North American Journal of Fisheries Management 38:120–139, 2018
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ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1002/nafm.10007

ARTICLE

Establishing Stock Status Determination Criteria for Fisheries with High Discards and Uncertain Recruitment

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Abstract
Maximum sustainable yield (MSY)-based reference points are often prescribed by national and international laws as the basis for catch limits (e.g., the Magnuson–Stevens Reauthorization Act in the United States). However, MSY is highly dependent on the assumed selectivity pattern and catch allocation of the fisheries. The addition of bycatch fleets or mortality from discarding further complicates MSY calculations, and no prescribed approach has been agreed upon for including complex fleet dynamics in dynamic pool models. Using the Gulf of Mexico Red Snapper *Lutjanus campechanus* fishery as an example, we demonstrate the various ways that MSY can be computed when multiple fleets and bycatch fisheries exist, and we illustrate the tradeoffs that occur between yield and spawning stock biomass (SSB). Presenting the full array of alternative MSY proxies, however, can lead to subjective decision making that may diminish the value of scientific advice by encouraging the maximization of yield at the expense of maintaining stocks within safe biological limits. We propose that the spawning potential ratio (SPR) associated with the global (theoretical maximum) MSY can be utilized as a reasonable proxy in most fishery applications. The yield streams required to achieve SPR_{MSY} can then be calculated conditional on extant selectivity patterns and bycatch levels. Our approach utilizes the inherently sustainable SSB associated with the global MSY as a rebuilding target while limiting disruption to the fishery by accounting for current fleet dynamics and avoiding unsustainable proxies that may result when bycatch or discard rates are high.

Fisheries management is predicated on the dichotomous balance of optimizing resource usage (in terms of yield or other socioeconomic factors) and maintaining population sizes within safe biological limits (Mace 1994; Punt et al. 2014). Maximum sustainable yield (MSY; see Table 1 for a complete description of symbols and acronyms) has often been prescribed by national and international laws as the basis for catch limits (e.g., the Magnuson–Stevens Reauthorization Act [MSRA] in the United States), but the MSY approach can be problematic (Larkin 1977). Because equilibrium calculations fail to account for a dynamic environment, extracting a fixed MSY has often caused stock collapses when populations naturally fluctuate (Mace 2001; Punt and Smith 2001). Since the epitaph for MSY was written (Larkin 1977), countless alternate biological reference points (BRPs) have been developed (Gabriel and Mace 1999). The focus of many BRPs has been either to achieve a portion of MSY (e.g., yield-per-recruit [YPR] proxies) or to prevent recruitment overfishing (i.e., to avoid harvesting at a rate that reduces the biomass to a level where recruitment becomes substantially impaired) through spawner-per-recruit analysis based on the spawning potential ratio (SPR; i.e., the fraction of the virgin spawning stock biomass [SSB] per recruit; Sissenwine and Shepherd 1987; Goodyear 1993). The YPR and SPR approaches are often theoretically appealing because they do not require an implicit or explicit understanding of the production function (unlike MSY analysis). However, YPR proxies focus solely on yield and do not account for recruitment overfishing, whereas SPR

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Received March 27, 2017; accepted October 24, 2017

proxies do not account for yield-optimizing metrics (Gabriel and Mace 1999).

A number of unifying theories among dynamic pool models (i.e., MSY, YPR, and SPR analyses) were developed in the 1980s and 1990s; through the inclusion of a stock–recruit curve in SPR analysis, these allowed explicit definition of SPR limits to prevent recruitment overfishing (Shepherd 1982; Sissenwine and Shepherd 1987; Mace 1994). Essentially, these methods suggested that the fishing mortality (matched to an associated limit SPR) corresponding to the slope of the stock–recruit curve at the origin represented the harvest rate above which the stock could no longer replace itself and fishing would no longer be sustainable (i.e., recruitment overfishing would occur; Mace and Sissenwine 1993). However, a critical limitation was the need to know the stock–recruit relationship (Gabriel and Mace 1999). Given the potential for weak compensation or Allee effects (i.e., depensation in recruitment) at low spawning population abundance (Frank and Brickman 2000; Keith and Hutchings 2012), determining the limit BRPs that identify the transition zone where recruitment overfishing is likely to occur is important for maintaining sustainable fisheries (Rosenberg et al. 1994). Based on estimates of fishing mortality at replacement, a variety of studies, including meta-analyses, empirical applications, and theoretical explorations, have concluded that SPR values below 20% represent high potential for recruitment overfishing (Goodyear 1993; Mace and Sissenwine 1993; Rosenberg et al. 1994; Gabriel and Mace 1999). However, SPR thresholds corresponding to recruitment overfishing may be higher for less-productive populations (Clark 2002; Forest et al. 2010) or when depensation exists in the stock–recruit relationship (Thompson 1993).

When considering proxies for MSY in the presence of unknown stock–recruit dynamics, Clark (1991, 1993) suggested a "min–max" approach to maximize the minimum yield across potential stock–recruit relationships and parameters. He demonstrated that even higher SPR values (35–45%) are warranted to achieve yields on par with MSY (i.e., >75% of MSY; Quinn et al. 1990; Clark 1991, 1993; Horbowy and Luzenczyk 2012; Punt et al. 2014). The approach has been widely utilized across an array of species (e.g., Pacific rockfish and crab stocks; Clark 2002; Siddeek 2003; Siddeek et al. 2004) and is often cited as the basis for SPR proxies worldwide. Although the approach is extremely useful when stock–recruit uncertainty limits the ability to calculate MSY, the results are still context dependent and should not be universally applied without case-specific applications (Clark 2002). Additionally, the methodology can be difficult to apply when bycatch or discards are an important factor in a given fishery and when these rates are volatile from year to year. Because discard and bycatch rates influence the level of yield that achieves a given rebuilding target, the full min–max analysis would need to be rerun yearly to ensure rebuilding if discard or bycatch levels are not stable.

Under the precautionary approach to fisheries management, MSY-based reference points continue to be utilized worldwide, albeit under a more refined methodology (e.g., harvesting at the fishing mortality that achieves MSY instead of at a constant catch; Mace 2001; Cadrin 2012; Punt et al. 2014). In the United States, federally managed fisheries are regulated under the MSRA, which includes provisions that explicitly require federal fishery management plans to provide for rebuilding stocks to a level consistent with producing the MSY (MSRA 2007). Although the MSRA is straightforward about managing stocks such that they can produce MSY, a number of complicating factors exists for calculating MSY (e.g., knowing the stock–recruit relationship), leading to a variety of proxies being utilized to define fishing mortality and biomass targets (Cadrin 2012). A brief meta-analysis of National Oceanic and Atmospheric Administration stock assessment reports, as collated in the National Marine Fisheries Service's Species Information System (https://www.st.nmfs.noaa.gov/sisPortal/), demonstrated the variety of BRP approaches that are currently utilized for federally managed species across the regional fishery management councils in the United States (Figure 1). The most commonly used were SPR proxies (consisting of 50% of the BRPs for the 116 stock assessments analyzed), followed by direct MSY-based BRPs (27%), but methods were highly variable across regions. The SPR approach has been widely adopted despite the many criticisms that exist (e.g., the potential for lack of proportionality between a cohort's spawning biomass and resulting recruitment if density dependence occurs during juvenile or adult life stages; Rochet 2000; Hilborn 2002).

Perhaps the most troublesome aspect of the MSRA guideline about managing a population to achieve MSY is the fact that MSY itself is not a well-defined concept, particularly when multiple fleets and fishing sectors exist (Goodyear 1996; Maunder 2002; Powers 2005). Strictly speaking, the theoretical global (or optimum/ultimate) MSY is achieved by fully harvesting at a single "critical" age where gains in population growth are balanced by losses due to natural mortality (Beverton and Holt 1957; Ricker 1975; Getz 1980; Reed 1980). However, in real-world applications, there is no practical way to achieve the global MSY (Ricker 1975) because fisheries cannot completely avoid fishing on younger animals, and the realized long-term yield is often considerably less than the global MSY (Beverton and Holt 1957; Goodyear 1996). The situation is further complicated when multiple fisheries compete for different components (e.g., size-classes) of the same resource and where the target species may be discarded as bycatch of another fishery, in which case the

TABLE 1. List of common symbols and acronyms used throughout the text.

Symbol or acronym	Definition	Meaning
MSRA	Magnuson–Stevens Reauthorization Act	Law governing marine fisheries management in United States federal waters
NS1	National Standard 1	Component of MSRA defining the use of maximum sustainable yield as the basis of management advice
BRP	Biological reference point	A target or limit biomass level or fishing mortality rate against which current stock status can be measured
MSY	Maximum sustainable yield	Maximum sustainable yield that can be obtained given the life history characteristics of the species and the fleet dynamics of the fishery, which accounts for stock–recruit dynamics
F_{MSY}	Fishing mortality that achieves MSY	The level of fishing mortality that, when fished over the long term, will achieve the MSY
$\mathrm{SSB}_{\mathrm{MSY}}$	Spawning stock biomass resulting from fishing at F_{MSY}	The level of spawning stock biomass that results when F_{MSY} is fished in the long term
MSY|global	Global MSY	Theoretical maximum sustainable long-term yield achieved by harvesting a single age-class where growth and death are balanced
OY	Optimum yield	MSY as reduced by any relevant economic, social, or ecological factors
YPR	Yield per recruit	Long-term yield that can be achieved at a given fishing level assuming that there is no relationship between spawners and recruits
MYPR	Maximum YPR	The maximum long-term yield that can be achieved assuming that there is no relationship between spawners and recruits (equivalent to associated MSY if steepness = 1.0)
SPR	Spawning potential ratio	Measure of depletion comparing resultant spawning biomass per recruit to the virgin level of spawning biomass per recruit
MSY|open_discards	MSY without bycatch or closed-season/individual fishing quota (IFQ) discards	MSY calculated with only directed fleets (including open-season discards) but assuming no closed-season or lack-of-IFQ discards and no bycatch
MSY|fixed_nondirect_discards	MSY with fixed closed-season and IFQ discards	MSY calculated with directed fleets (including open-season discards) assuming fixed closed-season and lack-of-IFQ discards but no shrimp bycatch
MSY|fixed_shrimp_bycatch	MSY with fixed shrimp bycatch	MSY calculated with directed fleets (including open-season discards) assuming fixed shrimp bycatch but no closed-season or lack-of-IFQ discards
MSY|fixed_discards	MSY with fixed closed-season and IFQ discards and shrimp bycatch	MSY calculated with directed fleets (including open-season discards) assuming fixed shrimp bycatch along with closed-season and lack-of-IFQ discards
MSY|linked	MSY with effort of all fleets proportionally linked	MSY calculated assuming that all directed (including open-season discards) and nondirected (i.e., shrimp bycatch, recreational closed season, and lack of IFQ) fleets are proportionally scaled based on a desired relative effort scheme
Landings from MSY|fixed_discards yield curve at $\mathrm{SPR}_{\mathrm{MSY}}$|global	SPR associated with global MSY or MYPR achieved with current fleet dynamics	Yield streams prescribed by the MSY|fixed_discards yield curve that achieve the SPR associated with global MSY

TABLE 1. Continued.

Symbol or acronym	Definition	Meaning
HL	Handline fleet	Commercial directed fishing fleet (includes both landings and open-season discards due to minimum size limits)
LL	Longline fleet	Commercial directed fishing fleet (includes both landings and open-season discards due to minimum size limits)
HBT	Headboat fleet	Recreational directed fishing fleet (includes both landings and open-season discards due to minimum size and bag limits)
MRIP	Recreational private/charter fleet	Recreational directed fishing fleet (includes both landings and open-season discards due to minimum size and bag limits)
C_No_IFQ	Commercial discard fleet without IFQ	Commercial nondirected discard fleet resulting from a lack of IFQ
R_Closed	Recreational discard fleet during closed seasons	Recreational nondirected discard fleet resulting from nondirected fishing effort during Red Snapper closed seasons
SHR	Shrimp bycatch fleet	Nondirected shrimp trawl bycatch fleet primarily discarding age-0–2 Red Snapper
SS3	Stock Synthesis 3	Integrated stock assessment program used for the current analysis

long-term yield and the spawning stock that will support it depend on the desired sector allocations (Maunder 2002; Powers 2005; Guillen et al. 2013). The resulting MSY can vary substantially depending on the fleet composition, the relative effort, and the mixture of selectivity patterns assumed (Beverton and Holt 1957; Maunder 2002).

Limited guidance has been provided on best practices for calculating MSY when multiple fishing sectors exist or on how to objectively choose from amongst the various MSY methods available. The MSRA addresses the issues of multiple fleets and discards by simply stating that MSY should be attained while simultaneously reducing bycatch to the extent practicable and achieving an equitable allocation amongst fishery sectors (MSRA 2007). Balancing the competing objectives of bycatch reduction and fair allocation can be challenging when a multitude of users with disparate interests exists, including various fisheries and other stakeholders, and the problem is further exacerbated when there is uncertainty about the long-term productivity of a stock. Goodyear (1996) noted that simply expounding MSY as a management target (as is done in the MSRA) is insufficient to provide management advice without further guidance on the desired long-term fleet allocations or resource age composition. Powers (2005) suggested that it is the job of managers to determine the "optimal" mix of fisheries desired and that the method utilized for calculating MSY should depend on the context of how bycatch has arisen and whether it can be effectively reduced. Maunder (2002) summarized the problem well:

> …the question becomes how do we define MSY with respect to the effort allocation among the fishing methods…? Is MSY defined as that achieved by the current proportional effort allocation, by the fishing method that produces the highest MSY, or something else? If we force effort to change to levels at MSY, it is unlikely that the proportional effort allocation will stay the same. If effort is restricted to the fishing method that produces the highest MSY, it may not be practical to increase effort to levels that would produce MSY.

We attempt to address these questions by demonstrating the various methods available to calculate MSY when a resource is harvested by multiple directed and bycatch fisheries; as a case study, we use Gulf of Mexico (hereafter, "Gulf") Red Snapper *Lutjanus campechanus*, for which fisheries management has been particularly contentious due to the high dimensionality of the stakeholder groups involved. The multiple-fleet MSY investigations of previous authors (i.e., Goodyear 1996; Schirripa 1999; Powers 2005) are extended by including the full complexity of fleet dynamics for Red Snapper and comparing the suite of methods available to calculate MSY. The various MSY-based overfishing proxies that managers must consider when multiple

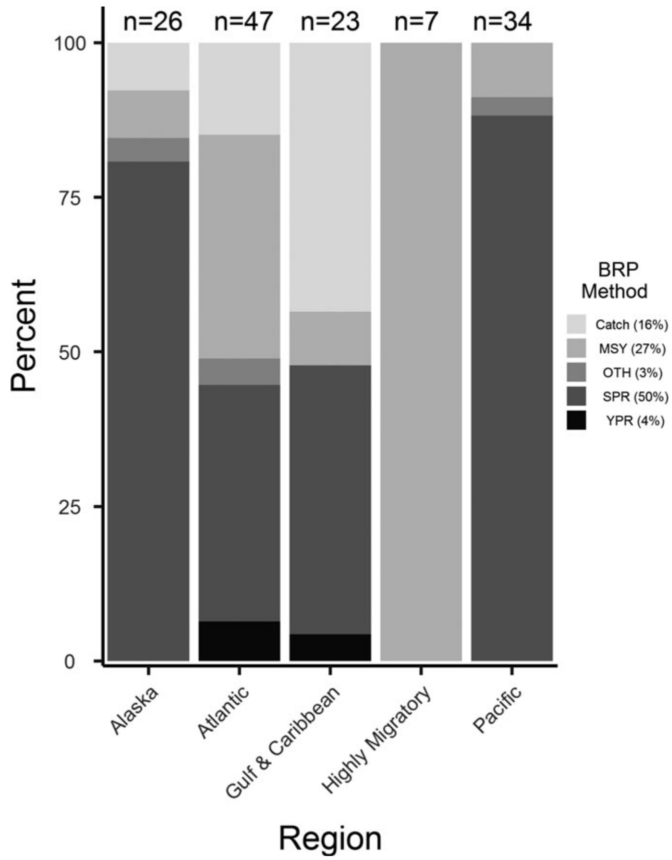

FIGURE 1. Summary of the various biological reference point (BRP) models used to manage federal fisheries in the United States (catch = catch-based BRP targets; MSY = maximum sustainable yield; OTH = other, non-specified BRPs; SPR = spawners per recruit; YPR = yield per recruit). Methods are presented by region and are given as a percentage of the total number of stock assessments included in the analysis for that region (sample size is provided above each bar). The percent composition of each method across all regions is provided in parentheses next to the corresponding method in the legend. Data are based on a meta-analysis of stock assessment reports from the National Marine Fisheries Service's Species Information System (https://www.st.nmfs.noaa.gov/sisPortal/).

fisheries harvest a resource are described, and the biological implications associated with each decision are illustrated. Finally, a methodology is developed based on global MSY theory, which can be utilized for cases where the production function is uncertain, to identify bounds on sustainable SPR targets. The approach is similar to Clark's (1991, 1993) min–max method but directly addresses issues of time-varying bycatch and rebuilding targets. We believe that the framework can provide a useful tool for determining sustainable SPR proxies that conform to the MSRA guidelines and can be applied when MSY is polyvalent or is not strictly determinable (e.g., uncertainty exists in the stock–recruit relationship).

METHODS

The long-term performance of potential MSY proxies was examined through the use of projections based on the results from the most recent stock assessment for Gulf Red Snapper (SEDAR 2015). The results presented here (e.g., reference points and resulting yield streams) are not meant for use as final management targets but provide a useful demonstration of how these methods could be applied.

Red Snapper background.— Red Snapper is one of the most prized reef fish in the Gulf; not surprisingly, it was one of the first species to experience overfishing in the region. It was estimated that by the 1980s, total egg production for Gulf Red Snapper had been reduced by more than 95% (Porch 2007; SEDAR 2015). Several management measures were implemented in the late 1980s to rebuild Red Snapper, including catch limits, minimum size restrictions, and requirements for shrimping vessels to install bycatch reduction devices in their trawl nets to reduce discards of juvenile Red Snapper (Hood et al. 2007). These measures appear to have led to modest increases in the Red Snapper population, but substantial gains were not evident until after 2006, when regulations reduced recreational and commercial catch limits by nearly half and offshore shrimp trawling was reduced by about 75% due to regulatory and economic factors. Since then, the number of Red Snapper has increased rapidly and is now several times higher than most anglers have experienced in their lifetimes (SEDAR 2015). As a result, more anglers are entering the fishery, and the recreational fishing season for Red Snapper has become progressively shorter to ensure that the recreational allocation is not exceeded.

A critical limitation for assessing and managing Red Snapper has been the inability to accurately determine the productivity of the stock. Productivity depends in part on the relationship between egg production (spawners [*S*]) and subsequent recruitment (*R*); for Gulf Red Snapper, this relationship is not well estimated, although productivity is known to be high (SEDAR 2015). When an asymptotic Beverton–Holt relationship is assumed in the stock assessment model, the estimates of steepness are typically near the mathematical limit of 1.0 because the estimates of recruitment have tended to increase after 1980 despite decreases in the corresponding spawner estimates. However, it is possible that the lower level of recruitment estimated prior to the 1980s is largely an artifact of the relative dearth of information available compared to the recent period (Porch 2007). Regardless of the cause or veracity of the apparent change in productivity, recent scientific advice has been predicated on forecasts assuming that recruitment levels in the near future will be similar to the average of the levels estimated for the more recent time period (Cordue 2005; SEDAR 2015). The long-term recruitment potential (i.e., spawner–recruit steepness) is regarded as high, but the exact level is indeterminate (due to difficulty in independently estimating the various stock–recruit parameters), making it impossible to calculate MSY or its associated reference points (i.e., the fishing mortality that achieves MSY [F_{MSY}] and the resulting SSB [SSB_{MSY}]) explicitly. The usual approach in this situation is to employ MSY proxies that do not require knowledge of the long-term recruitment potential but are assumed to produce stock levels that can consistently support MSY (e.g., SPR proxies).

The Gulf of Mexico Fishery Management Council's (GMFMC) Scientific and Statistical Committee recognized the difficulty in specifying the MSY for Red Snapper and has recommended maintaining the spawning potential of the stock at 26% of the unfished level as a proxy for the level that would produce MSY based on analysis using a conditional MSY approach (i.e., MSY||linked; see the Maximum Sustainable Yield Reference Points section below; GMFMC 2007). However, there remains considerable interest in alternative proxies with lower spawning potential thresholds, such as the maximum YPR (MYPR) from the directed fishery after allowing for the incidental mortality from shrimp trawls and closed-season discarding. Porch (2007) showed that this proxy would likely drive the Red Snapper stock down to only a few percentage points of the unfished level unless the bycatch level and closed-season discarding were greatly reduced. A confounding factor in allowing low SPR values for Red Snapper is that target SPR proxies are set for the Gulf-wide stock and variable regional harvest can lead to differential SPR by region (often causing the eastern stock component to be considerably lower than the Gulf-wide SPR target; SEDAR 2015). Accordingly, it is crucial to explore proxies for MSY that are robust to uncertainties regarding recruitment and also accommodate the dynamic mix of fisheries that exploit Red Snapper.

Modeling framework.— The deterministic projection models were implemented using Stock Synthesis 3 (SS3, version 3.24U; Methot and Wetzel 2013) based on the model structure of the most recent stock assessment model for Gulf Red Snapper and using the terminal year stock assessment outputs to initialize projection runs (SEDAR 2015). Stock Synthesis 3 is a forward-projecting, generalized statistical catch-at-age modeling platform for use in fisheries stock assessment and catch projections (Methot and Wetzel 2013). It can be utilized as both an estimation model and a simulation model and is highly scalable to fit a variety of population dynamics and data availability scenarios. For the current application, various updates and minor revisions were made to the final accepted SS3 assessment model used as the basis of management for Gulf Red Snapper. To mimic the complex population and fleet dynamics of the most recent assessment, particularly the discard and retention assumptions, it was necessary to utilize the SS3 framework for the projections and maintain the general model structure. The projections assumed the presence of two distinct populations—east and west of the Mississippi River outfall area—that seldom intermix after settlement to the adult habitat; however, these populations were assumed to have identical life history parameters (i.e., time-invariant growth, natural mortality, fecundity, and weight–length conversions; see Table 2 and Supplementary Table S.1 available in the online version of this article). The fisheries on the two populations were modeled separately, with unique fleet dynamics, effort levels, and selection patterns.

Maximum sustainable yield for the various methods implemented was calculated in an iterative fashion by projecting a series of constant total fishing mortality rates (F) for 100 years and selecting the F that produced the highest average yield (retained catch only; not including discards) during the last 10 years of the projections (by which time the projections had stabilized into approximate equilibrium). Different methods for assigning the overall fishing mortality to individual fleets were utilized depending on which MSY value was being calculated (e.g., maintaining a constant proportion among fleets or fixing fleet-specific fishing mortalities at a particular value; see Fleet Dynamics and Reference Points sections below for more details). Although the two populations were modeled separately, with distinct fisheries and different abundance levels, the metrics used for the proxies such as long-term yield and spawning potential were calculated Gulf-wide (i.e., for both populations combined) to reflect current management practice.

Recruitment assumptions.— Following the most recent assessment, the annual Gulf-wide recruitment of age-0 Red Snapper was modeled by a Beverton–Holt function of Gulf-wide spawning potential (total egg production), where the recruits that contributed to each population were allocated based on the assessment terminal year (i.e., 2013) apportionment factor (Table 2). To explore how assumptions regarding the reliance of recruitment on spawning potential impacted the various reference points, the Beverton–Holt model was applied assuming steepness values of 0.70 (moderate density-dependent compensation), 0.85 (high density-dependent compensation), and 1.0 (constant recruitment independent of spawning potential). For each recruitment parameterization, the entire assessment model was rerun, and all parameters were re-estimated with the new fixed steepness value to rescale the SS3 models and maintain consistency across projections. The parameter estimates were highly consistent across steepness runs except for values of the virgin recruitment (R_0; see Table 2 for R_0 values), which was due to the high levels of correlation among recruitment parameters (i.e., between steepness and virgin recruitment). The base

TABLE 2. Modeled population dynamics for the maximum sustainable yield (MSY) projections, including pertinent parameter values and equations (P = recruit apportionment to each region; h = steepness; R_0 = virgin recruitment; SSB_0 = virgin spawning stock biomass; F_{Dir_Mult} and F_{Byc_Mult} are the yearly, region- and fleet-specific fishing mortality multipliers that are defined by the total fishing mortality being input for the given projection). Note the new R_0 and SSB_0 for alternate recruitment parameterizations (although all parameters were re-estimated when h was changed, parameter estimates were similar to those from the base model): for $h = 0.85$, R_0 was 231 million fish, and SSB_0 was 6.69×10^{15} eggs; for $h = 0.70$, R_0 was 291 million fish, and SSB_0 was 8.41×10^{15} eggs. See Table 1 for additional definitions.

Derived quantity	Equation	Parameter values or description
Recruitment (R)	$R_{Reg} = P_{Reg}\dfrac{4hR_0 SSB_{Year}}{SSB_0(1-h) + SSB_{Year}(5h-1)}$	$P_{East} = 0.38$, $P_{West} = 0.62$, $h = 1.0$, $R_0 = 169$ million fish
Growth curve	$L(t) = L_\infty\left[1 - e^{-k(t-t_0)}\right]$	Asymptotic length (L_∞) = 85.64 cm, growth coefficient (k) = 0.19 year^{-1}, theoretical age at zero length (t_0) = −0.39
Weight–length relationship	$\text{Weight} = aL^b$	$a = 1.7 \times 10^{-5}$, $b = 3$
Fecundity at age (Fec)	Input	See Table S.1
Selectivity (S)	Input	See Figure 2; SEDAR 2015
Retention (Ret)	Input	See SEDAR 2015
Discard mortality (DM)	Input	See SEDAR 2015
Natural mortality (M)	Input	See Table S.1
Directed fishing mortality (F_{Dir}) by fleet	$F^{Fleet}_{Dir,Reg,Age,Year} = S^{Fleet}_{Dir,Reg,Age} F^{Fleet}_{Dir\_Mult,Reg,Year} Ret^{Fleet}_{Dir,Reg,Age}$	Directed fleets are HL, LL, HBT, and MRIP
Directed discard fishing mortality (F_{Disc}) by fleet	$F^{Fleet}_{Disc,Reg,Age,Year} = S^{Fleet}_{Dir,Reg,Age} F^{Fleet}_{Dir\_Mult,Reg,Year}(1 - Ret^{Fleet}_{Dir,Reg,Age}) DM^{Fleet}_{Dir}$	Fishing mortality due to open-season discards for a directed fleet
Total directed fishing mortality (F_{Tot_Dir}) by fleet	$F^{Fleet}_{Tot\_Dir,Reg,Age,Year} = F^{Fleet}_{Dir,Reg,Age,Year} + F^{Fleet}_{Disc,Reg,Age,Year}$	Total fishing mortality for a directed fleet
Bycatch or discard (closed season or no IFQ) fishing mortality (F_{Byc}) by fleet	$F^{Fleet}_{Byc,Reg,Age,Year} = S^{Fleet}_{Byc,Reg,Age} F^{Fleet}_{Byc\_Mult,Reg,Year}$	Bycatch and discard fleets are C_No_IFQ, R_Closed, and SHR
Total fishing mortality (F_{Tot})	$F_{Tot,Reg,Age,Year} = \sum_{Fleet} F^{Fleet}_{Tot\_Dir,Reg,Age,Year} + F^{Fleet}_{Byc,Reg,Age,Year}$	Total fishing mortality summed across all fleets
Total mortality (Z)	$Z_{Reg,Age,Year} = F_{Tot,Reg,Age,Year} + M_{Age}$	
Abundance at age (N)	$N_{Reg,Age+1,Year+1} = N_{Reg,Age,Year} e^{-Z_{Reg,Age,Year}}$	
SSB	$SSB_{Year} = \sum_{Reg}\sum_{Age=0}^{20}(Fec_{Age} N_{Reg,Age,Year} e^{-0.5 Z_{Reg,Age,Year}})$	Note that mortality is discounted for midyear spawning

TABLE 2. Continued.

Derived quantity	Equation	Parameter values or description
Retained catch at age (C) by fleet	$C^{Fleet}_{Dir,Reg,Age,Year} = N_{Reg,Age,Year}(1 - e^{-Z_{Reg,Age,Year}})\dfrac{F^{Fleet}_{Dir,Reg,Age,Year}}{Z_{Reg,Age,Year}}$	Retained catch for a directed fleet
Retained yield (Y) by fleet	$Y^{Fleet}_{Dir,Reg,Year} = \sum_{Age=0}^{20} \overline{W^{Fleet}_{Age}} C^{Fleet}_{Dir,Reg,Age,Year}$	See SS3 manual (Methot 2015) for a complete description of the length-integrated, fleet-specific weight at age (W)
SPR	$\mathrm{SPR} = \left(\dfrac{\mathrm{SSB}}{R}\right) / \left(\dfrac{\mathrm{SSB}_0}{R_0}\right)$	$\mathrm{SSB}_0 = 4.91 \times 10^{15}$ eggs

assessment model (steepness = 1.0) provided the best fit to the data. Alternate runs demonstrated slightly degraded diagnostics but generally performed well and were deemed sufficient for the current analyses. Although steepness values other than the assessment estimate of 1.0 are completely hypothetical, they represent a plausible range for similar, relatively productive reef fish (SEDAR 2009).

Fleet dynamics.— The most recent assessment explicitly modeled seven distinct fleets in each region (i.e., eastern or western Gulf, denoted by E or W, respectively, following the fleet abbreviation): four fleets that are directed at Red Snapper (commercial handline [HL_E; HL_W], commercial longline [LL_E; LL_W], recreational headboats [HBT_E; HBT_W], and recreational private/charter [MRIP_E; MRIP_W]), and three fleets that generally discard Red Snapper (commercial vessels without individual fishing quota [IFQ] [C_No_IFQ_E; C_No_IFQ_W], recreational fishing during the Red Snapper closed season [R_Closed_E; R_Closed_W], and shrimp trawl bycatch [SHR_E; SHR_W]). For each of the directed fleets, open-season discards were also modeled through the use of size-based retention functions with associated input discard mortality rates, which allowed incorporation of discards due to regulatory measures (i.e., minimum size and bag limits; see SEDAR 2015 for a complete description of the retention functions used). Selectivity, retention, and discarding practices for each fleet were assumed to continue as they had in the terminal year of the assessment (i.e., terminal year = 2013; see Figure 2 for selectivity curves and see SEDAR 2015 for retention curves).

It is important to note that the various types of discarding (open season, closed season, and no commercial IFQ) and bycatch arise from different fishery dynamics. Each projection (except the global MSY calculations) had directed fishery open-season discards (based on retention functions defining the fraction of fish retained), which were included because they are an inherent result of a fishery with a minimum size limit. Meanwhile, discards owing to recreational closed seasons and commercial fishing with no IFQ were due to restrictive quotas, which resulted in discards of legal-size fish (see Discard Selectivity panel in Figure 2) from fleets that would have otherwise retained those fish if more quota had been available (or if closed seasons had not been in effect). The SS3 projections treat these fleets as independent sources of discards with their own selectivity patterns because these discards do not occur from normal directed fishing operations on Red Snapper (i.e., they may result from the same directed fleets but at times of the year when those fleets were not targeting Red Snapper). Treatment of discards as unique fleets has been utilized in a handful of SS3 models (e.g., U.S. West Coast Arrowtooth Flounder *Atheresthes stomias* and China Rockfish *Sebastes nebulosus*; Dick et al. 2015; Sampson et al. 2017) and is necessary to adequately model discards of legal-size fish that otherwise would have been retained (instead of discards of sub-legal-size fish). On the other hand, discards from the shrimp fishery are the result of bycatch due to shrimp trawling. Juvenile (ages-0–2) Red Snapper are caught incidentally in shrimp trawls and are assumed to be discarded dead. Therefore, discards from the commercial and recreational fisheries, especially discards due to a lack of IFQ or due to closed seasons, are much different from discards arising due to shrimp bycatch, particularly in terms of discard age composition.

An assumption about the relative distribution of overall total fishing mortality was necessary to partition fleet-specific fishing mortalities for each projection run. The method utilized was dependent on the MSY value being calculated (see Maximum Sustainable Yield Reference Points section below). Fleet-specific fishing mortalities were maintained in a constant proportion or were fixed at a specific value for the duration of the projection, but either way the relative proportions or fixed values were obtained based on the terminal assessment year's estimates of fishing mortality by fleet (see Figure 2, bottom left panel). In addition, the total catch within a sector (recreational or commercial) was constrained by the currently prescribed catch allocation of 48.5% commercial and 51.5% recreational (SEDAR 2015). Although fishing mortality by fleet was scaled proportionately to achieve the MSY, the scaling was also constrained by the catch allocation by sector. Therefore, the approach utilized to scale the fishing mortality was essentially the same as scaling the catch directly.

Maximum sustainable yield reference points.— Maximum long-term yields (retained catch only) and associated SPR values were calculated for six methods commonly used to define MSY. The global MSY represents the theoretical maximum possible harvest, while the five other methods were calculated conditional on comparatively suboptimal selection patterns. As mentioned previously, each MSY method utilized a unique approach to apportion the total fishing mortality to each fleet. Depending on the MSY method, the fishing mortality rates for certain fleets (bycatch and discard) were fixed (based on 2013 values; Figure 2, bottom left panel) rather than being scaled with total fishing mortality (i.e., MSY was achieved contingent on fixed fishing mortality rates of certain fleets). The fleet-specific fishing mortalities for the remaining fleets that were not fixed were then calculated by multiplying the 2013 fishing mortalities by a common scaling factor α, which was adjusted up or down until the total fishing mortality was obtained that maximized equilibrium yield. Obtaining MSY was thus constrained such that the 2013 relative fleet effort allocations (Figure 2, bottom right panel; dependent on which fleets used fixed rates) and sector catch allocations were maintained throughout the projection.

A description of each MSY method is given below, including a breakdown of both the fixed and scaled components of F_{MSY}. Because Gulf Red Snapper are managed as a single population, Gulf-wide F_{MSY} and SPR are calculated. The eastern (E) and western (W) components of each fishery were treated similarly, but the region-specific values were included in each calculation of F_{MSY} (see Tables 1 and 2 for symbol definitions):

1. MSY|global was calculated by fully harvesting a single "optimal" age-class and searching over each potential age of entry to the fishery to determine which age provided the greatest equilibrium yield (no fleet structure existed, so F_{MSY} simply corresponded to the fishing mortality that removed all fish at the age where growth and mortality were balanced).
2. MSY|open_discards assumed that the four directed fleets would continue to operate (with open-season discarding) as they did in each region, with the total directed effort scaled up or down as necessary to maximize long-term landings, but discards owing to shrimp bycatch, closed seasons, and a lack of IFQ were eliminated:

$$F_{\text{MSY},a} = \propto \Big(F^{HL}_{TOT\_Dir,E,a} + F^{HL}_{TOT\_Dir,W,a} + F^{LL}_{TOT\_Dir,E,a} + F^{LL}_{TOT\_Dir,W,a} + F^{HBT}_{TOT\_Dir,E,a} + F^{HBT}_{TOT\_Dir,W,a} + F^{MRIP}_{TOT\_Dir,E,a} + F^{MRIP}_{TOT\_Dir,W,a} \Big).$$

3. MSY|fixed_nondirect_discards assumed that the four directed fleets would continue to operate (with open-season discarding) as they did in each region, with the total directed effort scaled up or down as necessary to maximize long-term landings contingent on closed-season discards and lack-of-IFQ discards that were fixed at 2013 levels but with no shrimp bycatch:

$$F_{\text{MSY},a} = F^{C\_No\_IFQ}_{Byc,E,a} + F^{C\_No\_IFQ}_{Byc,W,a} + F^{R\_Closed}_{Byc,E,a} + F^{R\_Closed}_{Byc,W,a} + \propto \Big(F^{HL}_{TOT\_Dir,E,a} + F^{HL}_{TOT\_Dir,W,a} + F^{LL}_{TOT\_Dir,E,a} + F^{LL}_{TOT\_Dir,W,a} + F^{HBT}_{TOT\_Dir,E,a} + F^{HBT}_{TOT\_Dir,W,a} + F^{MRIP}_{TOT\_Dir,E,a} + F^{MRIP}_{TOT\_Dir,W,a} \Big).$$

4. MSY|fixed_shrimp_bycatch assumed that the four directed fleets would continue to operate (with open-season discarding) as they did in each region, with the total effort scaled up or down as necessary to maximize long-term landings contingent on shrimp bycatch rates that were fixed at 2013 levels, but recreational closed-season discards and lack-of-IFQ discards were eliminated:

$$F_{\text{MSY},a} = F^{SHR}_{Byc,E,a} + F^{SHR}_{Byc,W,a} + \propto \Big(F^{HL}_{TOT\_Dir,E,a} + F^{HL}_{TOT\_Dir,W,a} + F^{LL}_{TOT\_Dir,E,a} + F^{LL}_{TOT\_Dir,W,a} + F^{HBT}_{TOT\_Dir,E,a} + F^{HBT}_{TOT\_Dir,W,a} + F^{MRIP}_{TOT\_Dir,E,a} + F^{MRIP}_{TOT\_Dir,W,a} \Big).$$

5. MSY|fixed_discards assumed that all fleets would continue to operate (with directed-fleet open-season discarding) as they did in each region, with the total effort of the directed fleets scaled up or down as necessary to maximize long-term landings, but with the effort of the nondirected fleets (i.e., closed-season discards and lack-of-IFQ discards along with shrimp bycatch) held

constant at 2013 levels (the current management strategy):

$$F_{\text{MSY},a} = F^{C\_No\_IFQ}_{Byc,E,a} + F^{C\_No\_IFQ}_{Byc,W,a} + F^{R\_Closed}_{Byc,E,a} + F^{R\_Closed}_{Byc,W,a} + F^{SHR}_{Byc,E,a} + F^{SHR}_{Byc,W,a} + \propto \Big(F^{HL}_{TOT\_Dir,E,a} + F^{HL}_{TOT\_Dir,W,a} + F^{LL}_{TOT\_Dir,E,a} + F^{LL}_{TOT\_Dir,W,a} + F^{HBT}_{TOT\_Dir,E,a} + F^{HBT}_{TOT\_Dir,W,a} + F^{MRIP}_{TOT\_Dir,E,a} + F^{MRIP}_{TOT\_Dir,W,a} \Big).$$

6. MSY|linked assumed that all fleets would continue to operate (with directed-fleet open-season discarding) as they did in each region, with the total effort scaled up or down as necessary to maximize long-term landings (i.e., the directed and nondirected fleets all experienced the same proportional change in effort):

$$F_{\text{MSY},a} = \propto \Big(F^{C\_No\_IFQ}_{Byc,E,a} + F^{C\_No\_IFQ}_{Byc,W,a} + F^{R\_Closed}_{Byc,E,a} + F^{R\_Closed}_{Byc,W,a} + F^{SHR}_{Byc,E,a} + F^{SHR}_{Byc,W,a} + F^{HL}_{TOT\_Dir,E,a} + F^{HL}_{TOT\_Dir,W,a} + F^{LL}_{TOT\_Dir,E,a} + F^{LL}_{TOT\_Dir,W,a} + F^{HBT}_{TOT\_Dir,E,a} + F^{HBT}_{TOT\_Dir,W,a} + F^{MRIP}_{TOT\_Dir,E,a} + F^{MRIP}_{TOT\_Dir,W,a} \Big).$$

Not all of these options for calculating MSY are viable in real-world applications. For instance, MSY|global is impossible to implement, and many (e.g., MSY|open_discards, MSY|fixed_nondirect_discards, and MSY|fixed_shrimp_bycatch) require permanent closure of important fishery sectors. Similarly, MSY|linked would require management to be focused solely on the target species and could suggest increasing bycatch to high rates (if a positive scalar is necessary) that would oppose the MSRA requirement to reduce bycatch to the extent practicable. All of the scenarios are included for comparative and illustrative purposes, but in practical application, it is likely that only MSY|fixed_discards could be implemented in a viable management regime.

In the special case where steepness is near the mathematical limit of 1.0 (i.e., recruitment is constant regardless of the level of spawning potential), the fishing mortality rates that achieve the global and conditional MSYs are the same as those that achieve the global and conditional MYPRs (e.g., $F_{\text{MSY|global}} = F_{\text{MYPR|global}}$; $F_{\text{MSY|fixed\_discards}} = F_{\text{MYPR|fixed\_discards}}$; etc.).

SPR_{MSY}|global as a biological reference point.— Each of the above F_{MSY} reference points has a corresponding SPR that could be regarded as a management target. A similar process is implemented for SPR analysis when the stock–recruit relationship is indeterminate. In such instances, a designated SPR level is chosen that is expected to achieve a predetermined biological goal (i.e., prevent recruitment overfishing) and is possibly linked to a yield-based metric (e.g., a percentage of MSY). Once the SPR target is chosen, the equilibrium yield that will achieve the designated SPR is then calculated (instead of using yield as the target metric as in MSY analysis). Although a number of fixed SPR proxies have been suggested (e.g., an SPR > 20–30% to prevent recruitment overfishing: Mace and Sissenwine 1993; or an SPR = 35–45% to attain >75% of MSY: Clark 1991, 1993), they can be arbitrary (Quinn et al. 1990; Cadrin 2012) and may not necessarily be appropriate for highly productive stocks.

Based on the tenets of modern MSY theory, SSB_{MSY}|global (i.e., the SSB that results from MSY|global) should, over the long term, be an inherently sustainable level of biomass given that it represents the point at which growth and mortality are balanced (on average). Therefore, we suggest that the SPR associated with MSY|global (i.e., SPR_{MSY}|global) could be used as an objective target reference point proxy when the stock–recruit relationship is well defined. Despite MSY|global being unattainable because it is not possible to avoid catching fish older or younger than the optimal age (among other issues), the SPR_{MSY}|global can be attained regardless of how the fisheries operate provided that the level of effort can be scaled appropriately. In addition, we believe that using SPR_{MSY}|global as a target biomass reference point would adhere to the MSRA guidelines by rebuilding the stock to a level consistent with providing the MSY (MSRA 2007).

In many instances, the parameters of the stock–recruit relationship are not well defined (particularly steepness), and hence there is a need to develop SPR or similar proxies. When the Beverton–Holt stock–recruit function can be reasonably assumed for a species but steepness is not well estimated, the SPR corresponding to MYPR|global (i.e., SPR_{MYPR}|global) could be used as a lower bound for potential biomass-based reference point proxies. Given that YPR analysis assumes the highest possible productivity of a population (i.e., a steepness of 1.0 implies that there is no relationship between spawners and recruits, an assumption that must eventually break down at low population sizes), the corresponding SPR_{MYPR}|global represents a lower bound on biomass levels that could still achieve MSY. If auxiliary information is available to determine a lower bound on steepness (e.g., through life history analysis or meta-analysis of similar species), then an associated SPR_{MSY}|global can be determined using this steepness value to provide an upper limit on reasonable SPR proxies. For Beverton–Holt stock–recruit functions, SPR

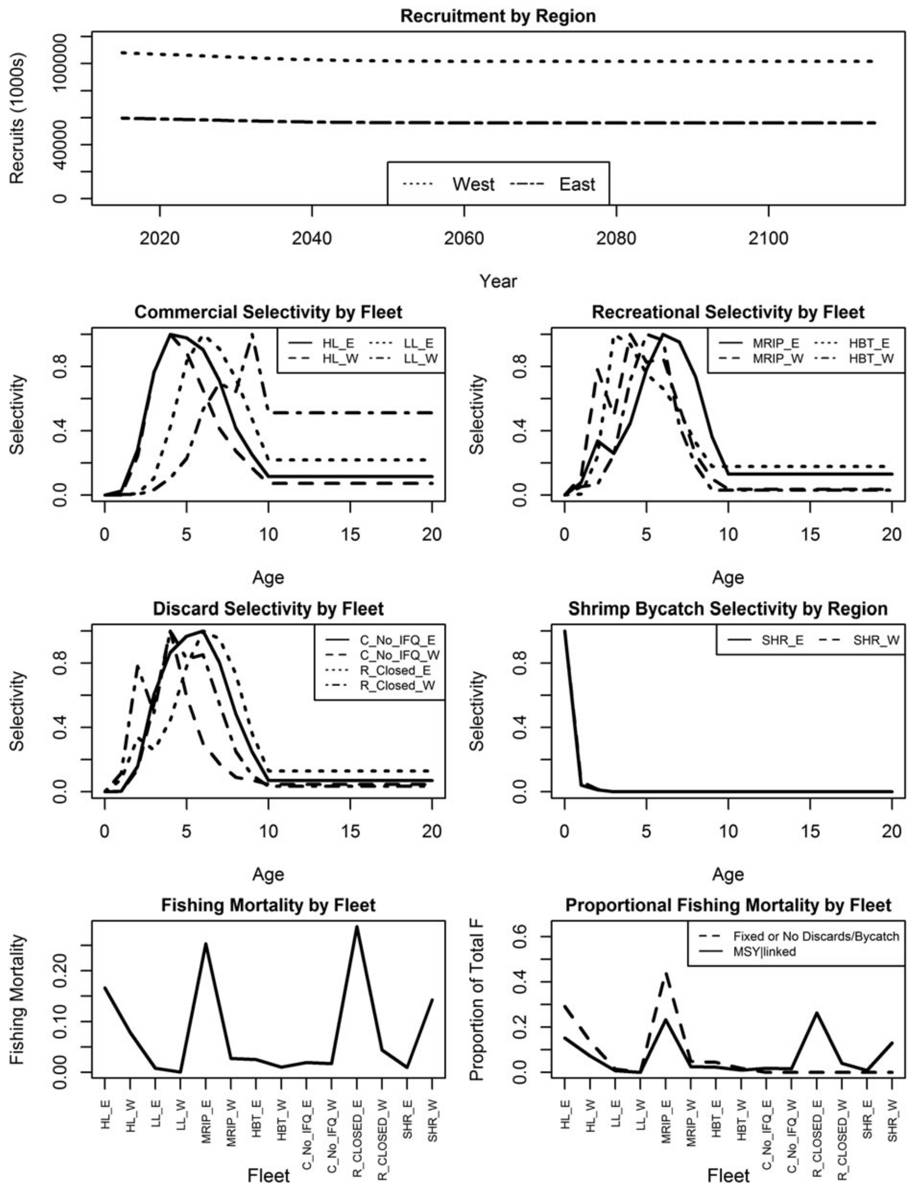

FIGURE 2. Projected recruitment along with assumed selectivity and relative fishing mortality rates among fleets for the base model (steepness = 1.0). The bottom left panel provides the starting fishing mortality rates for each projection (assessment estimates from the terminal year, 2013). For runs with bycatch or discard rates fixed at recent values (e.g., MSY|fixed_discards; see Table 1 for symbol definitions), the fleet-specific fishing mortalities that are fixed are taken from this plot. The solid line in the bottom right panel provides the portion of F_{MSY} assigned to each fleet when both the directed and nondirected fleets are scaled proportionately (i.e., MSY|linked). On the other hand, for MSY methods where only the directed fishing mortalities are maintained in a constant proportion, the dashed line provides the fraction of the directed portion of F_{MSY} attributed to each directed fleet (the nondirected fishing mortalities are taken from the bottom left panel when they are nonzero).

values within this range are likely to maintain the population at a size where recruitment overfishing would not be a risk (since the death rate is unlikely to exceed growth/birth), and a large portion of MSY|global would be achievable if optimal resource utilization was possible. It should be noted that for less-productive species, a lower SPR bound corresponding to a steepness of 1.0 may be too low; if information exists to bound steepness at a value less than 1.0, then calculations based on this steepness value can be utilized to define the lower bound on SPR.

Additionally, when uncertainty exists in the stock–recruit relationship itself or when recruitment dynamics do not conform to the Beverton–Holt stock–recruit function, the search process would need to be expanded. With uncertainty in the functional form of the stock–recruit function, it would be necessary to perform an extensive search across both stock–recruit functional forms and steepness values to determine appropriate lower and upper SPR bounds. On the other hand, if the functional form is known but is not a Beverton–Holt stock–recruit function, then it would be necessary to search over the plausible extent of steepness values to determine both the upper and lower bounds of SPR (e.g., when Ricker stock–recruit functions are assumed, the lower SPR bound would no longer be expected to occur where steepness = 1.0).

Once the range of SPR values has been established, the desired relative mix of fleets along with the extant bycatch or discard rates can be utilized to calculate the long-term yield required to achieve the SPR bounds. Essentially, MSY|fixed_discards can be calculated for the range of steepness values (associated with the SPR bounds), and the total fishing mortality that achieves the desired SPR level can be determined. The lower bound of the SPR values (e.g., SPR_{MYPR}|global for Beverton–Holt stock–recruit functions) provides a limit below which the population would not be expected to be able to produce MSY|global. The upper bound (associated with the highest steepness value for Beverton–Holt stock–recruit functions) provides a cutoff above which rebuilding targets would be overly conservative given that the population should be more productive than indicated by this steepness value. A simple risk analysis based on the degree of biological uncertainty (in the estimated stock–recruit parameters and functional form) and accounting for any important socioeconomic factors could then be implemented to determine the desired SPR target and allowable catch from the range provided by the SPR bounds (see Figure 3 for a flow diagram describing the SPR_{MSY}|global method). We illustrate how the method can be applied by comparing SPR bounds (and associated retained catch) for a plausible range of steepness values (0.7–1.0) for Red Snapper.

Sensitivity run.— To provide a more in-depth comparison between the two MSY methods that are most commonly utilized when there are multiple fleets and bycatch, MSY|fixed_discards and MSY|linked (Powers 2005; SEDAR 2015), we implemented a sensitivity run with increased bycatch and discard rates. The purpose of this run was to demonstrate that despite a previous analysis implying that MSY|linked was greater than MSY|fixed_discards (e.g., Powers 2005), the relationship between these MSY methods is context dependent. To illustrate a situation where MSY|linked became greater than MSY|fixed_discards, the two MSY methods were calculated in a sensitivity run with a 15-fold increase in initial bycatch and discard rates. The sensitivity run levels of bycatch and discards were not meant to represent any real-world scenario for Red Snapper; they were simply chosen to illustrate the relative properties of the two MSY methods.

Metrics.— The results of the six MSY methods for each value of steepness were compared based on equilibrium yield and resulting SPR. Analyzing results across MSY methods and stock productivity levels (i.e., steepness values) demonstrated the tradeoffs and biological implications inherent in each assumption for calculating MSY-based BRPs. The same metrics were then provided for SPR_{MSY}|global, where yield was calculated assuming current bycatch and discard levels (i.e., from the MSY|fixed_discards yield curve) to demonstrate how using our proposed SPR_{MSY}|global framework compared with current MSY methods.

RESULTS

The MSY|global for the base model (steepness = 1.0) occurred at an SPR of 24% when fish were harvested at age 10 (Table 3). As the steepness values decreased, the age of optimal harvest and resulting SPR increased for MSY|global (Table 3; Figure 4). Similarly, MSY|global consistently produced the highest yield and often the highest SPR compared to conditional MSY methods assuming the same steepness level (Table 3; Figure 5; Figures S.1 and S.2). However, with steepness values less than 1.0, the SPR associated with MSY|linked was higher than SPR_{MSY}|global, but MSY|linked always resulted in the lowest yield (not including the sensitivity run; see below). Although MSY|open_discards, MSY|fixed_nondirect_discards, MSY|fixed_shrimp_bycatch, and MSY|fixed_discards demonstrated similar SPR levels across steepness values, the resultant yield was higher for MSY|open_discards and MSY|fixed_nondirect_discards (Table 3; Figure 5). The effect of decreasing steepness was similar for all of the conditional MSY reference points. The SPR increased with declining steepness in all cases, while the foregone yield (compared with the yield that could be achieved at MSY|global) often became more pronounced (Table 3; Figure 5; Figures S.1 and S.2). Additionally, in the absence of a relationship between spawners and recruits (i.e., steepness = 1.0), there was little risk of recruitment overfishing and therefore little consequence to fishing the stock down to low SPR levels. Therefore, the equilibrium yield curves associated with a steepness of 1.0 became highly skewed toward lower SPR (Figure 5), whereas those associated with lower steepness values (Figures S.1 and S.2) did not have this property. Indeed, as steepness values declined, the SPR values associated with each of the conditional MSY methods rapidly converged toward SPR_{MSY}|global.

Utilization of SPR_{MSY}|global as a biomass target, where the yield streams required to achieve it were calculated using current discard and bycatch practices (i.e., determined based on the MSY|fixed_discards yield curve), resulted in limited foregone yield compared to using MSY|

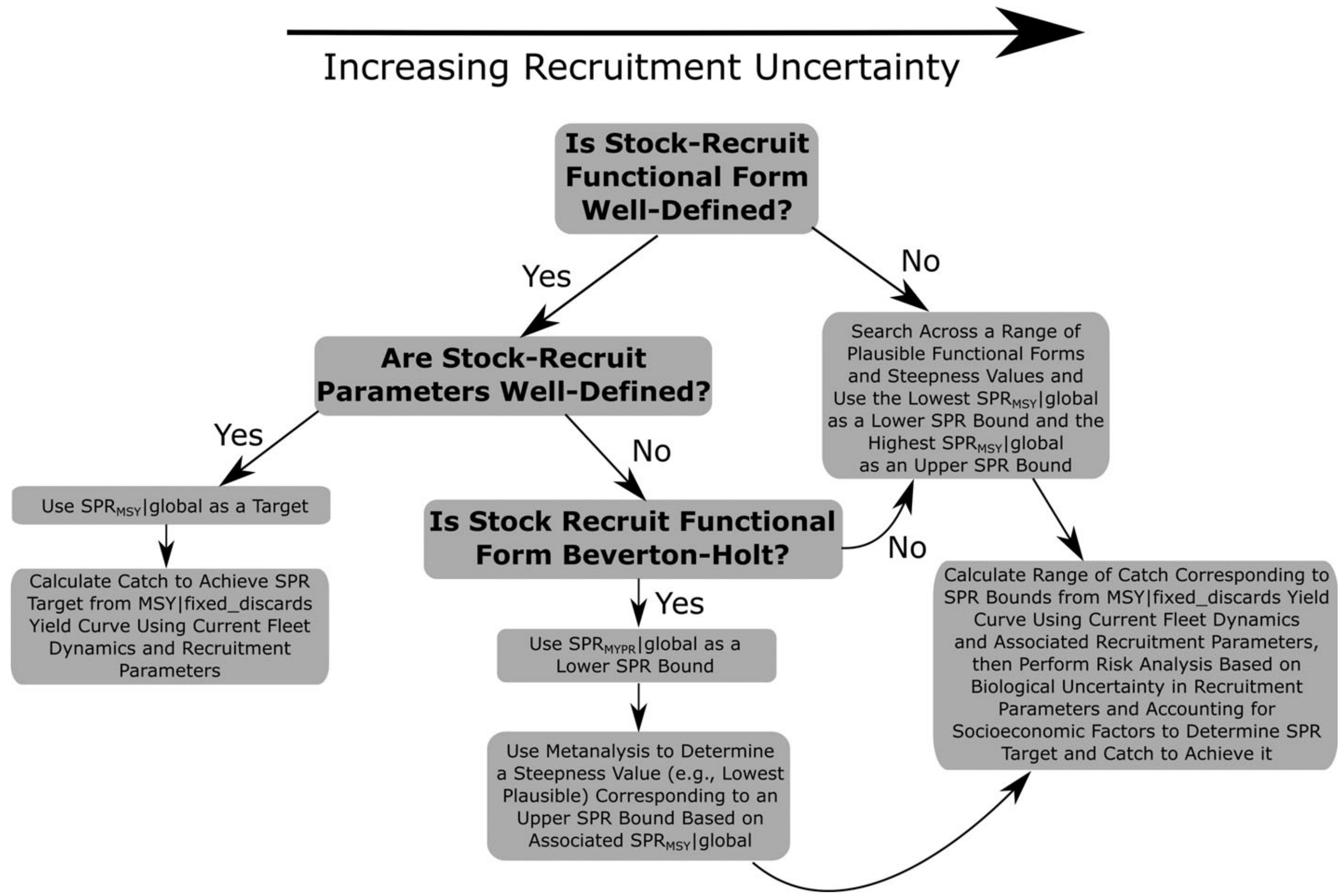

FIGURE 3. Flow chart describing the use of SPR$_{MSY}$|global as a spawning potential ratio (SPR) proxy depending on the level of recruitment uncertainty (see Table 1 for symbol definitions). Decision points are in bold. When steepness is indeterminate but the stock–recruit function can be reasonably surmised to be of a Beverton–Holt functional form, SPR$_{MYPR}$|global can be implemented as a lower bound on potential SPR proxies. When uncertainty in the functional form of the stock–recruit relationship exists, the search for SPR bounds should be extended to multiple functional forms (e.g., Ricker and Beverton–Holt) and steepness values to identify appropriate bounds on SPR$_{MSY}$|global.

fixed_discards directly (Table 3; Figure 6). In fact, the fraction of MSY|global obtained for each steepness value was nearly identical between the two approaches despite the greatly increased SPR values associated with SPR$_{MSY}$|global (particularly at high steepness values). For the current case study, the yield curve tended to be relatively flat near MSY|fixed_discards, which allowed the yield associated with obtaining SPR$_{MSY}$|global (assuming current discards and bycatch) to be similar to MSY|fixed_discards.

The relationship between MSY|linked and MSY|fixed_discards was variable depending on the assumed level of discards (Figure S.3). An interesting facet of comparing the base model to the sensitivity run was the demonstration that MSY|linked became more conservative (i.e., favored higher SPR values) as bycatch and discards increased, whereas MSY|fixed_discards led to declining SPR values under these circumstances.

DISCUSSION

When multiple fleets exist and when bycatch or discards are important factors in the total catch, attempting to uniquely define MSY is not possible (Goodyear 1996). A variety of methods can be utilized to determine the maximum long-term yield conditional on the allocation of the resource among fishing fleets and between directed and nondirected sectors (Maunder 2002). Assumptions about the relative mix of fleets can have important implications for the resulting MSY (Beverton and Holt 1957). However, less acknowledged is the impact of MSY method on the resulting reference points (Powers 2005). Our results demonstrate that stock productivity, fleet allocation, and MSY method are all important factors influencing the resulting yield streams and rebuilding targets. Results presented here support the assertion by Powers (2005) and Porch (2007) that MSY|fixed_discards can drive a population to low equilibrium abundance as discard or bycatch levels increase and may lead to population collapse if steepness values are overestimated. Thus, it may not provide a sustainable target reference point (Figure S.3). The MSY|fixed_discards method essentially treats bycatch and discards as independent sources of mortality with which the directed fleets must compete to maximize yield (i.e., in the same manner that yield maximization must balance death due to natural mortality). Therefore, when bycatch or discard rates are fixed at high levels, directed fishing mortality rates must also be increased to maximize yield (to avoid losing potential landings to dead discards), which can lead to critically low resulting SSB.

Despite the dangers, there is often support for the MSY|fixed_discards approach because it is an MSY-based target that allows increased harvests compared to alternative MSY methods (e.g., MSY|linked) when high levels of bycatch and discard are occurring (Porch 2007). The results presented here clearly illustrate that for the highly contentious and complex case of Red Snapper, simply calculating the suite of MSY methods (when multiple fisheries exist with relatively high levels of bycatch and discards) may result in non-conservative SPR targets if managers freely choose among MSY values without fully understanding the biological implications of each. In addition, ignorance of complex biological dynamics (e.g., spatial processes) in the models used to calculate MSY can exacerbate such decisions and can lead to extremely low biomass targets (SEDAR 2015).

On the other hand, MSY|linked resulted in biomass levels that were often similar to those associated with MSY|global. Contrary to MSY|fixed_discards, the SPR targets based on MSY|linked become more conservative as bycatch or discards increase (see Figure S.3), as it is assumed that discards or bycatch will proportionately change with directed fishing effort. Although directed fishery discards may be expected to scale with directed effort, the same is not true for bycatch or closed-season discards. Therefore, the MSY|linked approach suffers from foregone yield, whereas MSY|fixed_discards may be unsustainable. Given the deficiencies in these two common forms of calculating MSY with bycatch and discards, alternate methods are warranted.

The SPR_{MSY}|Global Approach

Proxies for SPR are widely used in the United States and worldwide, where the desired level of SPR is usually chosen to retain the stock within safe biological limits based on life history characteristics and meta-analysis (Cadrin and Pastoors 2008). However, the choice of SPR can be subjective (Quinn et al. 1990; Cadrin 2012), and unless a value is chosen a priori to viewing assessment results, it can lead stakeholders and managers to make post hoc decisions that are overly dependent on resultant yield and ignore the biological basis of the SPR analysis (Schirripa 1999). Clark (1991, 1993) proposed a min–max approach to optimize catch when faced with uncertainty in recruitment dynamics, and that approach has become one of the most often-cited methods for defining SPR proxies. He demonstrated that for a wide array of life history, stock productivity, and recruitment variability combinations, SPR values ranging from 25% to 45% would usually provide at least 75% of MSY and maintain populations within safe biological limits. However, without a predefined and fixed MSY value against which to compare life history or stock productivity uncertainty, the min–max approach can be difficult to implement. For instance, the SPR target will differ significantly depending on whether MSY|linked or MSY|fixed_discards is used as the yield metric to be optimized, while year-to-year variations in bycatch or discards could lead to fluctuations in SPR targets as the analysis is rerun in subsequent years of the rebuilding plan. One approach to avoid "moving targets" for stock rebuilding plans is to assume that bycatch rates will remain constant over the course of the rebuilding plan, thereby maintaining a constant rebuilding target when using MSY|fixed_discards as the basis of the min–max approach (e.g., the approach utilized for various species of crab in the U.S. North Pacific; Siddeek 2003; Siddeek et al. 2004; Siddeek and Zheng 2006). However, when bycatch rates are volatile and differ substantially from year to year, assuming constant bycatch could lead to projected yield streams that may not support stock rebuilding.

We suggest that an alternate approach may be better suited for complex fleet dynamics including variable rates of discarding and bycatch (e.g., Red Snapper), and we propose that aiming to rebuild to the inherently sustainable level of SSB associated with MSY|global can be an objective biomass target in such circumstances. Although MSY|global is not obtainable, the associated SPR will usually be achievable in the long term given the correct management (i.e., yield streams) regardless of fleet dynamics. Given that MSY|global is independent of selectivity, discards, or bycatch and relies only on life history factors, we believe that using SPR_{MSY}|global as an SPR target provides a more stable and conservative reference point compared to using the biomass associated with any of the conditional MSY values. Additionally, when the yield streams required to achieve SPR_{MSY}|global are calculated based on extant fleet allocations, selectivity patterns, discard levels, and bycatch rates (i.e., from the MSY|fixed_discards yield curve), the framework can be employed without disruption to the various fisheries. In situations where bycatch and discard levels are moderate or low, it is likely to lead to limited foregone yield compared to MSY|fixed_discards (Table 3). If bycatch or discard rates vary throughout the rebuilding period (particularly discards due to closed seasons or discards due to limited IFQ, both of which might be expected to decline, in most cases, as the stock rebuilds), updated MSY|fixed_discards yield curves can be computed to adjust

TABLE 3. Maximum sustainable yield (MSY) and resulting spawning potential ratio (SPR) values for each recruitment parameterization and yield maximization method (ordered by decreasing steepness and decreasing SPR within each steepness scenario). The retained yield that achieves SPR_{MSY}|global (see Table 1) given current fleet dynamics and bycatch/discard rates (i.e., from the MSY|fixed_discards yield curve) is also provided. Harvest rate (retained numbers/total abundance) is provided as a fishing mortality metric. For MSY|global, the age of optimal harvest is provided in parentheses.

Scenario	Yield relative to MSY|global	SPR	SPR relative to SPR_{MSY}|global	Harvest rate
	Steepness = 1.0 (base model)			
MSY|global (age 10)	1.00	0.24	1.00	0.0097
Landings from MSY|fixed_discards yield curve at SPR_{MSY}|global	0.38	0.24	1.00	0.0502
MSY|linked	0.33	0.23	0.98	0.0669
MSY|fixed_nondirect_discards	0.46	0.14	0.56	0.0182
MSY|open_discards	0.45	0.13	0.45	0.0184
MSY|fixed_shrimp_bycatch	0.41	0.13	0.54	0.0546
MSY|fixed_discards	0.40	0.12	0.50	0.0555
	Steepness = 0.85			
MSY|linked	0.30	0.33	1.13	0.0552
MSY|global (age 11)	1.00	0.29	1.00	0.0088
Landings from MSY|fixed_discards yield curve at SPR_{MSY}|global	0.34	0.29	1.00	0.0500
MSY|fixed_nondirect_discards	0.40	0.27	0.92	0.0146
MSY|open_discards	0.39	0.25	0.87	0.0152
MSY|fixed_shrimp_bycatch	0.35	0.25	0.86	0.0513
MSY|fixed_discards	0.34	0.24	0.83	0.0520
	Steepness = 0.70			
MSY|linked	0.28	0.42	1.10	0.0455
MSY|global (age 13)	1.00	0.38	1.00	0.0073
Landings from MSY|fixed_discards yield curve at SPR_{MSY}|global	0.30	0.38	1.00	0.0487
MSY|fixed_nondirect_discards	0.36	0.37	0.97	0.0123
MSY|open_discards	0.35	0.35	0.93	0.0128
MSY|fixed_shrimp_bycatch	0.31	0.35	0.92	0.0497
MSY|fixed_discards	0.30	0.34	0.89	0.0503

projected catches to maintain the rebuilding schedule. However, SPR targets would not change as catches are updated.

We believe that this framework provides a unique method with which to choose an SPR proxy based on the inherently sustainable scientific basis of MSY|global analysis (i.e., choosing an SPR value corresponding to the point on the MSY|global curve where growth and mortality are balanced). Interestingly, our analysis suggested that regardless of the underlying recruitment dynamics tested (i.e., steepness values) for Red Snapper, the SPR_{MSY}|global values (24–38%) were within the range of values suggested by Clark (1991, 1993) as both sustainable and likely to provide a large fraction of MSY. Given that the application was for a highly productive species, we would expect that the resulting SPR values achieved here would be toward the lower bound calculated for most other species.

Similarly, given that the base model with a steepness of 1.0 represents the most productive and resilient population dynamics possible (i.e., constant recruitment) when a Beverton–Holt stock–recruit function is assumed, we suggest that SPR_{MYPR}|global can be effectively utilized as a lower bound for SPR proxies. In the case of Beverton–Holt stock–recruit functions, SPR_{MYPR}|global is always lower than the SPR_{MSY}|global associated with lower steepness values. Thus, where SPR_{MSY}|global is unknown because steepness is poorly determined, one can be reasonably assured that it is greater than SPR_{MYPR}|global. Additionally, if the functional form of recruitment is also uncertain, we suggest that the lowest SPR_{MSY}|global over a range of both plausible steepness values and stock–recruit functional forms should be used as the lower bound for an MSY proxy (Figure 3).

As with any analysis based on dynamic pool models, the proposed framework has a number of caveats and limitations. Foremost, it is expected that the results (e.g., associated levels of foregone yield and the value of SPR targets) will be highly context dependent. We only applied the method to a single species and life history. Although the results may hold for similar reef fish species, it is unknown how the results may differ for species with vastly different life history or recruitment dynamics. In addition, the projections assumed parameter stationarity (an inherent assumption of most dynamic pool models; Forest et al. 2010), and the yields necessary to achieve the long-term SPR target may differ as estimates of selectivity, bycatch, and discarding are updated in subsequent years. However, because the SPR target is independent of these factors, it will not change unless fundamental life history characteristics are altered, which is one of the strongest qualities of using SPR_{MSY}|global as a biomass reference point.

National Standard 1 and the Use of SPR Proxies

National Standard 1 (NS1) of the MSRA states that conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield (OY) from each U.S. fishery (MSRA 2007). The MSRA defines "optimum," with respect to the yield from a fishery, as the amount of fish that (1) will provide the greatest overall benefit to the nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems; (2) is prescribed as such on the basis of the MSY from the fishery, as reduced by any relevant economic, social, or ecological factor; and (3) in the case of an overfished fishery, provides for rebuilding to a level consistent with producing the MSY in that fishery. As we interpret the MSRA, the third provision implies that regardless of how OY is reduced in comparison to MSY, the target stock size should not fall below the level that would produce the MSY.

In this paper, we have shown that setting OY equal to one of the conditional MSY metrics, as has been proposed for Gulf Red Snapper, would tend to drive the stock below the SSB level that would support MSY|global. In our opinion, it would seem more consistent with the intent of the MSRA to maintain the spawning stock at or above the level that will produce the global MSY. In practice, however, the level of spawning stock that will support the global MSY is often uncertain because the relationship between spawning stock and subsequent recruitment is poorly estimated or undetermined. In such cases, it is common to use SPR proxies that are thought to correspond closely to the MSY. Given the various limitations of MSY proxies and the high degree of uncertainty in the stock–recruit dynamics for most species, we recommend SPR_{MYPR}|global as a lower bound for SPR-based reference points when Beverton–Holt stock–recruit functions are assumed. In these cases, the SPR proxy selected should be greater than SPR_{MYPR}|global, with the selection process guided by a simple risk analysis wherein the upper bound is defined by the SPR_{MSY}|global corresponding to the lowest plausible steepness value (Figure 3).

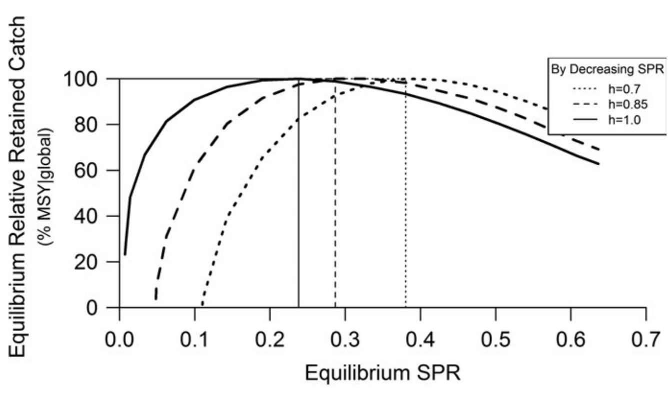

FIGURE 4. Comparison of MSY|global and associated SPR_{MSY}|global (see Table 1 for symbol definitions) for steepness (h) values of 0.7, 0.85, and 1.0. Relative yield is provided as a percentage of the MSY|global for the given h-value.

Implications for Red Snapper

The GMFMC's Scientific and Statistical Committee (GMFMC 2007) recommended that Red Snapper be managed using an SPR target of 26% based on previous MSY|linked analyses and the recognition that MSY targets were not well defined. The current SPR target falls within the range of SPR_{MSY}|global values (0.24–0.38) given plausible steepness levels for the population (i.e., 0.7–1.0). The current analysis indicates that there is likely limited foregone yield with a rebuilding target of SPR = 26% compared to fishing at the rate that achieves MSY|fixed_discards, yet the conservation benefits are likely to be substantial as the target SPR of 26% is twice that of MSY|fixed_discards. Additionally, because target SPR values are set for the entire Gulf Red Snapper resource, lower target values risk allowing regional (eastern or western Gulf) SPR to fall well below the Gulf-wide target. For instance, when region-specific SPR was calculated for Red Snapper, the MSY|fixed_discards approach led to SPR values below 5% for the eastern stock region (SEDAR 2015). At such low regional SPR, the potential for recruitment failures may be greatly enhanced, even for a highly productive species like the Red Snapper. The current Gulf-wide SPR target is likely to avoid such severe regional depletion.

As mentioned earlier, there are a number of caveats for this analysis, mainly due to various factors that were not included or explored in the projections. For the Red Snapper application specifically, given the importance of discards and particularly shrimp bycatch, an assumption that warrants further consideration is the impact of density-dependent juvenile mortality on projected yield. Because shrimp bycatch mainly selects age-0–2 fish, there is a high degree of interaction between bycatch fishing mortality

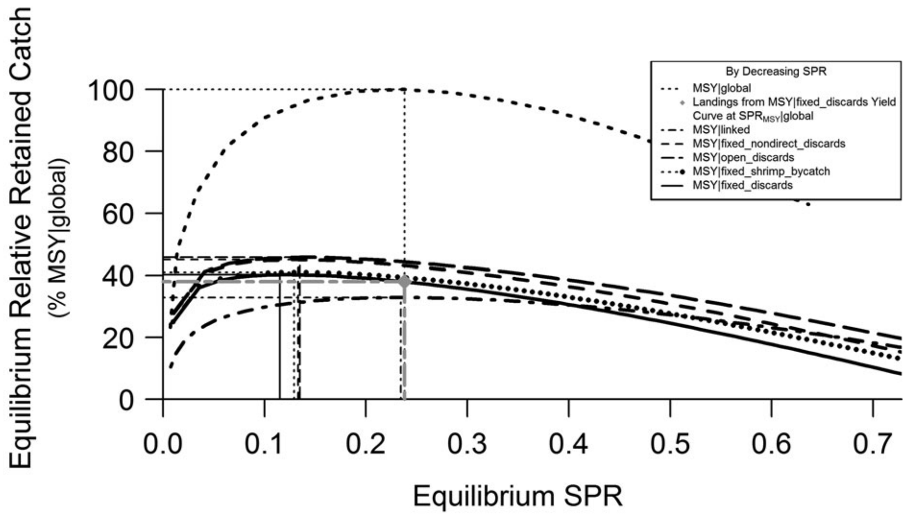

FIGURE 5. Relative retained yield (percentage of MSY|global) versus spawning potential ratio (SPR) across MSY methods for the base case (Beverton–Holt stock–recruit function with steepness = 1.0 and virgin recruitment = 169 million fish; see Table 1 for symbol definitions). The relative retained yield that achieves SPR$_{MSY}$|global given current fleet dynamics and bycatch/discard rates is illustrated with a point on the MSY|fixed_discards yield curve.

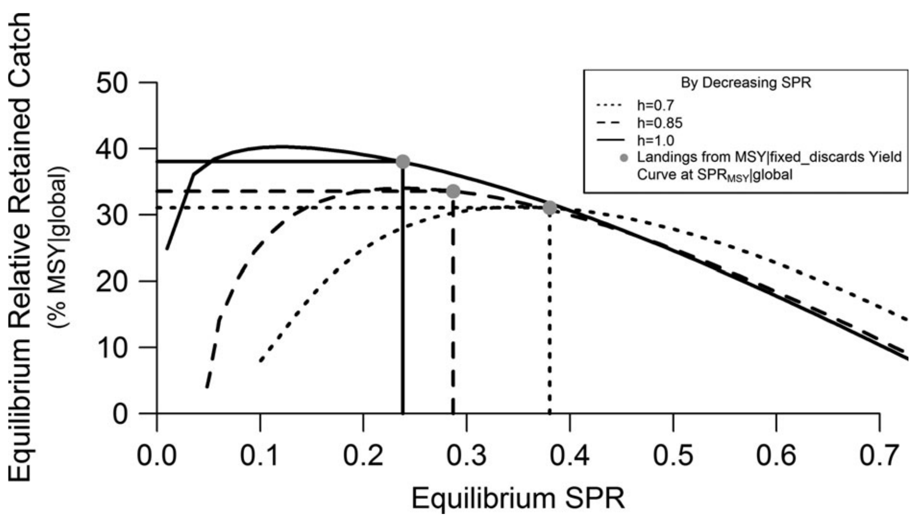

FIGURE 6. Relative retained yield (percentage of MSY|global for the given steepness [*h*] value) versus spawning potential ratio (SPR) for MSY|fixed_discards with *h*-values of 0.7, 0.85, and 1.0 (see Table 1 for symbol definitions). The relative retained yield that achieves SPR$_{MSY}$|global given current fleet dynamics and bycatch/discard rates is illustrated with a point on the associated MSY|fixed_discards yield curve.

and juvenile natural mortality (Gazey et al. 2008; Gallaway et al. 2017). When density-dependent natural mortality during juvenile life stages is not accounted for in the assessment and resultant projections (i.e., the current approach), there is a possibility of overestimating MSY and rebuilding potential by assigning juvenile natural mortality to other mortality sources (e.g., shrimp bycatch; Forrest et al. 2013). Incorporation of density-dependent juvenile mortality would likely alter the results of our analysis, and future work is warranted to investigate the specific impacts that it would have on reference points and associated yield streams.

The results of the current study generally support those of similar Red Snapper-based MSY studies by Schirripa (1999) and Powers (2005). For MSY|fixed_discards (the method used by Schirripa 1999; method II of Powers 2005), both studies demonstrated that as the bycatch increased, the resulting SSB at MSY declined. In contrast, when MSY|linked (method I of Powers 2005) was utilized, higher bycatch rates were associated with lower directed fishing mortality (due to the proportionality constraint) and resulted in higher SPR. Both results are supported by our analysis (Figure S.3), and lower SPR values were associated with MSY|fixed_discards compared to MSY|

linked for the same initial directed and nondirected fishing mortality rates (similar to Powers 2005).

Our calculation that MSY|fixed_discards exceeds MSY|linked (in the base model) differs from the simulations conducted by Powers (2005), which suggested the opposite. However, the opposite conclusion was reached in our sensitivity run when these metrics were recalculated with a 15-fold increase in initial bycatch and discard fishing mortalities (Figure S.3). Therefore, our results demonstrate that the relationship between MSY|linked and MSY|fixed_discards is context dependent but strongly influenced by initial relative fishing mortalities and the scaling required to achieve MSY. Powers (2005) illustrated only one of the possible relationships between these two MSY methods, whereas we have generalized those results in our sensitivity run. Based on first principles (assuming the same initial and relative fishing mortalities among methods), when all directed and nondirected fleets are scaled proportionately (MSY|linked), the resulting MSY will be higher than the corresponding MSY|fixed_discards (where only the directed fleets are linked) if achieving F_{MSY} requires decreasing the initial fishing mortalities (i.e., if the scalar α from the equation is less than 1.0). On the other hand, if achieving F_{MSY} requires increasing the initial fishing mortalities (i.e., if the scalar is greater than 1.0), then MSY|fixed_discards could be—but will not necessarily be—greater than MSY|linked. The reason for the reversal in relative MSY values is that when the scalar is less than 1.0, the equilibrium bycatch/discard fishing mortality must be lower for MSY|linked than for MSY|fixed_discards because bycatch/discard fishing mortality is fixed in the latter method and reduced (below the initial values) in the former. Thus, MSY|linked would kill fewer fish due to bycatch and discards; because some of these fish are able to survive and be landed by the directed fishery, yield must be greater for MSY|linked. When α is greater than 1.0, the situation is reversed, and bycatch/discard mortality is increased for MSY|linked. However, in this situation, the relationship between MSY|linked and MSY|fixed_discards will depend on the fleet-specific selectivity, relative fishing mortalities, and stock–recruit relationship. Additionally, these results are based on MSY being defined by retained yield and not total catch.

Summary

Attempting to limit bycatch or discards can be extremely difficult (Diamond 2004). In such instances, it is imperative that projections of BRPs and the yield required to attain them account for these sources of nondirected incidental catch. It is often most realistic to assume that bycatch or discards are going to remain at some average or recent rate and to perform MSY|fixed_discards analysis. However, MSY|fixed_discards can lead to detrimentally low SPR values because bycatch and discards are essentially treated as an additional source of mortality against which directed fisheries must compete to maximize yield. In response to the question posed by Maunder (2002; i.e., "…how do we define MSY with respect to the effort allocation among the fishing methods…?"), we suggest that perhaps this is the wrong question to be asking. Instead, we propose that the goal should be to define sustainable biomass targets based on the only invariant (assuming stable life history parameters) version of MSY: that is, MSY|global. Using $\mathrm{SPR_{MSY}}$|global as a biomass proxy, with associated yield taken from the MSY|fixed_discards yield curve, provides an objective alternative for determining proxies that conform to the MSRA NS1 guidelines while accounting for the current effort allocation among fleets (i.e., the allocation that results in the least disruption to fishery practices). The results presented here may not necessarily hold for all life history patterns or bycatch and discard scenarios, but it is expected that the general framework could be useful for defining SPR proxies for almost any fishery. The Red Snapper fishery in the Gulf represents one of the most complex assessment and management scenarios in the United States given the many stakeholders and competing sectors (e.g., commercial, recreational, and shrimp bycatch) vying for a portion of the resource (Schirripa 1999). Based on our analyses using Red Snapper as a case study, we believe that using $\mathrm{SPR_{MSY}}$|global as an SPR proxy can be a feasible method for objectively determining reference points when complex fleet dynamics exist, when global MSY cannot be achieved in practice, and when there is a lack of agreement on appropriate SPR-based reference points.

ACKNOWLEDGMENTS

We thank two anonymous reviewers along with Andre Punt, Adyan Rios, and Matt Lauretta for providing comments that greatly improved the manuscript. Additionally, we appreciate input from Rick Methot and John Walters on how to estimate global MSY within the SS3 framework. This work would not have been possible without all of the Southeast Fisheries Science Center team members who helped in developing and implementing the 2015 Gulf of Mexico Red Snapper stock assessment and associated projections. Many of the ideas regarding alternative MSY proxies were stimulated by discussions with the GMFMC Science and Statistical Committee and associated interdisciplinary plan teams. There is no conflict of interest declared in this article.

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