recreational fleet in each area-specific sub-model with a random walk function, which produces age-specific parameter estimates that indicate the rate of change in selectivity between ages. The random walk approach allows for flexibility in age-selectivity schedules and was used in the assessment model because too few empirical data existed regarding the form of selectivity for red snapper in either the neGOM or nwGOM to inform more rigid functions available within the SS framework. Bounds were specified such that the selectivity curve could take on an asymptotic or domed shape according to maximum likelihood estimates but also constrained the model from estimating parameters that resulted in unreasonable functional behavior (e.g., dramatic shifts from positive to negative rates of change between two adjacent age classes). Selectivity of age classes ≥ 12 was fixed as constant (i.e., 0 rate of change) at the parameter estimate for age-11 fish because red snapper are thought to dissociate from reef structures at older ages (SEDAR, 2005). Size selectivity in the 2015 model was fixed at 1 across all length bins (i.e., 20 mm bin widths from 120 to 1100 mm TL, n = 50) because size composition data were not available in the stock assessment model to directly estimate size-selectivity parameters.

2.2. Simulation description

Simulations were computed to evaluate the sensitivity of the 2015 model to alternative selectivity assumptions to inform and evaluate hypothetical hook-size regulations, hereafter referred to as hook regulations. Alternative selectivity parameterizations were directly

Table 1
Description of changes made to base model during sensitivity runs under each simulation set. "Values imposed" indicates changes in base model parameters of size-selectivity (θ or β) imposed on either the eastern (Rec. east) or western (Rec. west) recreational fleet.

Component	Base model	Simulation set 1 Size-selectivity	Simulation set 2 Hook-size regulations
Fleet(s) affected		Rec. east, Rec. west	Rec. east, Rec. west
Selectivity			
Time blocks	2008–2010, 2011–2014	2008–2010, 2011–2014	2008–2010, 2011–2013, 2014
Rec. open season fleets			
Age-selectivity	Estimated	Estimated	Fixed to opt. values from scenario 1
eq. used	Random walk	Random walk	Random walk
Size-selectivity	Fixed	Values imposed	Values imposed
eq. used	$S_l = 1$	Exponential-logistic	Exponential-logistic
Rec. closed season fleets			
Size-selectivity	$S_l = 1$	$S_l = 1$	$S_l = 1$
Age-selectivity	Mirrored to rec. fleets	Fixed to opt. base model parameters	Fixed to opt. base model parameters
Fishery-dependent indices	Mirrored to rec. fleets	Mirrored to rec. fleets	Mirrored to rec. fleets
Bycatch fleets	Fixed to 2014 estimates	Fixed to 2014 estimates	Fixed to 2014 estimates
Projections	2014–2074	2014–2074	2014–2074

informed by recent studies that investigated recreational fisher behavior and provided empirical estimates of contact selectivity for gears (i.e., circle hooks) typically used by recreational fishers to target red snapper (Patterson et al., 2012; Campbell et al., 2014a, b; Garner et al., 2014; Garner and Patterson, 2015; Garner et al., 2017). Deterministic model runs were conducted in two simulation sets: 1) to assess the impact of imposing different selectivity patterns on model fit (maximum likelihood) during the recent past (2008–2014) and 2) to assess percent change in the retained catch in weight (metric tons, mt), numbers (millions of individuals), or discards (millions of individuals) under different parameter sets that represent hook regulations imposed during the future projected period (2015–2074). Percent change was estimated with the equation:

$$Percent\ change = \left(\frac{(Simulation\ estimate - Base\ model\ estimate\ )}{Base\ model\ estimate}\right) * 100$$

where the simulation estimate is the projected equilibrium estimate of retained catch or discards from each simulation run and the base model estimate is the equilibrium estimate of retained catch or discards from the 2015 model. Projections were carried through to 2074 to represent equilibrium conditions as was done during the 2015 assessment. Fishing mortality rates for the 6 bycatch fleets (shrimp trawl, recreational closed season, and commercial fleets without IFQ allocation for each sub-stock) were assumed to continue (i.e., fixed) at 2013 levels, the most recent year of data. Selectivity patterns of recreational bycatch fleets (i.e., closed season catch) were given fixed parameter values based on maximum likelihood estimates from the 2015 model to insulate bycatch fleets from effects of re-parameterizing directed fleets during simulations.

Size-selectivity curves were modeled with a flexible-form function available in the SS framework to represent contact selectivity imposed by recreational fleets. Of the multiple functions available to model size-selectivity (S) in SS, we chose the exponential-logistic equation:

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

where α is the ascending limb parameter, β is the descending limb parameter, θ is the parameter for size-at-peak selectivity, and l corresponds to the midpoint of the population length bin. The exponential-logistic function (Eq. (1)) was chosen over other commonly used, more flexible functions (e.g., double-normal or double-logistic) due to its reasonable flexibility (can be flat-topped or dome-shaped) and having fewer estimable parameters. The three-parameter exponential-logistic function facilitates a more straightforward translation of empirical estimates to selectivity parameterizations in the assessment model. All values used to parameterize size selectivity for relevant fleets were input as fixed values and the corresponding age-selectivity parameters were estimated from the observed catch-at-age data.

Size selectivity in the 2015 model was set equal to 1 at all lengths, which represents the default assumption when size-based information is not included or is insufficient to estimate a size-selectivity curve. A re-parameterized version of the 2015 model was developed prior to implementing simulation set 1 to allow meaningful comparisons between simulation outputs and the 2015 model. The re-parameterized version of the 2015 model, hereafter referred to as the base model, was developed by specifying a flexible-form equation that maintained full selectivity at all size classes as was assumed in the 2015 model by specifying the parameters α = 0.01, θ = 0.225, and β = 0.001, which produce a horizontal line at S = 1. Age-selectivity parameters for each recreational fleet were re-estimated, which resulted in no discernible change in parameter estimates or derived quantities (e.g., equilibrium spawning stock biomass, recruitment, or catch). The suite of size-selectivity curves was then imposed on the base model as changes in θ or β parameters; all models were given a similar ascending limb (α) parameter value. Specific changes to the base model in each simulation set are described in the following sections and in Table 1.

2.2.1. Simulation set 1: contact selectivity

Recently reported estimates of size-based contact selectivity (Patterson et al., 2012; Campbell et al., 2014a, b; Garner et al., 2014, 2017) were used to inform size selectivity in the red snapper assessment model in sensitivity runs. Nearly all empirical estimates suggest red snapper contact selectivity is dome shaped with Garner et al. (2014, 2017) estimating size-at-peak selectivity ranging from 284 to 424 mm TL; larger circle hooks selected for larger fish.

In simulation set 1, the θ parameter, which controls size-at-peak selectivity, was systematically increased by 0.1 units from 0.2 to 0.6. The value of θ is calculated as half the difference between the maximum and minimum population length bins. Here, θ values of 0.2, 0.3, 0.4, 0.5, and 0.6 correspond to total lengths (TL) of 300, 400, 500, 600, or 700 mm, respectively. The β parameter, which controls, the descending limb was input as 0.0001, 0.01, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, and 0.60 in a factorial design with θ values (0.2 to 0.6) to generate a wide range of selectivity curves (Fig. 1). The α parameter was fixed to approximately equal parameter values reported in Garner et al. (2017) after accounting for stabilizing transformations automatically applied in SS. Therefore, corresponding α values were set equal to 0.3 for all size-selectivity parameterizations in this simulation set, except when β = 0.0001 (α = 0.9) and β = 0.01 (α = 0.57), which were adjusted to maintain similarity among the ascending limbs of all size-selectivity curves (Fig. 1).

In the 2015 assessment model, selectivity during the recent past

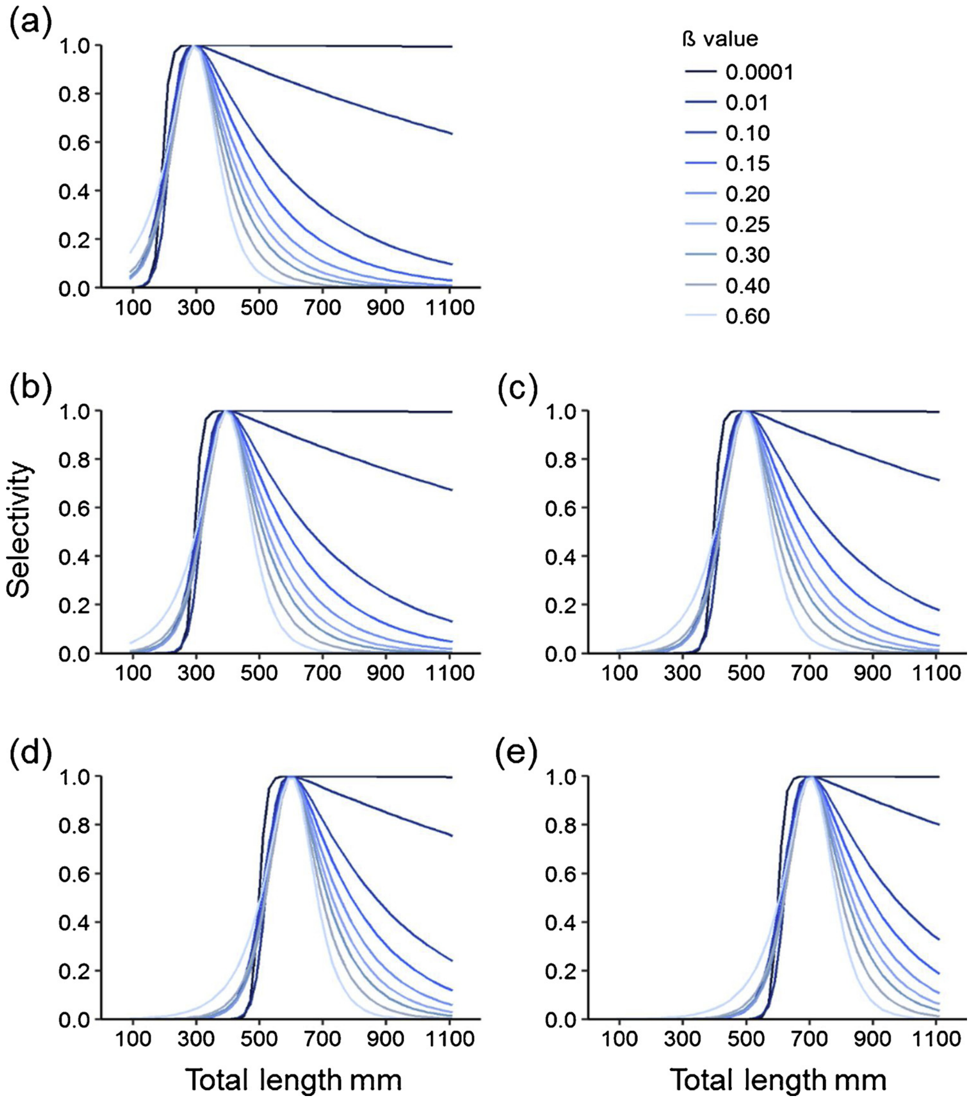

Fig. 1. Size-based selectivity curves imposed on the eastern or western recreational fleet for combinations of θ (selectivity peak) and β (descending limb) parameters. Theta values were a) 0.2 (300 mm TL), b) 0.3 (400 mm TL), c) 0.4 (500 mm TL), d) 0.5 (600 mm TL), or e) 0.6 (700 mm TL) and β values for each curve are shown in the legend at the top right of the figure. For example, $\beta = 0.0001$ (darkest blue line) results in a flat-topped curve while $\beta = 0.60$ (light blue line) results in the most strongly domed curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

(2008–2014) was split into two time-blocks (2008–2010, 2011–2014) to address observed shifts in age composition data during recent years (SEDAR, 2013, 2015). As only potential changes in selectivity that possibly resulted from Amendment 27 were of interest in this study, size-selectivity curves associated with time blocks prior to 2008 were parameterized with default values in accordance with the 2015 base model. The set of selectivity parameter values described above for sensitivity runs were imposed on either the eastern or western private recreational fleet during both the 2008–2010 and 2011–2014 time-blocks. Headboat fleets were not included in re-parameterized sensitivity runs because empirical contact selectivity estimates reported in the literature pertain to charterboats (Patterson et al., 2012; Garner et al., 2014, 2017) and may not represent fishing behaviors typically exhibited by headboat operators. All other model settings in this simulation set remained the same as in the 2015 assessment model.

2.2.2. Simulation set 2: hook regulations

In order to evaluate effects from potential hook regulations, a single set of size-selectivity parameters was chosen based on the maximum likelihood estimates from simulation set 1, as well as recent empirical estimates (Garner et al., 2014, 2017), to represent size selectivity during the recent past (2008–2013). The chosen parameter set was $\theta = 0.3$ (400 mm TL), $\beta = 0.2$ (a moderately dome-shaped curve), and α was set equal to 0.3 as in simulation set 1. Conditional on this parameter set, a suite of contact-selectivity curves (i.e., $\beta = 0.0001$, 0.1, 0.3, or 0.6; $\theta = 0.3$, 0.4, or 0.5) were then input in a factorial design as fixed parameters of size-selectivity starting in the last year of the data (2014) through 2074 to provide equilibrium estimates of yield (weight or numbers) or discards (numbers). A reduced parameter set was imposed in simulation set 2 to more parsimoniously represent the range of size-selectivity curves thought plausible to result from imposing hook regulations. The α parameter was again fixed to the appropriate value for each β such that the ascending limbs of all curves were similar as in simulation set 1. All other model settings in this simulation set remained the same as in the base model.

Each of the size-selectivity curves described above was imposed on the eastern or western recreational sector separately and maximum likelihood estimates of selectivity-at-age parameters corresponding to each size-selectivity curve were input as fixed values. Size selectivity prior to 2008 was fixed to parameter values effectively representing size selectivity equal to 1 at all lengths consistent with the base and 2015 model. Age-selectivity of each recreational bycatch fleet (i.e., closed-

Table 2
Change in total negative log-likelihood (nLL) values relative to the base model for each combination of θ and β imposed on size-selectivity parameters for the eastern (Rec. east) or western (Rec. west) private recreational fleet in simulation set 1. The total likelihood values from each base model are 5279.8 for eastern and 5281.0 for the western recreational fleet, respectively. Each model included 1309 active parameters. Models with reduced nLL values compared to the base model (2015 model) are indicated in bold.

β	θ				
	0.2	0.3	0.4	0.5	0.6
Rec. east					
0.0001	**−1.3**	**−0.1**	+59.0	+471.6	+2406.1
0.01	**−1.4**	**−0.5**	+77.4	+221.1	+995.9
0.10	+3.3	+5.3	+11.4	+37.3	+233.4
0.15	+6.4	**−1.2**	+22.8	+36.0	+59.2
0.20	+8.3	**−1.2**	+20.9	+37.4	+57.9
0.25	+14.3	**−0.9**	+13.6	+26.0	+50.2
0.30	+18.8	**−2.4**	+18.3	+19.1	+39.2
0.40	+29.1	+3.0	+12.8	+15.5	+27.6
0.60	+51.5	+13.1	+0.7	+9.2	+6.1
Rec. west					
0.0001	**−4.6**	+8.0	+73.5	+533.5	+1802.9
0.01	+5.0	+11.2	+87.5	+264.4	+787.0
0.10	**−3.9**	+6.1	+30.7	+50.4	+68.7
0.15	**−2.8**	+6.7	+32.7	+47.5	+60.2
0.20	**−0.8**	**−4.4**	+31.4	+34.1	+50.7
0.25	+2.2	**−4.9**	+30.6	+40.5	+41.1
0.30	+5.8	**−5.3**	+28.1	+36.9	+42.6
0.40	+12.9	**−5.3**	+15.1	+19.9	+31.1
0.60	DNC	**−0.4**	+14.1	+10.6	+10.7

season catch) in the neGOM or nwGOM was fixed to the maximum likelihood estimates for the corresponding directed fleet (i.e., open-season catch) in the 2015 model. Hook regulations were not applied to recreational bycatch fleets because hook choice would be driven by targeting of other species during red snapper closed seasons.

3. Results

3.1. Contact selectivity

Compared to the base model with parameter set α = 0.01, θ = 0.225, and β = 0.001 (i.e., all size classes fully selected), imposing either flat-topped or dome-shaped size-selectivity curves reduced model likelihood when applied to either the eastern (between 0.1 and 2.4 points) or western (between 0.8 and 5.3 points) private recreational fleet (Table 2). However, maximum likelihood was reduced only when size-at-peak selectivity (θ) was centered on small size classes (300 or 400 mm TL). Flat-topped selectivity (i.e., β = 0.0001) reduced model likelihood only when θ = 0.2 (300 mm TL); dome-shaped selectivity reduced model likelihood only when θ = 0.3 (400 mm TL). With size-at-peak selectivity equal to θ = 0.3, moderate (β = 0.15) to strongly dome-shaped (β = 0.40) curves provided the greatest reduction in model likelihood compared to the re-parameterized base model for both recreational fleets. However, the two curves with the lowest likelihood value for either fleet were not significantly different from other models that also had reduced likelihood values (Table 2). Size-selectivity curves peaking at size classes > 400 mm TL greatly degraded total likelihood values regardless of the descending limb parameter (Table 2).

Increasing the doming intensity of imposed size-selectivity curves (i.e., increasing β) shifted corresponding age-selectivity curves. As doming intensity increased, the corresponding selectivity-at-age values increased for age-1 and age-10+ fish. In the 2015 assessment model, age-selectivity is assumed to be constant starting at age 12 based on the ecology of the species and attempts to maximize model parsimony (SEDAR, 2015). Age-selectivity for ages-10+ increased from < 0.10 when selectivity was flat-topped to ~0.2–0.5 when doming intensity was strong (Fig. 2). Aside from the spike in age-1 selectivity, the age-selectivity function became smoother as doming intensity increased in the western recreational sector, which is theoretically more realistic based on gradual changes in body morphology affecting selectivity probabilities.

3.2. Hook regulations

Equilibrium estimates of yield and discards were affected by size-selectivity curves representing hook regulations. Hook regulations imposed on eastern or western recreational fleets resulted in moderate changes in equilibrium yield and large percentage changes in equilibrium discards (Figs. 3–5). When peak selectivity was set equal to θ = 0.3 (400 mm TL), doming intensity had a strong, bidirectional effect on model outputs. Increasing size-at-peak selectivity to θ = 0.4 (500 mm TL) or θ = 0.5 (600 mm TL) caused model outputs to converge regardless of the doming intensity. The direction and magnitude of percent change in model outputs often differed between eastern and western recreational fleets for a given set of parameter values (Figs. 3–5). For example, for size-at-peak selectivity equal to 500 mm TL (θ = 0.4), equilibrium percent change in retained catch was decreasingly positive as doming intensity increased for the eastern recreational fleet, whereas percent change was increasingly negative as doming intensity increased for the western recreational fleet (Fig. 4, column 2).

3.2.1. Retained catch

Equilibrium estimates of retained catch (by weight or numbers of fish) were sensitive to changes in doming intensity and size-at-peak selectivity (Figs. 3 and 4). For the eastern fleet, when size-at-peak selectivity was set equal to 400 mm TL (i.e., θ = 0.3), imposing flat-topped selectivity resulted in a 29.5 % increase in equilibrium retained catch by weight; imposing a weakly domed selectivity resulted in a 10.6 % increase (Fig. 3, row 2). Percent change in retained catch by numbers followed a similar pattern but with decreased magnitude (Fig. 4, row 2). When size-at-peak selectivity (θ) was increased, all but one size-selectivity curve resulted in a positive percent change in retained catch by weight. Increasing the size-at-peak selectivity to 500 mm TL (θ = 0.4) increased percent change in retained catch in numbers but increasing to 600 mm TL (θ = 0.5) decreased percent change in retained catch regardless of doming intensity (Fig. 4, row 2). For the western fleet, retained catch by weight increased by 10.5–15.1% only when future selectivity was flat-topped, regardless of the size-at-peak selectivity (Fig. 3, row 3); any degree of doming resulted in a negative percent change value. All selectivity curves and sizes-at-peak selectivity resulted in decreased retained catch by numbers (Fig. 4, row 3).

3.2.2. Discards

When size-at-peak selectivity was equal to 400 mm TL, simulations indicated equilibrium projected discards would increase if size selectivity were strongly domed (30.9 % for β = 0.3 and 184.7 % for β = 0.6) (Fig. 5, row 2) but decrease dramatically when size selectivity was flat-topped. A similar pattern of lesser magnitude was observed for the western fleet for the same parameter set (Fig. 5, row 3). Discards decreased dramatically when size-at-peak selectivity was shifted to 500 (θ = 0.4) or 600 (θ = 0.5) mm TL regardless of doming intensity (Fig. 5, rows 2 and 3); the same pattern was observed for the western fleet.

4. Discussion

Hook regulations are a rarely used but viable tool for increasing harvest efficiency in hook-and-line fisheries when catches are predominantly comprised of undersized individuals (i.e., individuals below the legal retainable size or retainable but of undesirable size) whose mouth gape is small relative to available hook sizes (Cooke et al., 2005;

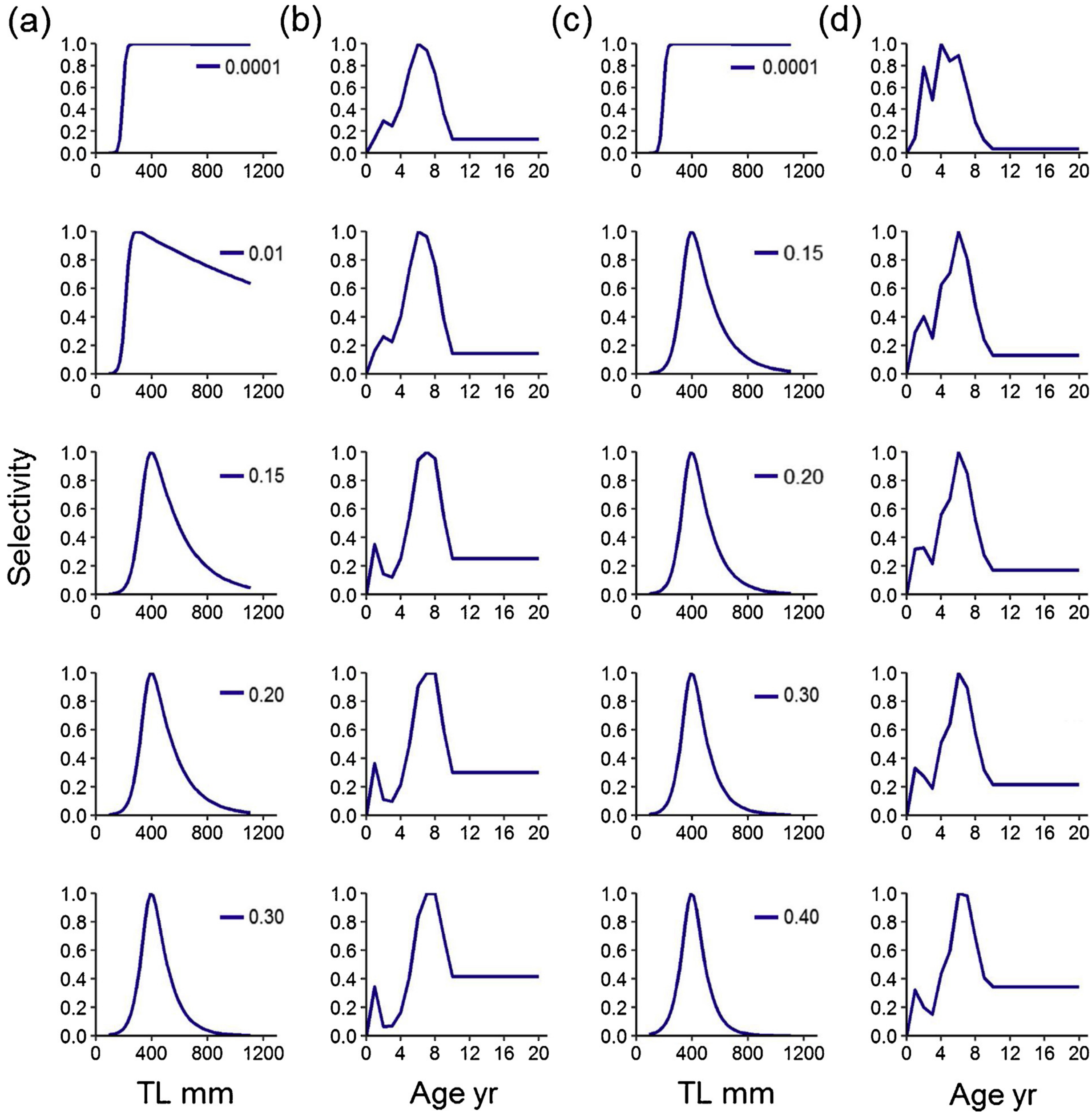

Fig. 2. Maximum likelihood estimates of size- (columns a and c) and age-selectivity (columns b and d) curves for the eastern (columns a and b) and western (columns c and d) recreational sector for each combination of θ and β imposed in the red snapper assessment model. Figures shown above represent parameter combinations that reduced the total likelihood by > 1.0 (eastern recreational sector) or > 4.0 (western recreational sector) units compared to the re-parameterized base model. The β value for each exponential-logistic function is shown at the right of each size-selectivity curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Cerdà et al., 2010). Our simulations suggest hook regulations mandating large circle hooks could increase the retained catch of red snapper by recreational fleets by 10–30% by shifting catch to sizes above the current MLL, which would dramatically reduce discards. Empirical data indicate that shifting contact selectivity above the current red snapper MLL is plausible with large circle hooks (Patterson et al., 2012; Campbell et al., 2014a, b; Garner et al., 2014, 2017). Therefore, hook size regulations have the potential to increase efficiency in the red snapper recreational fishery provided that the current MLL approximates the true inflection point of the retention curve, fishers are willing to accept trade-offs between catch rates and efficiency, and compliance with hook-size regulations is high. Although our simulation results represent equilibrium estimates, hook regulations could have immediate impacts on discard rates because contact selectivity is primarily driven by gape limitation, not stock demographics.

One objective of this work was to evaluate if including empirical estimates of size selectivity improved model fit. By including this information, we were able to better inform the processes underlying recreational fishing mortality and evaluate whether empirical estimates of contact selectivity were plausible at the fishery level. Maximum-likelihood estimates from the first simulation exercise agreed with recent empirical contact-selectivity estimates that size-based selectivity is likely dome shaped with size-at-peak selectivity near the current MLL. However, without including size composition data in the assessment model, the power to discern among candidate models is low. Regardless, only models with contact selectivity peaking at smaller sizes (i.e., 300 or 400 mm TL) improved model fit; models that fully

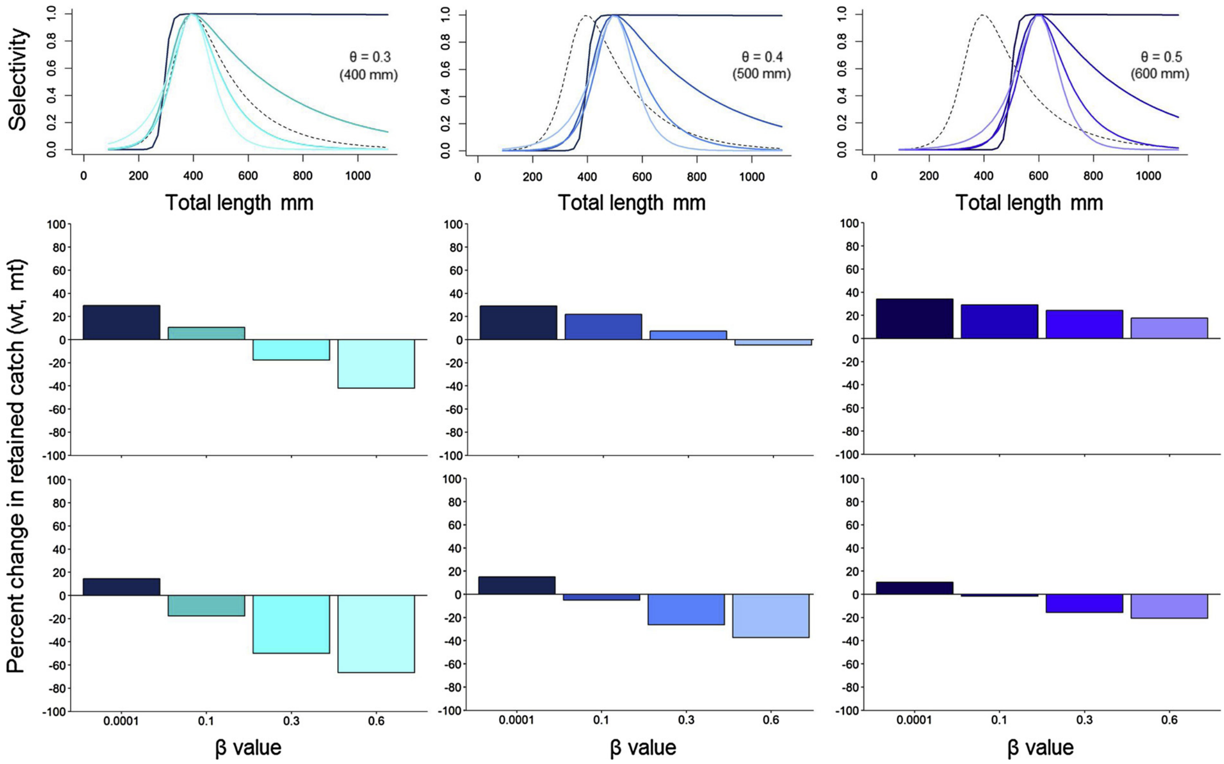

Fig. 3. Equilibrium percentage change in retained catch (weight, mt) under different future contact-selectivity regimes (β = 0.0001 to 0.6, θ = 0.3 to 0.5; solid lines), relative to the likely current contact-selectivity regime (β = 0.3, θ = 0.3; dashed line) based on likelihood values from simulation set 1 and empirical estimates. Row 1 indicates increasing theta values (size-at-peak selectivity) and increasing doming intensity values are shown on the x-axis at the bottom of the figure. Rows 2 and 3 indicate equilibrium percent change values when contact-selectivity curves are imposed on the eastern (row 2) or western (row 3) recreational fleet.

selected for large size classes (i.e., 500 or 600 mm TL) dramatically decreased model fit.

Our simulation approach and results are supported by red snapper ecology and ontogeny. We assumed that size selectivity rapidly increased towards peak selectivity because red snapper enter the fishery at approximately age-2 where fishers primarily target them at artificial reef structure. Large crustaceans comprise a greater proportion of red snapper diet with increasing size (McCawley and Cowan, 2007), which may become rapidly depleted near artificial reefs where invertivore abundances are high (Davis et al., 1982; Langlois et al., 2005; Campbell et al., 2011; Patterson et al., 2014). Thus, red snapper are thought to increasingly dissociate from reef structure at older ages, which provides an ontogenetic mechanism for dome-shaped selectivity for the vertical hook-and-line fleets. Fishery-dependent and fishery-independent surveys that set bottom-longline gear over unconsolidated mud and sand-bottom habitat are thought to fully select for large size classes because older red snapper (> 10 yr) comprise much of the catch (SEDAR, 2005). Imposing size-selectivity curves on recreational fleets in the assessment model had the effect of increasing age selectivity (i.e., availability) of older age classes (10 +), the ages preferred for retention by recreational fishers because of their large size. If contact selectivity by the recreational fleet is indeed strongly domed, availability of older individuals may be higher than previously thought.

In addition to recently collected empirical selectivity estimates provided by other authors, Garner and Patterson (2015) provided evidence that the progression of older ages since 2008 may have been exacerbated by live high-grading likely motivated by a combination of a low daily bag limit (2 red snapper per person per day) and perceived high abundance of red snapper. The sizes-at-peak selectivity that improved model fit (300 or 400 mm TL) in our simulations were below the mean size-at-age for the most frequent ages (ages-5–7) observed in neGOM recreational catch data since 2008 (SEDAR, 2015). Retention behavior is difficult to estimate within the assessment model because discard numbers are self-reported by fishers and size-composition data cannot be collected by port samplers for fish discarded from vessels at sea. Empirically derived retention estimates could alter model estimates if significantly different from the current assumption that retention rapidly approaches 1 (i.e., knife-edge retention) at the MLL (SEDAR, 2013; 2015).

Assumptions of knife-edge selectivity at the MLL during years prior to 2008 were reasonable given the consistently small mean size of landed fish relative to maximum TL and larger MLL in some years (SEDAR, 2013). Based on data collected during 2012 and 2013, Garner and Patterson (2015) reported nearly 85 % of red snapper captured during open seasons were of legal size, a significant portion of which were discarded in favor of potentially catching and retaining larger individuals; the length at which 50 % of individuals were retained was approximately 500 mm TL (Garner, unpublished data). Fishers have openly acknowledged and voiced concerns regarding live high-grading behavior at Gulf Council meetings. Results of a recent analysis indicated catches (landed catch and self-reported dead discards) were constrained by daily bag limits (SERO-LAPP-2012-11, 2012), but the potential effects of live-high grading were not included because the data consisted of only landed catch and self-reported dead discards. Considering the low daily bag limit, truncated open season lengths, high catch rates, and extended recreational fishing seasons in state waters in recent years, the potential for discarding of undersized individuals or live high-grading is high, especially if current regulations do not fully constrain daily catch.

Another focus of this work was to assess the efficacy of hook regulations to reduce the catch of undersized red snapper and improve fishery efficiency. Hook regulations were previously considered as part of Amendment 27 (i.e., the circle hook amendment) but were ultimately removed from the final legislation due to a lack of empirical

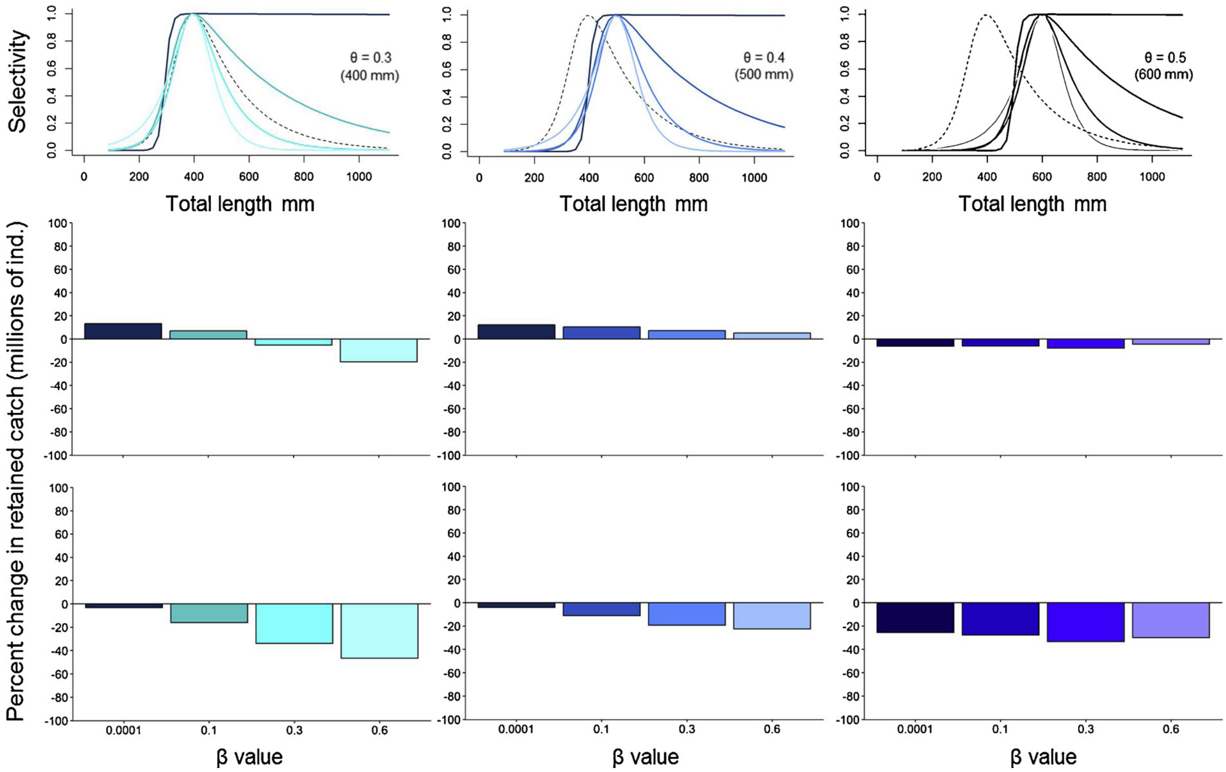

Fig. 4. Equilibrium percentage change in retained catch (millions of individuals) under different future contact-selectivity regimes (β = 0.0001 to 0.6, θ = 0.3 to 0.5; solid lines), relative to the likely current contact-selectivity regime (β = 0.3, θ = 0.3; dashed line) based on likelihood values from simulation set 1 and empirical estimates. Row 1 indicates increasing theta values (size-at-peak selectivity) and increasing doming intensity values are shown on the x-axis at the bottom of the figure. Rows 2 and 3 indicate equilibrium percent change values when contact-selectivity curves are imposed on the eastern (row 2) or western (row 3) recreational fleet.

information. Our simulations suggest large hooks could reduce discard levels by increasing selectivity of larger fish (i.e., decreased doming intensity of contact-selectivity) or shifting size-at-peak selectivity above 400 mm TL. Additional bait and gear combinations or other fishing tactics concomitant with hook regulations might shift selectivity peaks towards or increase contact selectivity of larger individuals (Garner et al., 2017). However, the effects of gear and bait combinations remain untested for red snapper.

The realized impact of hook regulations will ultimately depend upon the retention and discarding behavior exhibited in the recreational fishery. Motivations for live-high grading are not well understood, and it is unclear how fisher behavior is affected by a variety of factors such as cohort strength, fish size, perceived abundance, and effort. This is not to say hook regulations would be ineffective but rather the effects of hook regulations alone are unlikely to fully compensate for retention behavior under certain demographic conditions. As strong cohorts move through the fishery, via fishing mortality or ontogenetic movement, hook regulations would become more impactful by reducing catch of new cohorts that do not yet meet fisher preferences. Empirical data also indicate large circle hooks dramatically reduce red snapper catch rates (Garner et al., 2014, 2017). If fishers are willing to accept reduced catch rates associated with large hooks, large hooks may indirectly reduce live-high grading behavior because fishers may perceive decreased availability of large red snapper for retention. Other high-value reef fishes (e.g., groupers, Serranidae) in the neGOM are rarely discarded when captured above the MLL likely because they are perceived to be uncommon due to low catch rates (Garner and Patterson, 2015).

Empirical data suggest large circle hooks could provide additional benefits during the red snapper open season by 1) reducing the bycatch of non-target species closely associated with red snapper at reef sites (Dance et al., 2011), several of whose stocks are currently in an overfished condition, and 2) possibly reducing red snapper catch rates to extend open season length (Garner et al., 2014, 2017). Currently, fishers must use circle hook gear when targeting reef fishes in the nGOM but are unrestricted regarding hook size and gear configuration. Mandating large hook sizes when targeting reef fishes during red snapper open seasons would place direct controls over gear choice preventing fishers from utilizing highly inefficient hook sizes when targeting red snapper and minimize targeting secondary species upon filling the daily bag limit of red snapper. However, enforcement of hook size regulations would be extremely difficult without also banning possession of non-compliant hooks onboard vessels targeting or possessing reef fishes. Amendment 27 mandated circle hook use when targeting reef fishes, but fishers can still carry other hook types onboard vessels when targeting reef fishes and can target other species with other hook types (e.g., trolling for pelagic species with J-hooks) before or after targeting and possessing reef fishes.

In addition to hook regulations, slot limits, which allow fishers to retain individuals above a minimum and below a maximum length, also have been proposed to the GMFMC to improve red snapper management as a means to increase retained catch (numbers), extend season lengths, or reduce mortality of larger, older spawners by focusing harvests on smaller, fully-selected individuals. Farmer et al. (2014) reported slot limits focusing harvest on small size classes (e.g., up to ~500 mm TL) could increase the number of fish landed by up to 50 %, but discards could increase by 30–40 % without increasing the maximum length limit. High catch rates of smaller red snapper fully selected by smaller circle hooks could quickly fill the low daily bag limit and motivate secondary targeting behavior, which could exacerbate red snapper discards during open seasons. Large circle hooks fished under a slot-limit scenario could minimize the catch of undersized red snapper and deter secondary targeting behavior by reducing catch rates, provided bait size or type effects do not strongly shift selectivity to large

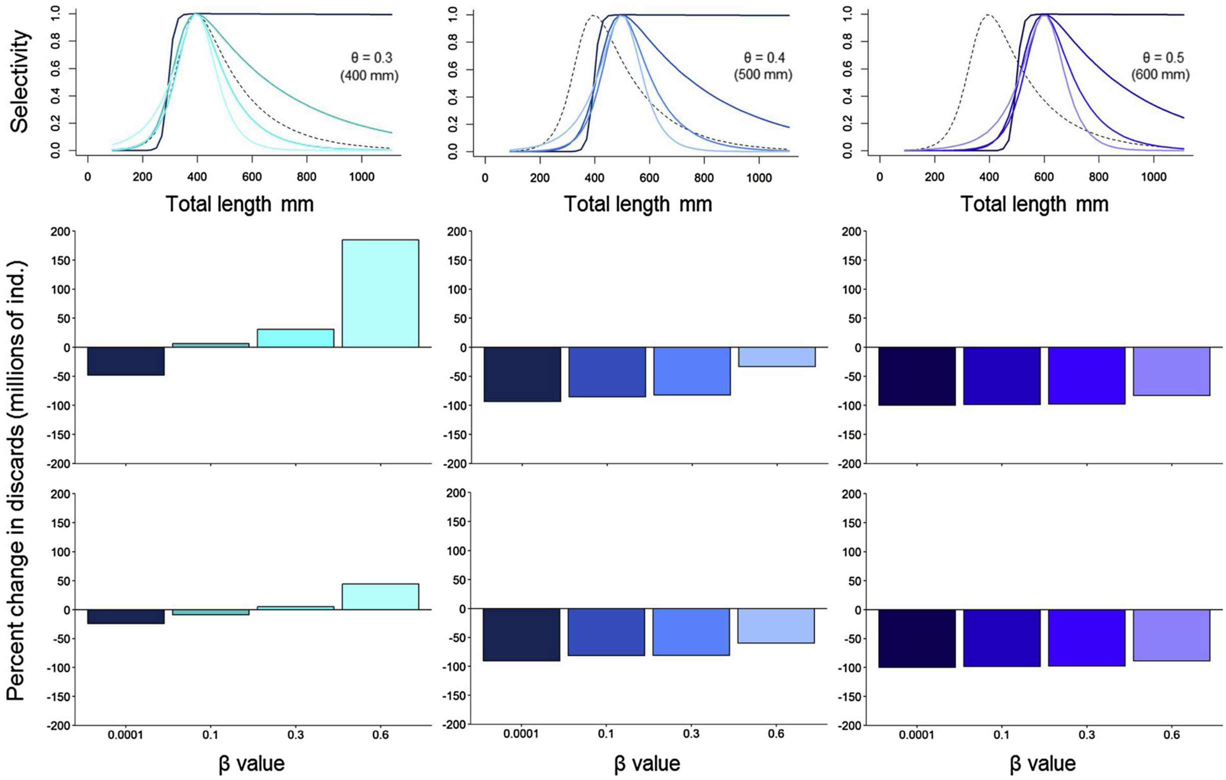

Fig. 5. Equilibrium percentage change in discards (millions of individuals) under different future contact-selectivity regimes (β = 0.0001 to 0.6, θ = 0.3 to 0.5; solid lines), relative to the likely current contact-selectivity regime (β = 0.3, θ = 0.3; dashed line) based on likelihood values from simulation set 1 and empirical estimates. Row 1 indicates increasing theta values (size-at-peak selectivity) and increasing doming intensity values are shown on the x-axis at the bottom of the figure. Rows 2 and 3 indicate equilibrium percent change values when contact-selectivity curves are imposed on the eastern (row 2) or western (row 3) recreational fleet.

size classes that exceed the upper slot limit. Descender devices, which are used to rapidly return and release fish at depth, could be mandated in conjunction with slot limits to reduce discard mortality, but too few empirical data currently exist to evaluate their effectiveness for red snapper (Curtis et al., 2015; Runde and Buckel, 2018). Other possible regulatory alternatives require fishers to retain the first *n* fish of legal size (i.e., a first fish rule) or limit the cumulative length of retained fish, but again are predicated on daily catch constraints and discarding practices.

5. Conclusions

Results of multiple studies have highlighted the potential for larger hooks to increase contact selectivity (or mean fish size) and thereby decrease the catch of undersized individuals or less desirable size classes (Ralston, 1990; Mapleston et al., 2008; Cerdà et al., 2010; Campbell et al., 2014a, b; Garner et al., 2014). Hook regulations represent a simple, easily enacted regulatory alternative that can reduce nominal discard mortalities in accordance with bycatch reduction guidelines, provided constituents are willing to accept potential reductions in catch rates associated with larger hooks. Such a compromise is plausible considering fishers are simply reducing catch of size classes that are not normally retained while receiving multiple incentives. Hook regulations mandating a minimum size have been successful in reducing undersized catch of recreationally caught labrids, sparids, and serranids in other systems (Cerdà et al., 2010), and results presented herein suggest hook regulations have the potential to similarly affect discards of red snapper and other reef fishes in the nGOM. If nGOM recreational fisheries exhibit strong preferential retention behavior, substantive increases in per-person harvests of red snapper or other reef fishes in the nGOM may only result from limiting fishery access to fewer constituents (Johnston et al., 2007; Abbott and Willar, 2017).

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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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105561.

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