Selecting proxy fishing mortality reference points for grouper-snapper fisheries under uncertainty about stock-recruitment steepness

Harford[1], W.J., Sagarese[2], S.R. & Karnauskas[2], M.

[1] Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, FL
[2] NOAA Southeast Fisheries Science Center, Sustainable Fisheries Division Miami, FL

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Abstract

The U.S. Magnuson-Stevens Fishery Conservation and Management Act requires management benchmarks to be defined in relation to maximum sustainable yield (MSY). However, supporting scientific information often lags behind this management expectation. This problem is epitomized by uncertainty about stock-recruitment steepness, which directly affects delineation of MSY-related reference points. We demonstrate a solution to the problem of selecting fishing mortality proxies under steepness uncertainty by coupling simulation modeling with the use of Bayesian belief networks. This approach is applied to 17 stocks of the southeastern US and US Caribbean that collectively represent an assemblage of gonochoristic reef fishes and a second assemblage of hermaphroditic reef fishes (families: Lutjanidae, Balistidae, Carangidae, Malacanthidae, Serranidae). Degree of belief is assigned to stock-recruitment steepness in the form of a prior probability distribution. We then identify proxy fishing mortality reference points based on spawning potential ratios (SPRs) that have the strongest probabilistic basis for achieving MSY-level catches for each of the two reef fish assemblages. Delineation of reference points occurs without reliance on any specific point estimate of steepness but instead reflects steepness uncertainty in the decision of selecting management reference points.

Introduction

Fishery legislation such as the U.S. Magnuson-Stevens Fishery Conservation and Management Act (MSFCA) has been put in place to ensure that stocks are managed at levels that will maximize social, economic, and ecological benefits of exploited species over the long term (NOAA, 2007). A key tenet of such legislation is to define an "optimum" stock level where extractive uses can be maximized, that is then maintained through time (NSG, 2016). In the case of the MSFCA, legislation requires the definition of management benchmarks such as maximum sustainable yield (MSY). However, the definition of MSY, and maintenance of a population toward this level, requires knowledge of stock productivity – which is notoriously challenging to measure. Stock-recruitment relationships strongly determine the theoretical stock size (i.e., B_{MSY}) at which surplus production is maximized (Brooks et al., 2010; Mangel et al., 2010; Punt et al., 2014). Delineation of reference points like B_{MSY} also depends on natural mortality rates and fishery selectivity (Brodziak, 2002; Mangel et al., 2013). In developing stock rebuilding plans, estimates of future numbers of recruits are required, which then help to determine appropriate fishing mortality rates to ensure that rebuilding occurs within an expected time frame (Punt and Methot, 2005). Because of the typically noisy relationship between spawning stock and recruitment, and due to the lack of direct estimates of natural mortality and selectivity, the availability of scientific information for many species has lagged behind the informational requirements necessary for management.

Fishery management for stocks belonging to reef fish complexes of the southeastern US and US Caribbean regions often face circumstances where relationships between spawning biomass and recruitment are highly uncertain. While it is possible to estimate parameters of stock-recruitment relationships during quantitative stock assessment, and this has been attempted for some of the stocks that we included in this study, data available to stock assessment models typically prevent reliable estimation of stock-recruitment steepness (Lee et al., 2012; SEDAR, 2014, 2012). The steepness parameter aids in describing the shape of stock-recruitment relationships and has an important influence on determining the stock size where surplus production is maximized (Fig. 1). Steepness uncertainty accordingly creates challenges in selecting optimality-based reference points like MSY, the rate of fishing that produces MSY (F_{MSY}), and the spawning stock biomass level that is associated with production of MSY (B_{MSY}). But despite challenges in establishing MSY-based reference points, reef fish fisheries are typically managed using regulatory frameworks based on these types of reference points, notwithstanding additional economic and ecosystem-based management objectives (CFMC, 1985; GMFMC, 1984; NOAA, 2007; SAFMC, 1983). As a consequence of a lack of direct information on steepness, it is necessary to use reference point proxies for achievement of MSY, such as the fishing mortality that produces a spawning potential ratio (SPR) of x% of unfished SPR, which is sometimes thought of as a proxy for SPR at F_{MSY}. However, selection of proxy reference points implies an assumption about the effect of steepness on stock productivity. In many cases, the use of assumed reference point proxies remains untested and can potentially affect achievement of fishery objectives.

Simulations were carried out to identify management benchmarks that had the highest probabilities of achieving optimality-based fishery objectives, given assignment of prior probability distributions to steepness as an expression of steepness uncertainty. Our objective was to provide guidance on selecting proxy fishing mortality reference points without dependence on an accurate estimate of steepness of the simulated stock. This objective was achieved through simulating the long-term or end-state performance expectations of alternative fishing mortality proxies against stock specified with a variety of different steepness levels specified in simulated stock dynamics. Performance outcomes were marginalized across simulations with different steepness values. Marginal performance of a fishing mortality proxy refers to the process of integration across simulations that differed in terms of “true simulated” steepness using an approach known as Bayesian networks and by assigning a prior probability distribution to steepness. Bayesian Networks (BNs) have previously been used to support resource management decision-making (Marcot et al., 2001; Parkes et al., 2016; Underwood et al., 2016). We applied this approach to a collection of 17 life histories from reef-associated stocks comprising gonochoristic species (families: Balistidae, Carangidae, Lutjanidae, and Malacanthidae), and hermaphroditic groupers (family: Serranidae). Our approach enables policy decisions to move past the speculation and conjecture that is sometimes present in specifying fishing mortality reference points when steepness is uncertain.

Methods

The study involved four steps. First, stock dynamics equations and input values for life history parameter were specified for each fish stock. Second, SPR-based fishing mortality proxies were specified. Third, the long-term or end-state performance of these proxies was simulated under different scenarios about stock-recruitment steepness. Fourth, BNs were used to synthesize simulation outcomes and highlight how weighted performance outcomes based on prior probability distributions for steepness can support reference point selection in the face of recruitment uncertainty.

Simulating stock dynamics

Selected reef fish stocks were judged to have sufficiently reliable and detailed life history information based on being previously subjected to peer-reviewed quantitative stock assessment

(Table 1). A few distinct stocks of the same species were included based on life history variation in growth and natural mortality. Population dynamics models were age-structured and functioned on an annual time step. Within each annual time step, growth occurred first, followed by reproduction, and then by total mortality (i.e., natural mortality plus fishing mortality). Age-0 or age-1 recruitment (depending on decisions made during stock assessments) followed a re-parameterization of the Beverton-Holt stock recruitment relationship based on steepness:

$$R_t = \left(\frac{0.8 R_0 h B_t}{0.2 B_0 (1-h) + (h-0.2) B_t} \right) \exp\left(\text{Normal}\left(0, \sigma^2\right) - \sigma^2 / 2 \right), \tag{1}$$

where t is the annual time step, R_t is recruits in numbers; B_t is a measure of spawning biomass; R_0 is unfished recruits, h is steepness, and σ is standard deviation of lognormal recruitment deviates. Steepness describes the fraction of unfished recruitment when spawning biomass has declined to 20% of its unfished level (Beverton and Holt, 1957; Mace and Doonan, 1988). Lognormal recruitment deviations were specified with a standard deviation of 0.6, which is a typical assumption for stochastic recruitment variation (Beddington and Cooke, 1983). Growth in length (L) followed a von Bertalanffy function $\left(L_{age} = L_{\infty}\left(1 - \exp\left(-K\left(age - t_0\right)\right)\right)\right)$, with Brody coefficient K, asymptotic length L_{∞}, and intercept parameter t_0, and length-whole weight conversion followed an exponential function $\left(W_{age} = \alpha L_{age}^{\beta}\right)$, with parameters α and β. For each stock, natural mortality was an inverse function of length and was scaled to a specified average lifetime rate based on empirical longevity observations (Hoenig, 1983; Then et al., 2015). Maturity ogives were available for each stock and reproductive output was specified as either eggs-per-female at age, where this information was available from the actual stock assessments, or as spawning weight-at-age.

Simulation design

Simulated evaluation of fishing mortality proxy reference points was carried out as a factorial combination of stock types (two assemblages: 10 gonochoristic stocks and 7 hermaphroditic stocks), steepness (6 levels), and fishing mortality proxy (4). Stock dynamics were simulated at six discrete steepness levels: 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9. Fishing mortality proxies were $F_{\mathrm{SPR30\%}}$, $F_{\mathrm{SPR40\%}}$, $F_{\mathrm{SPR50\%}}$, and $F_{\mathrm{SPR60\%}}$. Per-recruit analysis based on the age-structured population dynamics (described above, but excluding the stock-recruitment function, as recruitment was constant in per-recruit analysis) was used for each stock to identify corresponding fishing mortalities that produced SPRs of *x*% of unfished SPR. To enable reasonable comparability of HCR performance across stocks, fishery selectivity was specified as knife-edge at the age coinciding with 50% maturity (Table 2). Given a fishing mortality rate *F*, and vulnerable biomass, B_{v}, calculation of total allowable catch (TAC; reflecting the OFL in MSFCA terminology) used at each annual time step to determine removals by the fishery:

$$TAC = \frac{F_{\mathrm{lim}}}{F_{\mathrm{lim}} + M}\left(1 - \exp\left(-F_{\mathrm{lim}} - M\right)\right) B_v . \tag{2}$$

Prior to simulation runs, 1,000 time series of recruitment deviations were generated, which were then applied in parallel to each of the factorial combinations; this prevented performance differences from being attributed to chance differences in recruitment variation (Punt et al., 2016).

Performance measures were calculated by determining “true simulated” MSY-based reference points for each stock and steepness combination. These “true” MSY-based reference points were calculated using the age-structured population dynamics (described above) and with knife-edge selectivity coinciding with 50% maturity. Long-term performance was obtained by simulating each HCR for a duration corresponding to four times the maximum lifespan of each stock. After ensuring that stable end-state dynamics were produced for all life history types, average catch and biomass was estimated for the final 25-year duration of each simulation run.

The factorial design (stock by steepness by fishing mortality proxy) facilitated the subsequent use of BNs in producing probability-weighted performance outcomes, but also influenced how performance measures were required to be summarized. Each of 1,000 performance outcomes pertaining to a given stock, steepness, and fishing mortality proxy combination were calculated in relation to "true simulated" MSY and B_{MSY}. Catches were divided by MSY and were binned into discrete performance categories of: 0 to <0.4, 0.4 to <0.8, 0.8 to <1.2, 1.2 to <1.6, 1.6 to <2.0, and 2.0 to <2.4. Likewise, biomasses were divided by B_{MSY} and were binned into discrete performance categories between 0 and 4.8 based on an interval size of 0.4. Binning of performance outcomes was required to populate node probability tables, which are used in constructing BNs. These node probability tables were constructed separately for each performance measure and fishing mortality proxy.

Probability weighted performance measures

Performance of a fishing mortality proxy is *conditional* on steepness specified in a given simulation scenario. Consequently, a more desirable modeling outcome would be to generate marginal performance (or *unconditional* performance), which integrates performance for a fishing mortality proxy across plausible steepness values and life histories within a fish assemblage. Using BNs, posterior probability weighted performance outcomes were based on simulation outcomes and prior probability weightings that were assigned to steepness levels used in simulation scenarios (i.e., 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9). Three different priors were specified to represent alternative viewpoints about stock-recruitment steepness: 'certain', where a nonzero weighting was assigned to only one of the steepness levels; 'less certain', where discrete prior probabilities for each steepness level were calculated based on an informative beta prior from a previous meta-analysis (Shertzer and Conn, 2012); and, 'least certain' using a discrete uniform prior. In the 'certain' case, a prior probability of one was assigned to steepness of 0.8, which is close to the mode of 0.84 from the informative beta prior of Shertzer and Conn (2012). Although steepness is a continuous parameter, discrete values were used in our simulation runs because in the authors recent experiences with data-limited MSEs in the US Caribbean and Gulf of Mexico we have found that highly integrative approaches (those which typically integrate across multiple parameters) are not easily interpretable and can sometimes complicate decision-making (see Butterworth et al., 2010 for further discussion). While BNs can be used to integrate across a continuous parameter, we focused on the clarity that constructing BNs based on a few discrete hypotheses can bring to policy discussions.

Marginalization produced *unconditional* performance, which was calculated according to probability rules. For example, $P(h,\theta)$ is the joint probability distribution of stock-recruitment steepness, *h*, and θ, which represents the discrete categories of any given performance measure. Because probabilistic outcomes associated with θ are *conditional* on steepness, the fundamental rule of conditional probability applies:

$$P(h,\theta) = P(h) \times P(\theta \mid h), \tag{3}$$

where $P(h)$ is prior probability of *h* and $P(\theta \mid h)$ is performance conditional on the specified steepness level. Marginalization across steepness levels, *i*, for a given level of θ_j is calculated:

$$P(\theta_j) = \sum_i P(\theta_j \mid h_i) \times P(h_i). \tag{4}$$

Probability distributions, θ, are the child nodes of the BNs that we present herein. The resulting analysis was used to produce separate marginal outcomes for each performance measures, fishing mortality proxy, and for two fish assemblages: gonochoristic and hermaphroditic stocks. In integrating performance across a fish assemblage, each stock within the assemblage was given equal weighting. Computations of BNs were carried out using the software AgenaRisk (Fenton and Neil, 2012).

Results

For 17 simulated reef fish life histories, "true simulated" reference points of B_{MSY}/B_0 and SPR associated the long-term achievement of MSY were between 0.1 and 0.5 and between 0.1 and 0.7, respectively, which of course depended on specified steepness level (Fig. 2). For gonochoristic reef fishes, marginal performance outcomes based on the prior distribution provided by Shertzer and Conn (2012) resulted in $F_{40\%\mathrm{SPR}}$ having the greatest probability mass centered around long-term achievement of MSY while maintaining also biomass in proximity to B_{MSY} (Figs. 3B & 4B). For the assemblage of hermaphroditic reef fishes, $F_{50\%\mathrm{SPR}}$ had the greatest probability mass centered around long-term achievement of MSY while also maintaining biomass in proximity to B_{MSY}. In the case of the 'least certain' uniform prior for steepness, greater weight is given to low steepness values, and thus more conservative fishing mortality proxies were required to achieve MSY-based fishery objectives (Figs. 3C & 4C). Conversely, from a viewpoint of certainty in selecting a point-estimate for steepness of 0.8, probabilities of achieving MSY-based reference points were most centered around $F_{30\%\mathrm{SPR}}$ for gonochoristic stocks and $F_{40\%\mathrm{SPR}}$ for hermaphroditic stocks (Figs. 3A & 4A).

Discussion

An inability of stock assessment models to generate reliable estimates of steepness, often a result of existing data limitations such as lack of contrast in available time series, can prevent the determination of MSY benchmarks for reef fish stocks (e.g., SEDAR, 2011, 2009). As a result, SPR-based reference points are often adopted and decisions regarding appropriate proxy values can vary by life history characteristics. Currently, fishing mortality rates are implemented for Gulf of Mexico red snapper based on a SPR of 26% (SEDAR, 2014), in contrast to the more conservative SPR of 50% used for the long-lived hermaphroditic goliath grouper in the southeast US (SEDAR, 2016a). The most common proxy used for defining fishing mortality rates for reef fishes in southeast US is a SPR of 30%. Our simulations suggest that achieving MSY-based performance outcomes is commensurate with $F_{40\%SPR}$ for gonochoristic reef fishes and $F_{50\%SPR}$ for hermaphroditic reef fishes. Notably, these findings are dependent on fishery selectivity being specified at age coinciding with 50% maturity, whereas other selectivity assumptions could lead to preference for other HCRs (Table 2). Brooks et al. (2010) suggested that a SPR of 30% would only be appropriate for very resilient stocks and reinforced the importance of selecting a level of SPR based on life history characteristics. Our results support this conclusion on the basis that a SPR of 30% was most strongly supported in simulations relying on a high steepness value (i.e., the ‘certain’ steepness prior of 0.8 used in Figs. 4 & 5). However, fishing mortality proxies based on SPR 40% or SPR 50% provided the strongest basis for achieving MSY-based reference points when the possibility of stocks having low steepness values was acknowledged in specifying prior probability distributions.

Our analysis contributes guidance to data-limited HCR design, as it pertains to reef fish management complexes of the Gulf of Mexico, South Atlantic, and Caribbean regions. Greater than 70% of all stocks (across a variety of life history types including pelagic and demersal stocks) in the US South Atlantic and Gulf of Mexico are considered data-limited, whereas in the US Caribbean all 179 stocks are data-limited and more than half of the 179 stocks of the US Caribbean lack rigorous management strategies (Anon., 2013; Berkson and Thorson, 2015; Newman et al., 2015; SEDAR, 2016b, 2016c). The manner in which we approached HCR design in the absence of certainty about stock productivity can be viewed as an example of coping with policy-driven mandates that sometimes outpace information availability.

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Figure captions

Figure 1. (A) Examples of two Beverton-Holt stock-recruitment relationships with different steepness values. (B) Stock-recruitment steepness influences the theoretical stock size (i.e., B_{MSY}) at which surplus production is maximized. Solid dots denote maximum sustainable yield, dashed lines are calculated using steepness of 0.8 and solid lines are calculated using a steepness of 0.5.

Figure 3. Simulated relationships between steepness and $B_{MSY}/B0$ (A, C & E) and between steepness and SPR-at-MSY (B, D & F) for gonochoristic and hermaphroditic reef fish stocks.

Figure 4. Probability weighted long-term biomass performance (as biomass relative to B_{MSY}) for four SPR-based fishing mortality proxies. Histograms illustrate steepness prior probability distributions, which are described as: (A) certain, using a point-estimate of 0.8; (B) less-certain, using an informative prior from meta-analysis of demersal fish stocks (Shertzer and Conn, 2012), and (C) least-certain, using a diffuse prior bound between 0.4 and 0.9.

Figure 5. Probability weighted long-term catch performance (as catch relative to MSY) for four SPR-based fishing mortality proxies. Histograms illustrate steepness prior probability distributions, which are described as: (A) certain, using a point-estimate of 0.8; (B) less-certain, using an informative prior from meta-analysis of demersal fish stocks (Shertzer and Conn, 2012), and (C) least-certain, using a diffuse prior bound between 0.4 and 0.9.

Table 1. Life histories of reef fish stocks included in simulation testing. K and L_∞ are von Bertalanffy growth parameters, M_{ave} is average lifetime natural mortality ($year^{-1}$), Max age is observed maximum age, GOM is Gulf of Mexico, SATL is South Atlantic, STT is Saint Thomas, US Virgin Islands, and PR is Puerto Rico.

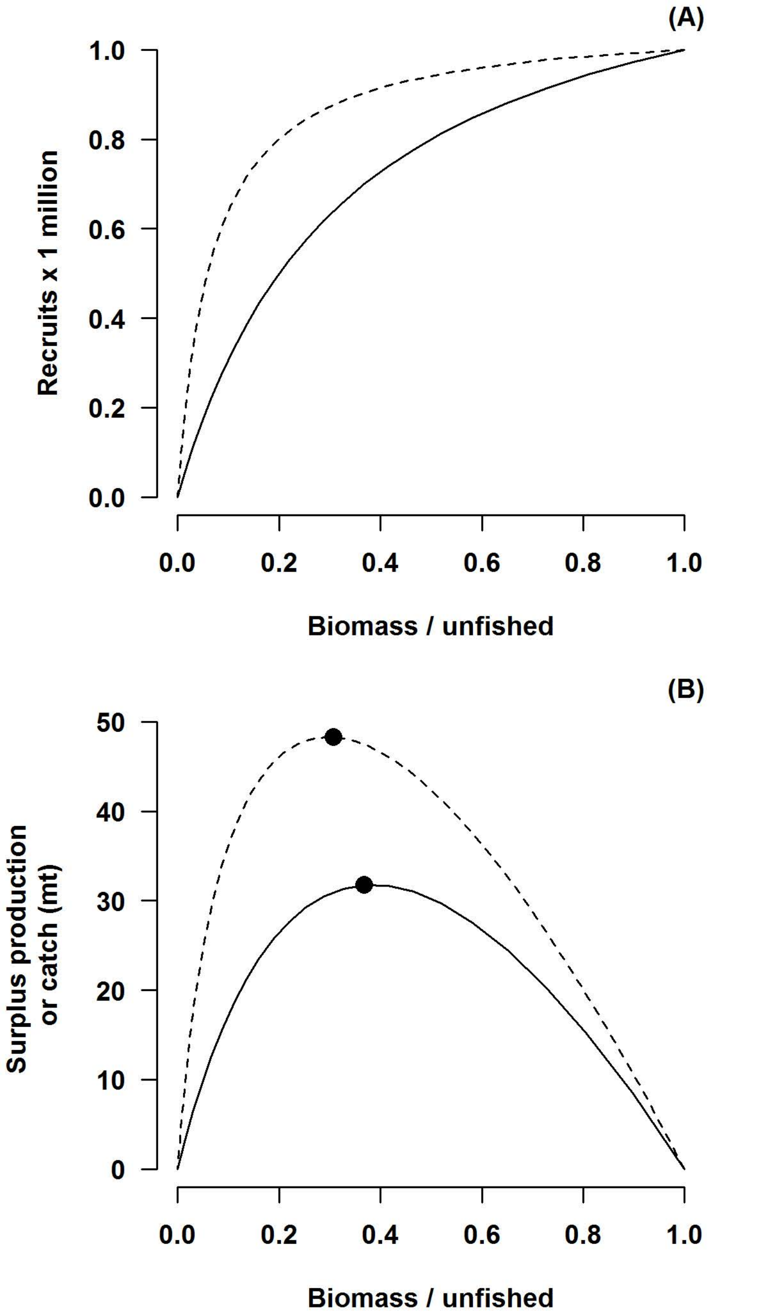
Scientific name	Common name	K yr^{-1}	L_∞ mm	Max age	M_{ave} yr^{-1}	SEDAR #
Gonochoristic assemblage						
Lutjanus analis	Mutton snapper (GOM)	0.16	861	40	0.11	15
Lutjanus campechanus	Red snapper (GOM)	0.19	856	48	0.09	31
Lutjanus campechanus	Red snapper (SATL)	0.24	902	58	0.08	24
Ocyurus chrysurus	Yellowtail snapper (SATL & GOM)	0.13	618	23	0.19	27
Rhomboplites aurorubens	Vermilion snapper (SATL)	0.12	506	19	0.22	17
Lopholatilus chamaeleonticeps	Tilefish (GOM)	0.13	830	30	0.14	22
Lopholatilus chamaeleonticeps	Tilefish (SATL)	0.19	825	40	0.10	25
Seriola dumerili	Greater amberjack (GOM)	0.17	1436	15	0.28	33
Balistes capriscus	Gray triggerfish (GOM)	0.14	590	15	0.27	43
Caulolatilus microps	Blueline tilefish (SATL)	0.19	739	43	0.10	50
Hermaphroditic assemblage						
Epinephelus morio	Red grouper (GOM)	0.12	827	29	0.14	42
Epinephelus morio	Red grouper (SATL)	0.21	848	26	0.14	19
Mycteroperca bonaci	Black grouper (GOM & SATL)	0.14	1334	33	0.14	19
Mycteroperca microlepis	Gag grouper (GOM)	0.13	1277	31	0.13	33
Hyporthodus niveatus	Snowy grouper (SATL)	0.09	1065	35	0.12	36
Epinephelus guttatus	Red hind (STT)	0.07	601	18	0.25	35
Epinephelus guttatus	Red hind (PR)	0.10	514	17	0.26	35

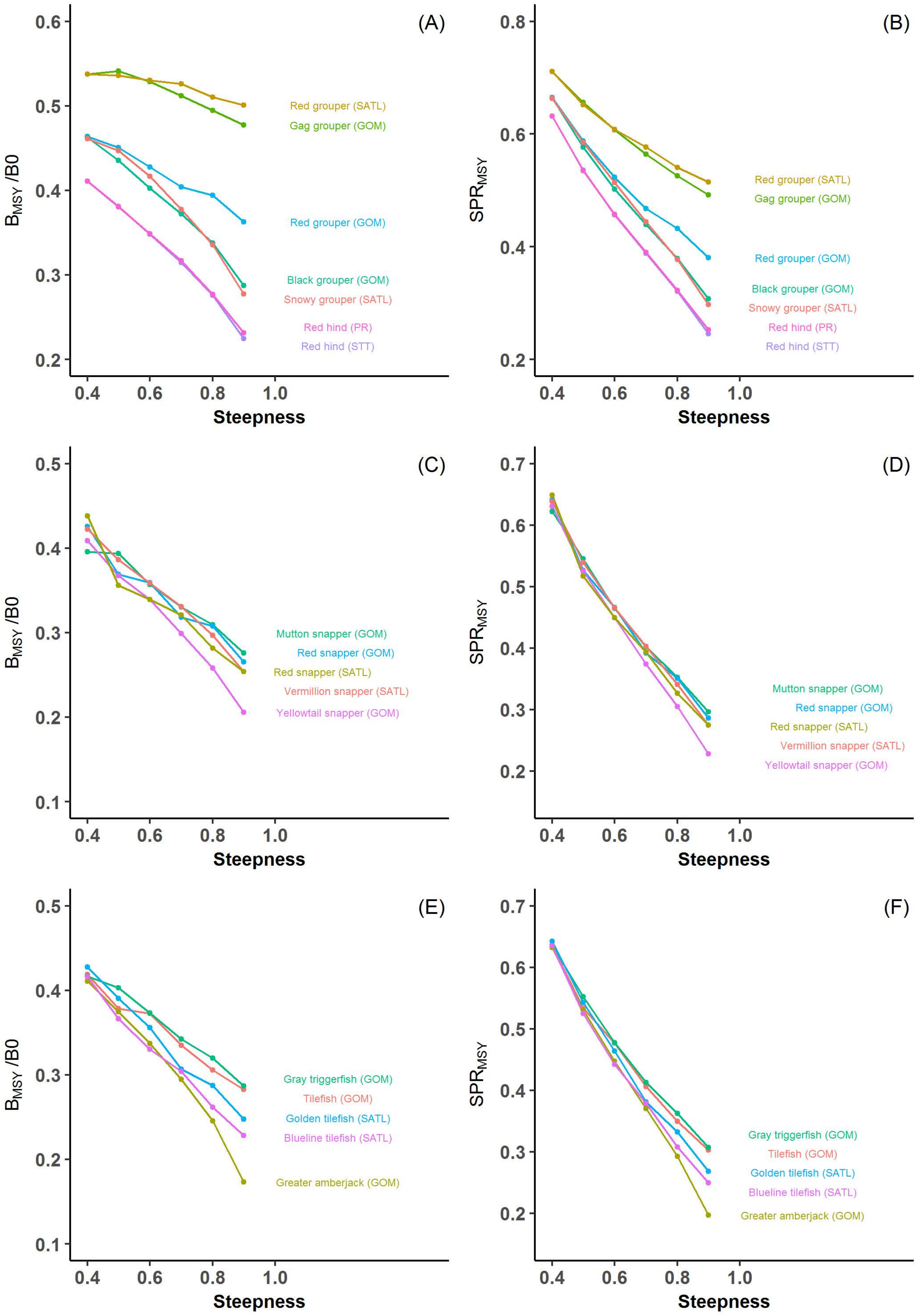
*Southeast Data, Assessment, and Review (SEDAR) stock assessments can be accessed at www.sedarweb.org.

Table 2. Summary of age and length at 50% maturity (A50 & L50, respectively) used in simulations and current regulatory minimum harvest size for federal waters. L50 was also used in simulation runs to designate knife-edge selection by the fishery. GOM is Gulf of Mexico, SATL is South Atlantic, STT is Saint Thomas, US Virgin Islands, and PR is Puerto Rico, TL is total length and FL is fork length.

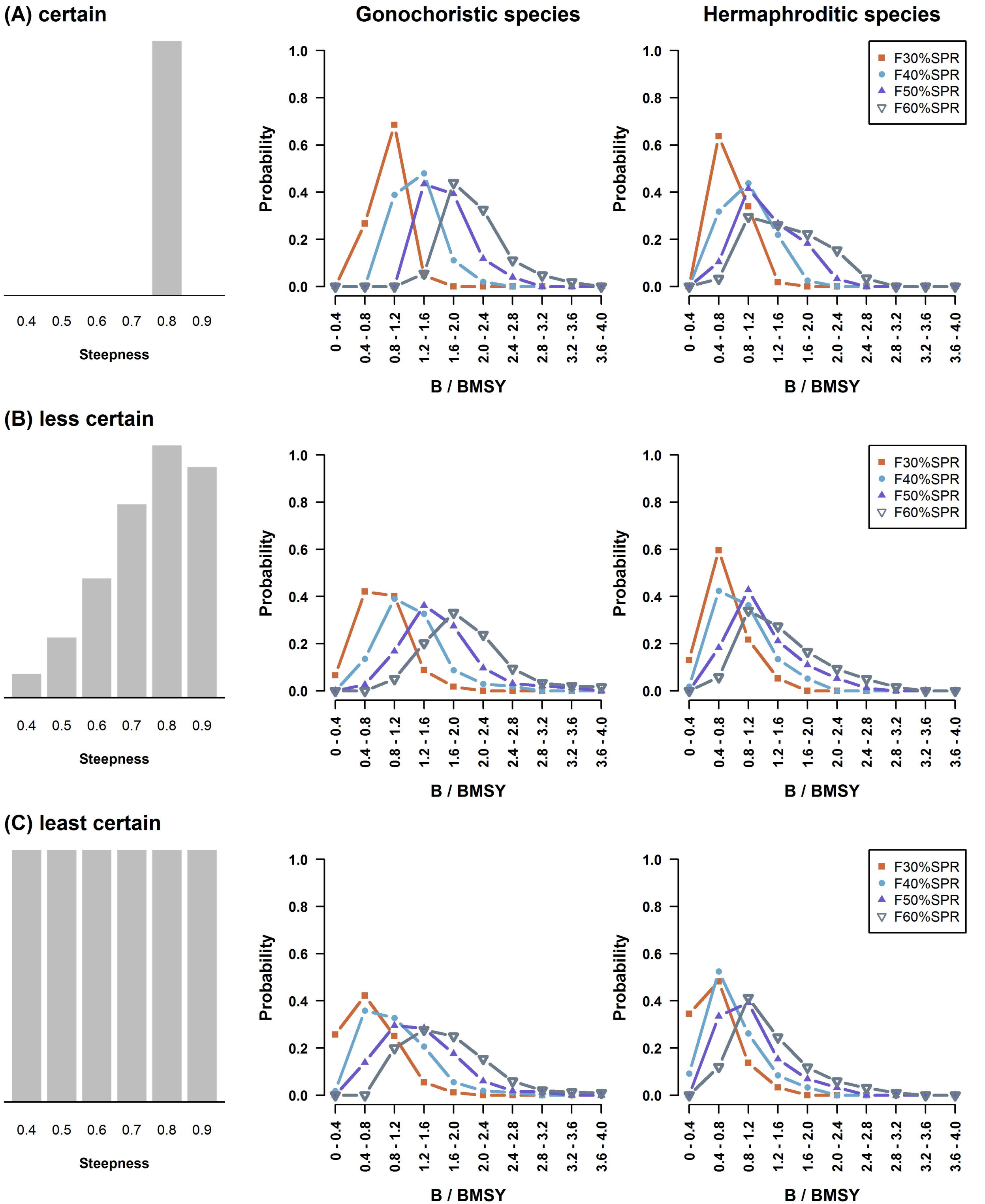
Common name	**A50**	**L50**	**Federal commercial regulatory size limit**
Mutton snapper (GOM)	3	433 mm TL	406 mm TL
Red snapper (GOM)	2	315 mm TL	330 mm TL
Red snapper (SATL)	2	348 mm FL	-
Yellowtail snapper (SATL & GOM)	2	305 mm TL	305 mm TL (GOM)
Vermilion snapper (SATL)	1	211 mm TL	305 TL
Tilefish (GOM)	2	345 mm TL	-
Tilefish (SATL)	3	399 mm TL	-
Greater amberjack (GOM)	4	832 mm FL	914 mm FL
Gray triggerfish (GOM)	1	183 mm FL	356 mm FL
Blueline tilefish (SATL)	3	445 mm TL	-
Red grouper (GOM)	3	328 mm TL	457 mm TL
Red grouper (SATL)	3	459 mm TL	508 mm TL
Black grouper (GOM & SATL)	7	904 mm TL	610 mm TL
Gag grouper (GOM)	4	605 mm TL	559 mm TL
Snowy grouper (SATL)	5	557 mm TL	-
Red hind (STT)	3	251 mm FL	-
Red hind (PR)	3	232 mm FL	-

*Southeast Data, Assessment, and Review (SEDAR) stock assessments can be accessed at www.sedarweb.org.

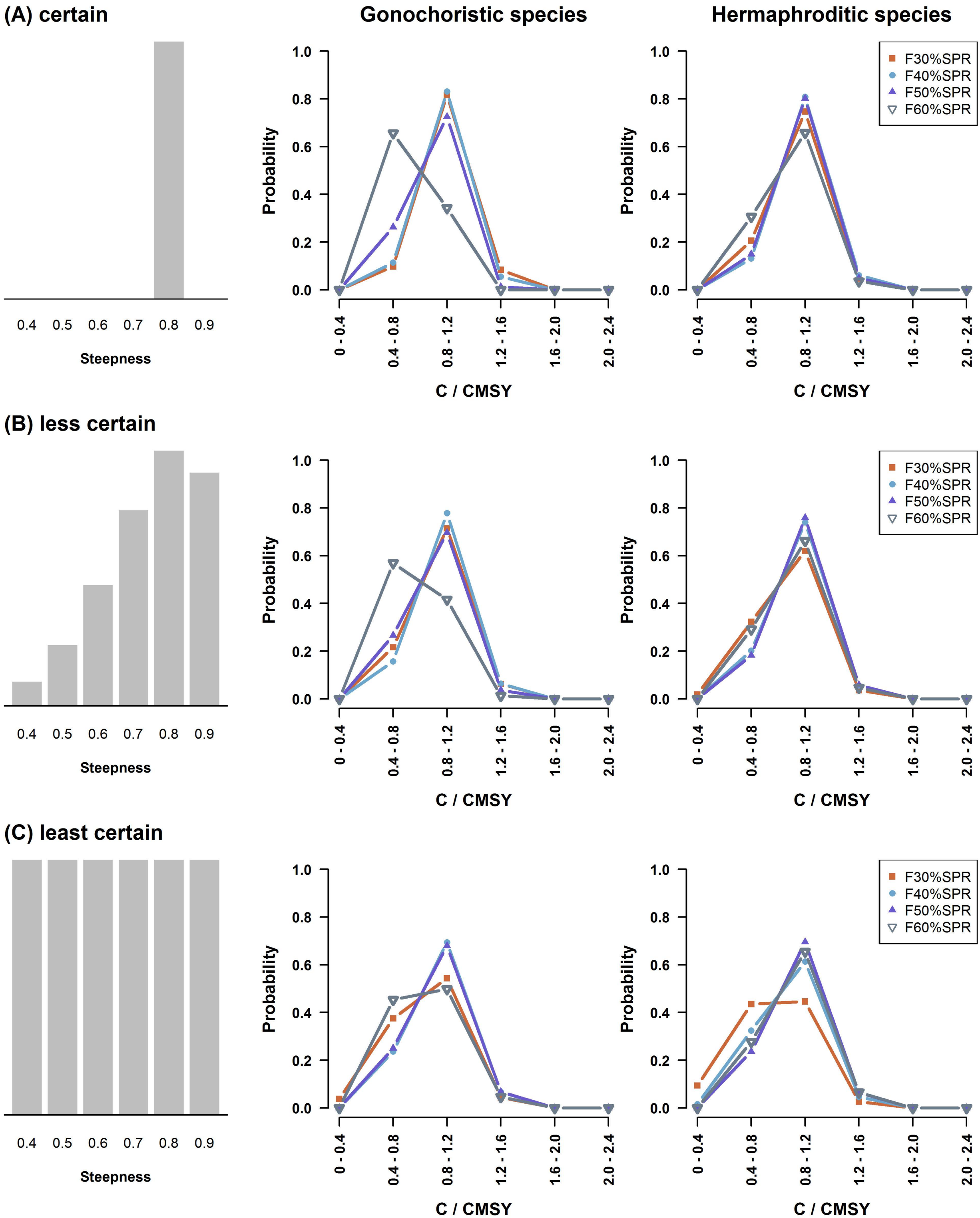

(A)
Recruits x 1 million
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Biomass / unfished
(B)
Surplus production
or catch (mt)
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
Biomass / unfished



(A)
(B)
(C)
(D)
(E)
(F)
B_{MSY} /B0
SPR_{MSY}
Steepness
0.4
0.6
0.8
1.0
Red grouper (SATL)
Gag grouper (GOM)
Red grouper (GOM)
Black grouper (GOM)
Snowy grouper (SATL)
Red hind (PR)
Red hind (STT)
Mutton snapper (GOM)
Red snapper (GOM)
Red snapper (SATL)
Vermillion snapper (SATL)
Yellowtail snapper (GOM)
Gray triggerfish (GOM)
Tilefish (GOM)
Golden tilefish (SATL)
Blueline tilefish (SATL)
Greater amberjack (GOM)



(A) certain
(B) less certain
(C) least certain
Gonochoristic species
Hermaphroditic species
Steepness
0.4
0.5
0.6
0.7
0.8
0.9
Probability
0.0
0.2
0.4
0.6
0.8
1.0
B / BMSY
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2.0
2.0 - 2.4
2.4 - 2.8
2.8 - 3.2
3.2 - 3.6
3.6 - 4.0
F30%SPR
F40%SPR
F50%SPR
F60%SPR



(A) certain
(B) less certain
(C) least certain
Gonochoristic species
Hermaphroditic species
Steepness
0.4 0.5 0.6 0.7 0.8 0.9
Probability
C / CMSY
0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
1.6 - 2.0
2.0 - 2.4
F30%SPR
F40%SPR
F50%SPR
F60%SPR