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ABSTRACT

We developed a simulation framework to explore the combined effects of harvest slot regulations, reductions in recreational discard mortality rate, and alternate bycatch accountability approaches on fishery management performance measures representing a broad range of stakeholder interests in a multi-sector marine fishery. Simulation results indicated reductions in recreational discard mortality rate, alone or combined with harvest slot regulations, may result in longer recreational fishing seasons, increased recreational catch rates, reduced dead discarded biomass, and an increase in the population of reproductively valuable older fish. Based on application to Gulf of Mexico red snapper (*Lutjanus campechanus*), we demonstrate the trade-offs among competing management objectives and illustrate how reduced recreational discard mortality rates and allocation of catch quotas between recreational and commercial sectors based on total dead biomass versus landed catch alone can influence the efficacy of regulatory actions. We suggest increased use of simulation analyses is warranted to aid fisheries management decision making and can spur development of performance measures that better communicate trade-offs among the diverse objectives of stakeholders in multi-sector marine fisheries.

1. Introduction

Marine fisheries can support diverse stakeholders with competing interests and priorities, posing a challenge to managers who must prescribe regulations to meet multiple management objectives while maintaining equity across user groups (Punt, 2017). Fisheries management policies including the United Nations Convention on the Law of the Sea (UNCOLS), the European Union Common Fisheries Policy, and the U.S. Magnuson-Stevens Fishery Conservation and Management Act all acknowledge management objectives are diverse and include maximized food production and sustainability together with economic, social, ecological, and environmental considerations. However, marine resources are often managed to maximize sustainable yield from commercial fishing fleets (Hilborn, 2007a), despite many stocks also supporting valuable recreational fisheries (Coleman et al., 2004; Cooke and Cowx, 2004; Hyder et al., 2018; Radford et al., 2018). Yet, there is limited guidance on how to account for recreational stakeholders' values or allocate catch equitably among commercial and recreational fishery sectors to better align with the broad goals of international fisheries legislation (Legault, 1998; Goethel et al., 2018). For instance, recreational fishers may prefer to forego harvest in favor of non-consumptive benefits such as higher catch rates, extended or more flexible fishing seasons, or the opportunity to catch very large fish (Cooke and Cowx, 2006; Ahrens et al., 2020). In addition to the priorities of commercial and recreational stakeholders, managers are tasked with considering multiple conservation objectives, such as minimizing adverse effects on marine habitat, reducing discarding of fishery catches, preserving diversity and resilience within populations, and avoiding harm to endangered and protected species (Worm et al., 2006; Punt, 2017).

Managers of fisheries with both commercial and recreational elements strive to attain, as equitably as possible, diverse commercial,

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recreational, and conservation objectives through the use of common regulatory tools. However, few regulations are universal tools that work equally well across all fishing sectors. For instance, limiting the number of participants in a fishery (e.g., by issuing a limited number of fishing permits or assigning harvest shares) has been used in the management of many commercial fisheries (Hilborn, 2007b; Chu, 2009), but managers of recreational fisheries are typically hesitant to exclude participation and instead prefer to use seasonal fishery closures to reduce fishing effort (Cox et al., 2002; Hilborn et al., 2005). The open-access approach to managing recreational fisheries, where an unlimited number of recreational fishers are allowed to harvest fish during at least some part of the year, can lead to a very short open fishing season and high discards during the relatively long closed season, which can be a significant source of mortality (e.g., northern red snapper, *Lutjanus campechanus*, in the U.S. Gulf of Mexico; SEDAR, 2018). In many instances, managing open-access recreational fisheries directly with fishing seasons and trip or bag limits has proven ineffective, mainly due to the challenges of accurately monitoring recreational catches and discards, the absence of incentives for fishers to minimize discarding, and fluctuations in catch efficiency and effort (Walters and Cox, 1999; Cox et al., 2002; Cooke and Cowx, 2006; MacKenzie and Cox, 2013).

Minimum size regulations are often implemented instead of direct effort reductions to limit recreational fisheries because they tend to be more readily enforceable (Caddy and Cochrane, 2001; Coggins et al., 2007). Minimum size limits have been shown to be effective in certain cases when the primary performance measure is yield maximization and the minimum size is set greater than the length at which a species has at least a 50% probability of reaching reproductive maturity, thus allowing fish to spawn at least once before harvest (van Poorten et al., 2013). However, minimum size limits can be ineffective at reducing fishing mortality when discard mortality rates are high, fishing seasons are short, or quota is limited, in turn leading to shortfalls in meeting management goals such as maximizing harvests, rebuilding depleted stocks, and providing recreational fishing opportunities (Cox et al., 2002; Birkeland and Dayton, 2005; Coggins et al., 2007; Gwinn et al., 2015). Maximum size limits and harvest slots (i.e., both a minimum and maximum size limit) discourage fishers from harvesting larger, reproductively valuable spawners (Berkeley et al., 2004; Hixon et al., 2014). If discard mortality rates are sufficiently low, harvest slots may protect both small, immature fish along with some large, fully mature fish, allowing fish to spawn at least once before harvesting. Protecting reproductively valuable larger fish can improve stock productivity, increase catch rates, lengthen fishing seasons, and increase the number of trophy fish caught (Farmer et al., 2014; Gwinn et al., 2015; Ayllón et al., 2019; Ahrens et al., 2020). Increased abundance of old, large fish also has conservations benefits as it may increase resiliency of populations to overexploitation, habitat degradation, and environmental perturbation (Berkeley et al., 2004; Hixon et al., 2014; Lowerre-Barbieri et al., 2015).

Management outcomes and empirical studies suggest harvest slots can be effective regulatory tools in some fisheries [e.g., red drum (*Sciaenops ocellatus*) and southern populations of spotted seatrout (*Cynoscion nebulosus*) in Florida, Chagaris et al. (2015); Addis et al. (2018)] while not in others [e.g., Lower Columbia River white sturgeon (*Acipenser transmontanus*), several stocks of striped sea bass (*Morone saxatilis*) in the U.S. mid-Atlantic states, and Murray cod (*Maccullochella peelii*) in New South Wales, Australia, Hildebrand et al. (2016); Ye et al. (2018); Northeast Fisheries Science Center (2019)]. Ultimately, the success of harvest slot regulations depends on the ability of fishers to minimize discard mortality of released fish, particularly the larger, older fish (Coggins et al., 2007; Ahrens et al., 2020). Harvest slots have mostly been used in freshwater and estuarine fisheries where discard mortality is expected to be low. In the marine environment, discard mortality rates are context dependent and fishers may be able to greatly reduce mortality of released fish, for example by using dehooking devices or circle hooks, or returning fish to depth with descender devices (Curtis et al., 2015; Brownscombe et al., 2017; Bohaboy et al., 2020). Thus, harvest slots could be a viable regulatory measure in marine fisheries that already have low discard mortality rates or where approaches exist to considerably reduce discard mortality rates, which might be better incentivized by alternate management approaches or regulations.

Although implementing fisheries management using top-down regulation such as effort controls or size limits can successfully limit fishing effort in the short-term, implementing multifaceted management regimes that incentivize changes in fishery practices to more rationally utilize the resource can result in more stable and effective long-term management (Hilborn et al., 2004; Pascoe et al., 2010; Lubchenco et al., 2016). For example, there is evidence that landings-based quotas encourage discarding, especially in mixed-species fisheries when the quota is small, because fishers are motivated to maximize the value of landings by keeping only the most profitable species and largest or highest quality fish, while they have little to no incentive to reduce dead discards (Rijnsdorp et al., 2007; Macdonald et al., 2014). Alternately, when catch quotas account for both landings and dead discards (i.e., total removals), implicit incentives can be created to minimize bycatch, discard mortality, and total discards (Catchpole et al., 2014; Condie et al., 2014; Somers et al., 2018). Furthermore, when indirect effort regulations, such as harvest slots, are embedded within appropriate management regimes it may ultimately lead to improved fishery performance metrics when stakeholders alter fishery practices (e.g., by reducing discard mortality). Thus, when combined with total removals-based quota accounting that incentivizes discard reductions, harvest slots represent a potentially useful management approach for marine recreational fisheries. However, the combined impacts of discard mortality reductions, harvest slots, and total removals-based quotas have not been well studied.

In the last few decades, the use of simulation testing to explore the potential performance of new management strategies and trade-offs among desired management objectives has become widely accepted as best practice prior to implementing new fisheries policies (Punt et al., 2016). By simulation testing the performance of an array of potential management strategies and summarizing results across a diversity of performance metrics associated with each stakeholder group involved with a fishery, simulation-based analyses help managers to understand the implications for the resource being managed along with the trade-offs across stakeholder objectives (Butterworth et al., 2010; Punt, 2017). A critical aspect of developing decision support for fisheries management is carefully choosing performance metrics pertinent to the diversity of concerned stakeholders, while also accounting for desired conservation metrics. Similarly, it is important to promote approaches and graphics that succinctly and clearly illustrate trade-offs among these often competing objectives to aid in stakeholder awareness and understanding of management implications (Punt, 2017; Goethel et al., 2019).

Northern Gulf of Mexico (GOM) red snapper exemplifies a large-scale marine fishery that supports diverse stakeholder groups, each with competing objectives, which is managed with an array of regulations. Commercial fishers of GOM red snapper have been managed under a limited access individual fishing quota (IFQ) program since 2007. Although the number of red snapper discarded annually by commercial fishers has declined since the implementation of the IFQ program in 2007, commercial discards still represent an important source of red snapper mortality, especially given the associated discard mortality rate ranges from 0.55 to 0.81, depending on gear, area, and whether the fisher possesses IFQ (SEDAR, 2018). The recreational fishery is largely open-access and has been managed primarily with minimum size regulations, closed seasons, and bag limits. Increased catch rates of smaller fish and large harvests from state waters have led to short federal fishing seasons (e.g., 3–10 days) and has resulted in greater than 70% of recreationally caught red snapper being discarded annually (NOAA, 2017; SEDAR, 2018). Managers of GOM red snapper have demonstrated interest in recreational harvest slots and reducing discard mortality (Farmer et al., 2014; Gulf of Mexico Fishery Management Council, 2018a; Federal Register, 2022), particularly given emerging evidence that recreational fishers may be able to reduce discard mortality by rapidly recompressing released fish (e.g., by releasing fish with descender devices; Curtis et al., 2015; Bohaboy et al., 2020). Additionally, GOM red snapper are currently managed with landings-based quotas. Thus, GOM red snapper provides an interesting case study to explore and compare the impacts of common recreational fisheries management approaches, while also providing insight into the potential multiplicative effects of combining indirect effort controls with quotas based on total removals within a multi-sector fishery.

In this study, we used conditioned operating models and simulation analysis based on the GOM red snapper resource and associated fisheries to provide one of the first explorations of the combined impact of recreational harvest slots, reductions in recreational discard mortality rate, and total removals-based quota accounting for multi-sector marine fisheries. Additionally, we demonstrated how the results of simulation analyses can be used to explore the complex trade-offs among competing recreational, commercial, and conservation objectives by developing exemplar linear utility functions, which provide a visual aid highlighting trade-offs between multiple management priorities. By tailoring the simulation framework to the GOM red snapper resource, we illustrate how this type of simulation analysis can be used in a management decision support context. Although our results provide direct insight for the GOM red snapper resource, we believe the general conclusions can help improve management of other large-scale multi-sector marine fisheries.

2. Methods

We developed a simulation-based decision support approach and applied it to GOM red snapper with the primary goal of understanding the impacts, both individually and in combination, of recreational fishery harvest slots, reduced recreational discard mortality rates, and alternate total removals-based quota accounting on common fishery performance metrics. We performed the simulation analysis in three stages: 1) re-running the most recent stock assessment population model (henceforth SEDAR 52; SEDAR, 2018) with alternate recreational discard mortality rates (DM_{rec}) to determine how assumptions of DM_{rec} within the stock assessment influence subsequent stages of the analysis; 2) projecting the impact of recreational harvest slots, with or without reductions in DM_{rec} during the projection time period, to explore whether this type of regulation alone or combined with reduced DM_{rec} could achieve management goals; and 3) projecting stock dynamics using landings-based and total removals-based quota accounting to examine how quota accounting approaches can influence the effects of harvest slots and reduced DM_{rec}. We compared results across management scenarios graphically to illustrate the trade-offs associated with various regulation combinations.

2.1. Population dynamics model

We used the population model from the most recent stock assessment of GOM red snapper (SEDAR, 2018) which was constructed in the integrated modeling software Stock Synthesis (SS; Methot and Wetzel, 2013). SS is a statistical catch-at-age model incorporating multiple data and error sources for catch and survey (e.g., landings, discards, relative abundance indices, and age and length compositions), biological information (e.g., growth, natural mortality, reproduction, and stock-recruitment), and fishery characteristics (age- or length- based selectivity or retention). SS model specifications unique to GOM red snapper are detailed in SEDAR (2013, 2018), summarized in Goethel et al. (2018), and contained in the SS input files used in this study (available at https://github.com/ErinBohaboy-NOAA/DecisionSupportRS). The SS assessment model time period was 1872–2016, included two areas (east and west subareas divided roughly by the Mississippi River at −89° E longitude), and was age-based (ages 0 through 20, where 20 was the plus group and included fish age-20 and older). Growth (length-at-age and weight-at-length, L_a and W_L, respectively), age-specific fecundity (E_a, in number of eggs), and age-specific natural mortality (M_a) were fixed, time-invariant inputs (Supplementary Table S1). Annual age-0 recruitment followed the Beverton-Holt stock-recruit function with annual estimated deviations, where steepness (h, describing the density-dependent compensation) was fixed at 0.99. Thus, the model essentially implemented an average annual recruitment assumption with deviations, such that the number of new recruits was independent of spawning stock size based on the estimated unfished recruitment, R_0. The R_0 parameter was estimated in two stanzas (historical, 1872–1983, and recent, 1984–2016) to account for apparent changes in stock productivity in recent years. Stock-wide annual recruits were distributed across the east and west subareas based on estimated annual apportionment parameters, which allowed for each subarea to have a unique time series of recruitment. Following recruitment, population dynamics were independent between the two subareas. Cohorts advanced through ages within the fished population assuming continuous natural mortality and model-estimated fishing mortality, and age- or length-based selectivity by area-specific fleets.

The SEDAR 52 GOM red snapper SS model included 14 fishing fleets and each fleet was specific to either the east or west subarea (Supplementary Table S2). Fishing fleets are groups of stakeholders that can be characterized by the gear types they use, where and when they fish, the ages of red snapper they catch, and the amount and sizes of red snapper they harvest. The GOM red snapper fishing fleets include directed recreational fishing (anglers targeting red snapper primarily with hook-and-line gear during the open fishing season), recreational closed season (anglers who catch red snapper during the closed fishing season and cannot legally land them), directed commercial fishing (fishers catching red snapper on longline or handline gears who can legally land them), non-directed commercial fishing (fishers who catch red snapper and cannot legally land them), and shrimp trawl bycatch (commercial fishers who catch and discard juvenile red snapper incidentally to bottom trawling for harvested shrimp species). Within the assessment model, the directed recreational fishing fleets were divided further into the private/for-hire component (which includes anglers fishing from privately owned boats as well as those who have chartered a fishing boat) and the headboat component (commonly referred to as “party boats” where individual fishers purchase a ticket for a fishing trip, often on a large fishing boat). The directed fishing fleets land and discard red snapper, which experience discard mortality, whereas the closed season recreational and non-directed commercial fishing fleets only generate dead discarded fish within the model. Fleet-specific discard mortality rates for commercial fishing fleets were fixed to the SEDAR 52 values, ranging from 0.55 to 0.81. In addition to fishing fleets, the GOM red snapper population model also included 11 survey fleets based on a variety of gear types (e.g., bottom trawl, plankton net, longline, or remote-operated camera) which contributed relative abundance indices and age or length composition data.

Selectivity, the differential availability and vulnerability of fish by age or length to capture, and retention, the actual proportion of fish by age or length that are harvested, are integral to age-specific instantaneous fishing mortality (F_a) and predicting the age or length composition of the catches within the SS model (see the Supplementary Material for more details). Fleet-specific apical fishing mortality (F'_{flt}) is the F experienced by the age with selectivity equal to 1. In SEDAR 52, red snapper selectivity for the recreational and commercial fleets was based on age and the parameters were estimated, while retention was length-based with fixed parameters for most fleets. The number of discarded fish that die (dead discards) was the product of discards at length and the fleet-specific discard mortality rate. Similar to parameters of the selectivity and retention functions, discard mortality rate can be time-varying within the SS model to reflect changes in regulations or fisher behavior that are expected to influence survival of discarded fish. In stage 1, the DM_{rec} values of the SEDAR 52 base model were altered and the model was rerun to rescale the starting point for projections and allow exploration of the impact of having a higher initial discard mortality rate on management scenarios in later stages (see the Management Simulation Scenarios section below for more details).

2.2. Projection methods

For each management scenario (outlined in the following section), we projected the fishery and population dynamics of GOM red snapper from 2017 to 2032 using the forecast component of SS. All projections adhered to the red snapper rebuilding plan by constraining stock-wide exploitation such that the spawning potential ratio (*SPR*, the fraction of the unfished spawning stock biomass per recruit) increased to 26% ($SPR_{26\%}$) in year 2032. Following the same approach used by managers to set overfishing limits and acceptable biological catches for GOM red snapper (Goethel and Smith, 2018), annual stock-wide recruitment was projected based directly on the stock-recruit relationship with $h = 0.99$ and no annual deviations using the estimated unfished recruitment from the recent time period ($R_{0,1984–2016}$). Age-0 recruits were distributed between east and west subareas using the average estimated regional apportionment from this same time period (approximately 34% to the east and 66% to the west).

Fishing mortality is handled by SS primarily in terms of F'_{flt} and relative F'_{flt} among fleets, which allows for scaling and summation of fishing mortality across fleets in the projection years (Supplementary Table S3). The SS forecast model determines the multiplier parameter $F\_mult_{overall}$ and the vector of 'benchmark' relative apical fishing mortality values ($F\_rel\_Bmark_{flt}$) to attain $SPR_{26\%}$ in 2032 while balancing landings or total removals between the recreational and commercial sectors according to each management scenario. The initial values of $F\_rel\_Bmark_{flt}$ were specified in this study as the average of years 2011–2015 F'_{flt} (initial $F\_rel\_Bmark_{flt} = \frac{F'_{2011-2015,flt}}{\sum_{flt=1}^{n} F'_{2011-2015,flt}}$). Apical fishing mortality by fleet (F'_{flt}) in the forecast years is calculated as the product of estimated $F\_rel\_Bmark_{flt}$ and $F\_mult_{overall}$. We allowed $F\_mult_{overall}$ and $F\_rel\_Bmark_{flt}$ to be applied to all fleets, including the directed and non-directed fishing fleets instead of holding non-directed F'_{flt} constant (i.e., as was done in the SEDAR 52 stock assessment projections; Goethel and Smith, 2018; Supplementary Fig. S1). Allowing the directed and non-directed forecast relative F'_{flt} to be estimated was needed for our analysis of the total removals-based quota accounting approach, which required maintaining the allocated proportion of dead biomass between the commercial and recreational sectors. We explored developing a functional relationship between directed and non-directed F'_{flt} within the projection model to better characterize fisher behavior, e.g., we expect shorter open fishing seasons would result in more fisher activity, greater F'_{flt}, and lower catch rates during the closed season. However, empirical estimates of fisher effort and catch rates for the non-directed recreational fishing fleets were insufficient to quantify the relationship. Instead, the SS forecast model maintained the same relative F'_{flt} among fleets within an allocation group when estimating $F\_rel\_Bmark_{flt}$ within the projection years.

For the landings-based quota accounting approach, landings were constrained by estimating the directed fleet relative F'_{flt} such that commercial fleet landings to recreational fleet landings were in a ratio 0.51–0.49, respectively (Fig. 1*a*). For the total removals-based quota accounting approach, estimated dead discards (including open season discards for both sectors, closed season recreational discards, and non-directed commercial discards) were counted with landings against each sector's quota (Fig. 1*b*). To be consistent with current management, we maintained the allocation (0.51 commercial to 0.49 recreational) for the total removals-based quota accounting approach. Dead discarded biomass from the shrimp trawl fleets, which typically accounts for less than 2.7% of annual stock-wide red snapper dead biomass (average 2012–2016; SEDAR, 2018), was not included in any allocation, as is consistent with current management.

Depending on the management scenario being simulated (see full descriptions below), various aspects of the projection model were altered to address the desired regulation. The retention function was modified to account for alternate minimum or maximum lengths for harvest slots, DM_{rec} was reduced, or the quota accounting approach was modified. The implementation of harvest slots required the most significant changes to the modeling framework. For instance, we modified retention at length for each directed recreational fishing fleet to mimic the effects of harvest slots, such that all fish above a maximum size limit would be discarded (see the Supplementary Material for a full description of these changes).

2.3. Management simulation scenarios

Each stage of the study design was combined with the results and conditions of the previous stage, which led to a total of 768 management scenarios (Table 1). In stage 1, all parameters for the base years (1872–2016) of the assessment model were re-estimated for a range of DM_{rec}. The SEDAR 52 assessment assumes a DM_{rec} of 0.22 in the east

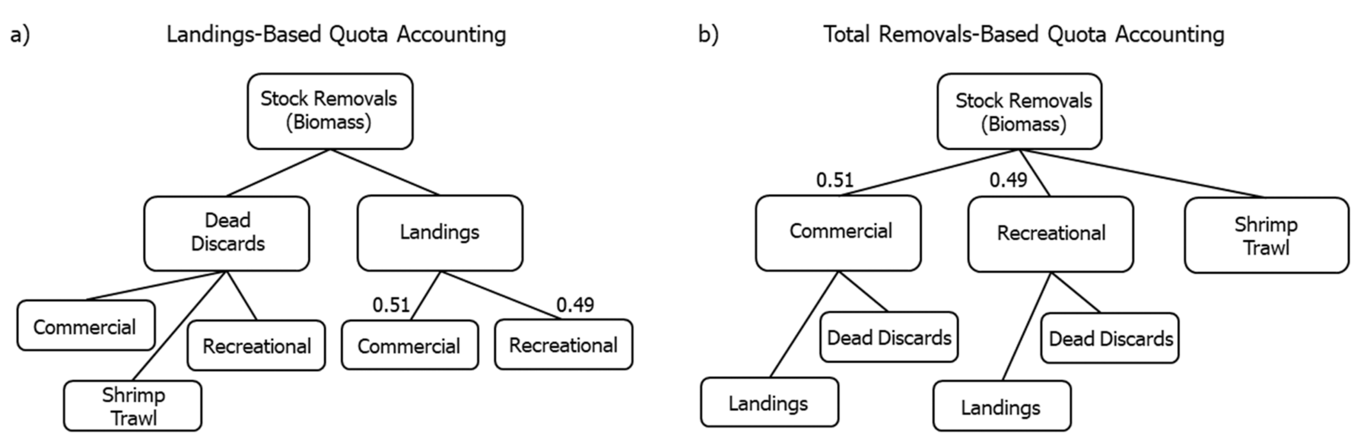

Fig. 1. Conceptual representation of quota accounting approaches. The *status quo* management approach is demonstrated in (a) where only landings are counted against each sector's quota assuming the current allocation ratio of 0.51–0.49 (commercial to recreational sectors). Dead discarded biomass is not included in either allocation group. The alternative total removals-based quota accounting approach is illustrated in (b) where total removals (biomass of landings plus dead discards) are counted against each sector's quota. GOM red snapper biomass removals from shrimp trawl bycatch (which accounted for less than 2.7% of total stock-wide removals from 2012 to 2016) are not attributed to either allocation group.

Table 1
Management scenarios organized by stages of the study design, including assessment recreational discard mortality rate (DM_{rec}), harvest slots and relative reduction of DM_{rec}, and quota accounting approach. For each stage, n represents the number of options or possible assumptions. Stage 1 assessment DM_{rec} values for SEDAR 52 were 0.22 and 0.21 in the east and west subareas of the GOM red snapper stock, respectively, from 1981 to 2007 and 0.118 for both subareas from 2008 to 2016.

Stage 1: Assessment DM_{rec} ($n = 4$)	Stage 2: Projecting harvest slots and relative reduced DM_{rec} ($n = 96$)			Stage 3: Quota accounting approach ($n = 2$)
	Minimum length (in., TL)	Maximum length (in., TL)	Relative DM_{rec}	
		22		
SEDAR 52		24	0%	
0.25	16	26	-10%	Status quo approach: landings-based quota accounting
0.50	18	28	-25%	
0.75		30	-50%	Alternate approach: total removals-based quota accounting
		32	-75%	
		34	-100%	
		none		

subarea and 0.21 in the west subarea from 1981 to 2007 and 0.118 for both subareas from 2008 to 2016. This change in DM_{rec} reflects regulations that were enacted in 2008 requiring recreational fishers to use circle hooks in an effort to reduce hooking injury and discard mortality. Because the SEDAR 52 model assumes relatively low values of DM_{rec}, we wanted to be able to explore the impacts that higher DM_{rec} values might have under the various harvest slots and quota accounting approaches implemented in subsequent stages. Thus, using a wide range of DM_{rec} values in stage 1 changed some model values and the resulting initialization point of the projections for stages 2 and 3. Additionally, given that harvest slots and total removals-based quotas have been hypothesized to incentivize changes in fishing practices (e.g., through stakeholder adoption of discard mortality mitigation measures), rescaling the starting point of the projections based on higher initial DM_{rec} allowed exploration of the benefits that might be attained by stakeholders if they were to subsequently reduce DM_{rec}. As described in stage 2, comparing different percent reductions in DM_{rec} for the projection period with a scenario where no change in DM_{rec} occurs, allows a better understanding of what the incentives might be for recreational fishermen (e.g., increased yield, longer fishing seasons, etc.). We explored assessment $DM_{rec} = 0.25$, 0.50, and 0.75, applied across all recreational fleets in both areas for the entire time series. Although the chosen DM_{rec} values reflect a reasonable range for GOM recreational caught red snapper based on recent discard mortality studies (Campbell et al., 2014; Curtis et al., 2015; Bohaboy et al., 2020), they are not meant to reflect any specific hypothesis for red snapper. Instead, these values were chosen to reflect the wide array of potential DM_{rec} observed in marine recreational fisheries, thereby enabling conclusions that can more adequately represent a diversity of fisheries, and not just the red snapper case study being used to demonstrate our simulation framework.

In stage 2, we projected the GOM red snapper population assuming the recreational fishing fleets were subject to harvest slots, while also investigating the combined impact of increased survival of released fish (i.e., relative reductions in DM_{rec} from the value assumed in the assessment model in stage 1). As noted, the latter assumption allowed for determination of the benefits that might be gained if recreational fishers adopted discard mortality mitigation measures, such as through the use of descender devices. We explored projection DM_{rec} equal to 0% (no change), −25%, −50%, −75% (relative reductions of 25%, 50%, and 75%), and −100% (no discard mortality or 100% survival of released fish). We incorporated recreational harvest slots by modifying the minimum and maximum retention lengths. We included the current minimum length = 16 in. total length (TL) and an increased minimum length = 18 in. TL. We chose to include an increased minimum length for our scenarios because it represents a management option that provides further opportunity for a fish to spawn by delaying harvest and is a common approach used to increase spawning biomass (Arlinghaus et al., 2007). In addition to the current regulation of no maximum length, we implemented maximum length of retained fish at 2 in. increments from 22 in. to 34 in. TL. Given that red snapper larger than 34 in. TL are rarely harvested [< 1% of red snapper harvested by private and charterboat fishers from 2014 to 2018 were greater than 34 in. TL; SEDAR, 2018; NOAA Office of Science and Technology, 2019], it is expected that a maximum length = 34 in. TL would have a limited effect on recreational fishers and stock dynamics. In contrast, a maximum length = 22 in. TL would result in a very narrow harvest slot and would be expected to greatly increase red snapper discarding because over 42% of red snapper harvested by recreational fishers were greater than 22 in. TL in 2014–2018 (SEDAR, 2018; NOAA Office of Science and Technology, 2019). Although the 2 in. increments in maximum length are relatively coarse, the wide range of potential harvest slots demonstrated the general trends associated with implementing no harvest slots, narrow harvest slots, or wide harvest slots.

In stage 3, we projected the population and fishery dynamics under two different approaches to accounting for the quota between the commercial and recreational sectors. Currently, population removals resulting from dead discards of red snapper are not counted against the quota for either sector (Fig. 1*a*). This landings-based quota accounting approach has been used for management since 1990 and the 0.51 commercial to 0.49 recreational landings ratio was based on estimated red snapper landings attributed to each sector during 1979–1987 (Gulf of Mexico Fishery Management Council, 1989). We also incorporated an alternative approach into the model projections where the quota is based on total removals, wherein both landings and dead discards were attributed to the associated sector and counted against the quota (Fig. 1*b*). For the total removals-based quota accounting approach, we also held the projected dead biomass ratio constant at 0.51 commercial to 0.49 recreational to adhere to current management regulations. Under the total removals quota accounting approach, high levels of dead discards would reduce the amount of fish that could be landed by a given sector, thereby reducing yield and the potential length of the recreational season. Both quota accounting approaches were implemented in the projection model for all combinations of assessment DM_{rec} assumptions (stage 1), harvest slots (stage 2), and DM_{rec} reduction levels (stage 2). By combining different quota accounting approaches with harvest slots and reductions of DM_{rec}, stage 3 provides one of the first demonstrations of how sector accountability of dead discards impacts management outcomes.

2.4. Performance measures

We evaluated the relative trade-offs across fishery sectors and conservation objectives for each management scenario using model outputs that illustrated the projected population and fishery performance (Table 2). Given that the primary conservation objective of rebuilding the stock to the *MSY* proxy of $SPR_{26\%}$ by 2032 was obtained in every simulation by design, *SSB* was not included in the suite of performance measures (*PMs*). The main *PMs* were: 1) recreational season length, 2) recreational catch rate (catch per unit effort as number per unit time), 3) commercial landings (by weight), 4) reduction of recreational dead discards (by weight), 5) the proportion of old (≥ 20 years) fish in the population, and 6) the realized ratio of commercial to recreational dead biomass. Recreational fishing season length was assumed to be directly proportional to open season recreational exploitation rate (i.e., number of fish killed divided by total population), such that a relative change in open season exploitation rate would represent an identical relative

Table 2
Performance measures (*PMs*) used to evaluate trade-offs across fisheries sectors and objectives. *PMs* are presented as the projected 2032 value for each management scenario relative to the projected 2032 value assuming current management regulations (16 in. TL minimum length with no maximum length and no reduction in discard mortality rate).

Performance measure (*PM*)	Sector/ objective	Description	Units
Recreational season length	Recreational	Open season recreational exploitation rate (landings + dead discards by number divided by total population size)	Unitless / relative only
Recreational catch rate	Recreational	Recreational catch (landings + discards, in numbers) divided by recreational exploitation rate (combined for both the open and closed fishing seasons)	Unitless / relative only
Commercial landings	Commercial	Sum of retained catch across all commercial fishing fleets	Metric tons
Recreational dead discards	Conservation	Sum of dead discards across all recreational fishing fleets (multiplied by −1 such that reductions in dead discards were represented by a positive value)	Metric tons
Proportion of old fish in the population	Conservation	Number of fish age 20 and older in the population divided by total population size	Proportion
Realized ratio of commercial to recreational dead biomass	Equity	Sum of recreational landings and dead discards by weight divided by sum of all fleets landings and dead discards by weight (excluding shrimp bycatch fleets)	Proportion

increase or decrease in the open season length. The basis of the season length assumption is that higher open season removals would require increased effort and, thus, a longer season length to enable that level of removals to occur. Our approach to calculating season length is essentially identical to that used for in-season management of the recreational red snapper fishery (i.e., projections of season lengths; Farmer et al., 2014). Recreational catch rates were calculated as projected recreational catch (landings plus discards, in numbers) per unit recreational effort based on the combined open and closed fishing seasons. Recreational effort was assumed proportional to recreational exploitation rate, following the same reasoning as for calculating season length, i.e., higher removals require greater effort. We used projected 2032 commercial landings (metric tons) calculated as the sum of retained catch across all commercial fishing fleets as the primary performance metric for the commercial sector. We considered two additional conservation metrics: the weight of recreational dead discards and the proportion of the population comprised of older fish (≥ 20 years). Projected 2032 dead discards were summed over all recreational fishing fleets. Finally, we considered the balance of total dead biomass among the commercial and recreational fishery sectors as an understanding of equitability because equitable allocation of resources among user groups is a highly valued management objective in many instances.

We presented *PMs* for each management simulation scenario as percent change relative to the 'business as usual' (*BAU*) value, which represented the projected 2032 value assuming current management regulations (i.e., 16 in. TL minimum length, no maximum length, and no relative reduction in DM_{rec}) based on the associated DM_{rec} in stage 1. Percent change relative to *BAU* for the recreational discards *PM* was multiplied by −1 such that reductions in dead discards were represented by a positive value. We used 6-axis (also known as kite, radar, or spider, e.g., Punt, 2017) plots to compare and illustrate the trade-offs among *PMs* for a small number of management scenarios representing combinations of a "wide" harvest slot (16–32 in. TL) or a "narrow" harvest slot (18–24 in. TL) and either a large (50%) reduction in DM_{rec} or no reduction in DM_{rec} (Table 3). To facilitate illustration and comparison between *PMs* using the 6-axis plots, we divided the output value for each management scenario and *PM* (relative percent change) by the standard deviation of that metric calculated over all management scenarios under consideration, such that the variance of each metric (over all management scenarios under consideration) equalled 1.

2.5. Summary metrics

We used a flexible summary metric (*SM*), which incorporates multiple *PMs* into a single value that can aid managers' understanding of the trade-offs inherent in a given management approach. Our *SM* is synonymous with utility, which is a single-dimension abstract measure of the relative desirability of prospective management actions. Utility weighs diverse stakeholder objectives and is sometimes used in risk management and decision analysis (Keeney, 1977; Walker et al., 1983; Lane and Stephenson, 1998; Robb and Peterman, 1998; Ahrens et al., 2020). We assumed a linear utility function by assigning weights to diverse management priorities (Lane and Stephenson, 1998; Peterson and Evans, 2003). Each of $i = 1$–6 of the 6 *PMs* described above were given exemplar weights (w_i) in the calculation of the *SM*, thus, $SM = \sum_{i=1}^{6} PM_i w_i$. To represent a range of emphasis in priorities, we explored example w_i values to reflect hypothetical priorities of recreational fishers, commercial fishers, conservation, or equitability (Table 4). The recreation-emphasis *SM* placed 25% of total utility weight on each recreational *PM* (recreational season length and recreational catch rate). Recreational season length and catch rates are easily quantifiable measures of the ability to go fishing and the experience of catching fish, which are valued by some recreational fishers over harvesting fish (Fedler and Ditton, 1994; Ahrens et al., 2020). In contrast, the production-emphasis *SM* placed 50% of total utility weight on commercial landings as a measure of direct economic benefit to commercial fishers who sell their catches (NMFS, 2018). The conservation-emphasis *SM* prioritized dead discard reduction and the population of fish age 20 years or older (25% of total utility weight is assigned to each *PM*) but downweighs the recreational and commercial priorities. Reduction of dead discards has been prioritized as general best practices for fisheries conservation (e.g., in the European Union Common Fisheries Policy and U.S. Magnuson-Stevens Reauthorization Act) and increased abundance of older, larger fish within a population is hypothesized to increase population resiliency (Berkeley et al., 2004; Hixon et al., 2014; Lowerre-Barbieri et al., 2015). The recreation + production-emphasis *SM* placed moderate weight (67% percent of total utility weight) on the

Table 3
Management scenarios presented to illustrate trade-offs among performance metrics (*PMs*). Assumed assessment discard mortality rate (DM_{rec}) was equal to either 0.5 over the entire time series or the values from SEDAR 52 (0.22 and 0.21 in the east and west subareas of the GOM red snapper stock, respectively, from 1981 to 2007 and 0.118 for both subareas from 2008 to 2016).

Scenario name	Minimum length (in., TL)	Maximum length (in., TL)	Reduction in DM_{rec}
No change	16	None	0%
Reduce DM_{rec} only	16	None	50%
Wide slot only	16	32	0%
Narrow slot only	18	24	0%
Wide slot + reduce DM_{rec}	16	32	50%
Narrow slot + reduce DM_{rec}	18	24	50%

Table 4
Weights (w_i) assigned to each performance measure (PM_i) for example summary metrics (*SMs*). Proportion of recreational to commercial (Rec:com) total removals is by weight. The sum of $w_i = 12$ for each *SM* below.

Summary metric (*SM*)	Recreational priority		Commercial priority	Conservation priority		Equitability priority
	Season length (w_1)	Recreational catch rate (w_2)	Commercial landings (w_3)	Dead discard reduction (w_4)	Population > = 20 years (w_5)	Rec:com total removals (w_6)
Recreation	3	3	2	1	1	2
Production	1	1	6	1	1	2
Recreation + production	2	2	4	1	1	2
Conservation	1	1	2	3	3	2
Balanced	1.5	1.5	3	1.5	1.5	3

recreational and commercial priorities combined, and is a hypothetical example of a management preference focused on fishers. Finally, the balanced-emphasis *SM* placed equal weight on each of the four main priorities: recreational, commercial, conservation, and equitability.

3. Results

3.1. Impacts of harvest slots and reduced discard mortality rate on performance measures

Recreational harvest slots and reduced discard mortality rate led to different trends across management scenarios for each *PM* (Fig. 2 first column, e.g., assuming SEDAR 52 assessment discard mortality rate and the landings-based quota accounting approach). Recreational open fishing season length increased with more narrow harvest slots and greater reductions in DM_{rec} (Fig. 2, Supplementary Figs. S3–S4). Even without reducing DM_{rec}, adopting a very narrow harvest slot (e.g., 16–22 in. TL) lengthened the recreational fishing season by over 40%. Recreational catch rate increased with more narrow harvest slots, mostly due to greater catch of younger, smaller fish (Fig. 2, Supplementary Figs. S5–S10). Commercial landings decreased with more narrow harvest slots, though the effect was modulated if DM_{rec} was concurrently reduced (Fig. 2, Supplementary Figs. S11–S12). Reducing DM_{rec} without instituting harvest slots increased commercial landings. Instituting harvest slots without reducing DM_{rec} increased recreational dead discard biomass, while reducing DM_{rec} together with wide or no harvest slots reduced recreational dead discard biomass (Fig. 2, Supplementary Figs. S13–S14). The proportion of the population comprised of age 20 or older fish increased with more narrow harvest slots and greater reductions in DM_{rec} (Fig. 2, Supplementary Figs. S15–S16). Increasing the minimum harvest slot length (16 in. or 18 in.) had only minor effects on commercial landings and recreational dead discards but did result in decreased recreational season length when combined with large maximum size limits (e.g., a wide harvest slot; Supplementary Figs. S3–S16).

3.2. Combined effects of assessment discard mortality rate, harvest slots, and reduced discard mortality rate on performance measures

Assuming higher assessment DM_{rec} reduced the assessment model goodness of fit, while estimated R_0 increased to account for the higher stock removals (Supplementary Table S4). For each of the alternate assessment DM_{rec} values, the terminal year estimated *SSB*, and associated initial biomass for the projection period, was reduced compared to SEDAR 52. Concomitantly, the *SSB* at the rebuilding target of $SPR_{26\%}$ in 2032 was higher (due to the larger SSB_0 and R_0; Supplementary Fig. S2). When higher DM_{rec} was assumed in the assessment years of the population model, it amplified the effects of relative reductions in DM_{rec} (alone and combined with harvest slots) on each *PM* during the projection years but did not affect the overall trends (Fig. 2 third column, Supplementary Figs. S3–S16).

3.3. Impacts of alternate quota accounting approaches on performance measures

When the total removals-based quota accounting approach was simulated, the impacts of recreational harvest slots and relative reductions in DM_{rec} became more directly attributed to the recreational fishery and the greater number of dead discards tempered the increase in season length (Fig. 2 second column). For example, if recreational fishers adopted a narrow harvest slot (e.g., 16–22 in. TL) without reducing DM_{rec}, the gain in season length was large under the current landings-based allocation approach (+42%), but less pronounced (+10%) under the alternate total removals-based quota accounting approach. In contrast, total removals-based quota accounting greatly diminished the effects on the commercial fishery (i.e., reduction in commercial landings was less). Following the same example, a narrow harvest slot (16–22 in. TL) in the absence of reduced DM_{rec} led to a 27% reduction in commercial landings under the landings-based quota accounting approach, but the reduction in commercial landings was lessened to 14% using a total removals-based quota accounting approach.

The total removals-based quota accounting approach also retained benefits of recreational fishery regulations within the recreational sector better than the landings-based allocation approach. Under the landings-based allocation approach, a large (e.g., 50%) reduction in DM_{rec} (in the absence of harvest slots) translated to only a 1.1% increase in recreational season length but resulted in moderate increases in commercial landings (+4.9%; Fig. 2 first column). However, using total removals-based quota accounting, the same reduction in DM_{rec} resulted in greater gains in recreational season length (+7.0%) and minimized gains in commercial landings (< +1%; Fig. 2 second column).

The effects of quota accounting approach on *PMs* showed consistent trends across all levels of assumed assessment DM_{rec} (Fig. 2; Supplementary Figs. S3–S16). However, the moderating effects of total removals-based quota accounting were more pronounced when assumed assessment DM_{rec} was greater. Following the previous example of a narrow harvest slot (16–22 in. TL) with no reduction in DM_{rec}, if assessment $DM_{rec} = 0.5$, recreational season length was + 63% for the landings-based quota accounting and −2.6% for the total removals-based quota accounting (compared to +42% and +10% for landings-based and total removals-based quota accounting for SEDAR 52 DM_{rec} values). Similarly, if assessment $DM_{rec} = 0.5$, lost commercial landings were 36% for landings-based quota accounting and 5% for total removals-based quota accounting (compared to 27% and 14% for landings-based and total removals-based quota accounting for SEDAR 52 DM_{rec} values).

3.4. Trade-offs among recreational-, commercial-, and conservation-based performance measures

Reducing DM_{rec} alone or combined with a wide recreational harvest slot led to increases (range 0.19–47.2% relative increase) for most *PMs* examined (Fig. 3*a*; Supplementary Table S5). Reducing DM_{rec} combined with a narrow harvest slot led to large gains in recreational season

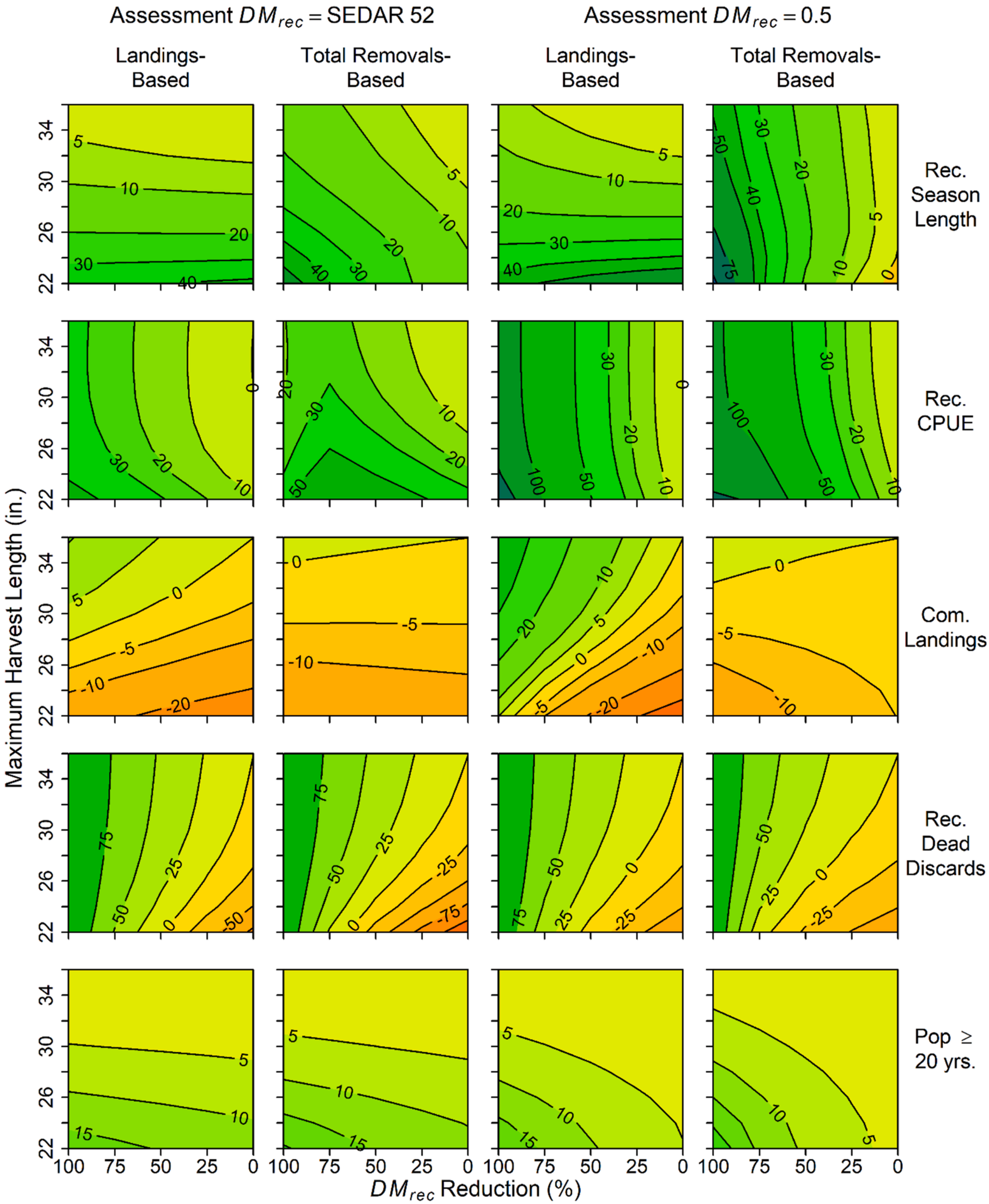

Fig. 2. Effects of recreational harvest slot maximum length (y-axis) and relative reductions in recreational discard mortality rate (DM_{rec}, x-axis) on five performance measures (*PMs*): recreational open fishing season length (Rec. Season Length; row 1), recreational catch rates (overall catch per unit effort, Rec. CPUE, number of fish; row 2), commercial landings biomass (Com. Landings; row 3), reduction of recreational dead discard biomass (Rec. Dead Discards; row 4), and the proportion of the population age 20 years and older (Pop ≥ 20 yrs.; row 5). Contour values are percent change of each performance measure relative to current regulations (16 in. TL minimum length with no maximum length and no reduction in discard mortality rate). Contour area is shaded with increasingly warm colors to signify greater negative change and increasingly cool colors to signify greater positive change. Landings- and total removals-based quota accounting approaches are shown for assumed assessment DM_{rec} = SEDAR 52 values (columns 1 and 2) and 0.5 (columns 3 and 4). For each contour plot, minimum harvest length is 16 in. TL and maximum harvest length ranges from 22 to 34 in. TL and no maximum length. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

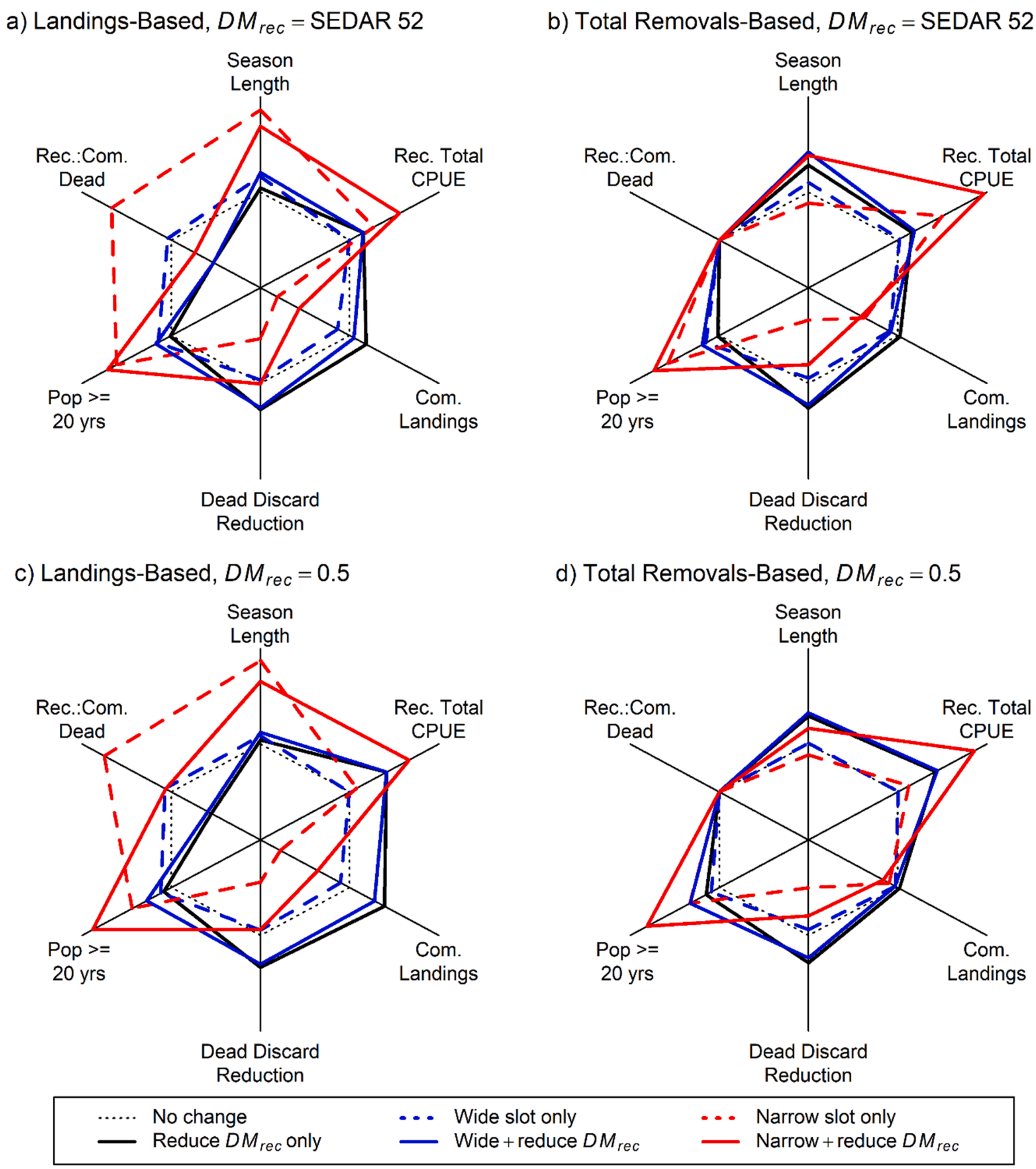

Fig. 3. Trade-offs among performance measures (*PMs*) illustrated for a prospective management scenarios comparing landings-based quota accounting (a and c) against total removals-based quota accounting (b and d). Assessment recreational discard mortality rate (DM_{rec}) was assumed equal to SEDAR 52 values (a and b) or 0.5 (c and d). The axes display 6 *PMs*: recreational season length, recreational overall catch rate (catch per unit effort, CPUE), commercial landings biomass, reduction of recreational dead discard biomass, the proportion of the population ≥ 20 years old, and the ratio of recreational to commercial dead biomass (rec.:com. dead). Six prospective management scenarios (Table 3) are shown: no change (16 in. TL minimum length, no maximum length, and no change in DMrec; black, broken), reduce DM_{rec} only (16 in. TL minimum length, no maximum length, 50% relative reduction in DM_{rec}; black, solid), wide harvest slot only (16 in. TL minimum length, 32 in. TL maximum length, no change in DMrec; blue, broken), wide harvest slot + reduce DM_{rec} (16 in. TL minimum length, 32 in. TL maximum length, 50% reduction in DM_{rec}; blue, solid), narrow harvest slot only (18 in. TL minimum length, 24 in. TL maximum length, no change in DMrec; red, broken), and narrow harvest slot + reduce DM_{rec} (18 in. TL minimum length, 24 in. TL maximum length, 50% reduction in DM_{rec}; red, solid). The values for each *PM* are unitless, have been scaled to have variance = 1 within each DM_{rec} assumption, and are relative to the 'no change' scenario with negative values (decreases) towards the origin and positive values (increases) towards the outside of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

length (+17.1%) and recreational catch rate (+53.3%) but at the cost of lost commercial landings (14.8%). Trade-offs in *PMs* were balanced more evenly under total removals-based quota accounting, especially for narrow harvest slots (Fig. 3*b*; Supplementary Table S5). Assuming higher assessment DM_{rec} increased the magnitude of effects but did not alter the general trends in trade-offs among recreational-, commercial-, and conservation- based *PMs* (Fig. 3*c–d*, Supplementary Table S6).

3.5. Summary metrics

Reducing DM_{rec} combined with wide recreational harvest slots increased all *SM* values (Fig. 4; Supplementary Tables S5–S8). However,

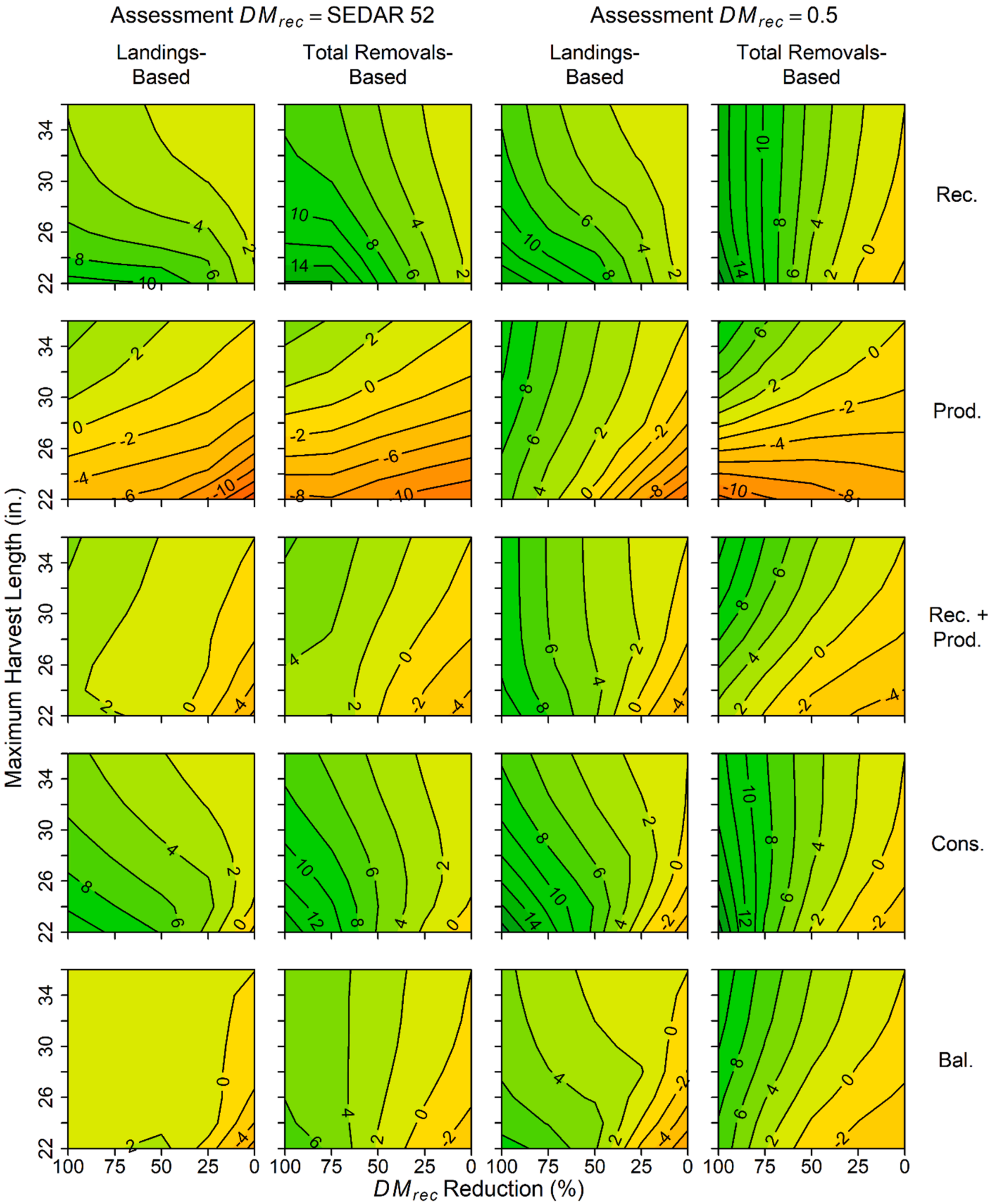

Fig. 4. Summary metric (*SM*) values (unitless) for harvest slots and reductions in recreational discard mortality rate (DM_{rec}) demonstrated for a variety of management priority emphasis schemes (Table 4): Recreation (Rec., row 1), Production, (Prod., row 2), Recreation + Production (Rec. + Prod., row 3), Conservation (Cons., row 4), and Balanced (Bal., row 5). For each contour plot, minimum harvest length is 16 in. TL, maximum harvest length ranges from 22 to 34 in. TL and no maximum (top) on the y-axis, and relative reduction of DM_{rec} in the projection years are shown on the x-axis. The landings-based and total removals-based quota accounting approaches are contrasted for assumed assessment DM_{rec} = SEDAR 52 values (left columns) and 0.5 (right columns).

narrow harvest slots combined with reduced DM_{rec} resulted in the greatest increases in all *SM*s except for the production-emphasis *SM*, which exhibited a decrease. If recreational harvest slots are used, reducing DM_{rec} was generally required for gains in the values of *SM*s, regardless of assumed assessment DM_{rec} or quota accounting approach. Similar to the effect on *PM*s, assuming higher assessment DM_{rec} amplified, but did not alter, the overall trends across harvest slot and reduced DM_{rec} combinations.

4. Discussion

The results of our simulation analysis demonstrate that common recreational fisheries management approaches, such as harvest slots and total removals-based quota accounting, may not necessarily achieve desired conservation and management performance metrics in isolation, and may also cause unforeseen consequences to other fishery sectors. Conversely, reducing the mortality rate of recreational caught and released fish alone resulted in longer open recreational fishing seasons, increased recreational catch rates, increased proportion of reproductively valuable older fish in a population, and reduced dead discarded biomass. Furthermore, combining harvest slots or total removals-based quotas with reductions in DM_{rec} led to substantial increases in an array of fishery performance metrics. Thus, our results suggest recreational harvest slots and alternate quota accounting mechanisms would potentially provide incentive to recreational fishermen to adopt discard mortality rate mitigation measures, thereby increasing desired fishery performance (e.g., the length of the fishing season or recreational catch rates) likely leading to better buy-in to the management framework. However, we caution that individual fishers may still not recognize the advantages of modifying their own behavior because the GOM red snapper recreational fishery is still an open-access fishery with a common seasonal catch quota. In addition, the fisheries scenarios presented in our simulation analyses assume managers could take the steps necessary to achieve complete implementation of harvest slot regulations and discard mortality rate reduction measures, which may not be possible in a geographically dispersed fishery such as GOM red snapper, even with a great deal of public outreach and enforcement resources.

Assuming fishers do effectively reduce DM_{rec}, our results further support the growing body of literature that suggests recreational harvest slots could be a valuable regulatory tool to achieve a balance of commercial, recreational, and conservation objectives (e.g., Farmer et al., 2014; Gwinn et al., 2015; Ahrens et al., 2020). We caution that instituting recreational harvest slots without concurrently reducing mortality rate of released fish would increase dead discards. Significant reductions in DM_{rec} (e.g., by 50%) are expected to have minimal effects on fisheries if DM_{rec} is already very low [e.g., 0.15 or less, as is the case with U.S. GOM gray triggerfish (*Balistes capriscus*), U.S. GOM red snapper, U.S. Gulf of Maine Atlantic cod (*Gadus morhua*), U.S. mid-Atlantic black seabass (*Centropristis striata*), and U.S. mid-Atlantic summer flounder (*Paralichthys dentatus*), Northeast Fisheries Science Center (2015); SEDAR (2015); Mid-Atlantic Fishery Management Council and Atlantic States Marine Fisheries Commission (2020)]. However, if DM_{rec} is in fact much higher than previously assumed in stock assessments and management decisions for these fisheries, then DM_{rec} reductions and recreational harvest slots will likely have important consequences for management outcomes and efficacy, as we observed in our case study of GOM red snapper.

Implementing recreational harvest slots in a multi-sector fishery, especially absent large reductions in DM_{rec}, may have indirect consequences on competing sectors. As recreational harvest slots become more narrow, fishers must discard a greater portion of the catch, requiring increased effort in the form of a longer open fishing season to fill the landings-based quota. However, discarded fish that die detract from the fishery-wide allowable catch, which reduces the commercial quota and results in reduced commercial landings. Discovering such unintended consequences of potential management actions is one of the primary benefits of performing decision support analyses drawing on simulations and a wide array of performance metrics. Narrow recreational harvest slots under an alternate management approach, where total removals formed the basis of quota accounting between the commercial and recreational sectors, tempered gains in recreational fishing opportunities and minimized consequences to the commercial sector. To this end, our results provide theoretical support for the general theory behind total removals-based quota accounting. Holding fishing sectors accountable for total removals, as opposed to only landings, likely incentivizes beneficial fishing practices (e.g., reducing discard mortality), while eliminating the effects of harmful practices (e.g., discarding) on other sectors (Catchpole et al., 2014; Condie et al., 2014; Somers et al., 2018).

Our conclusions regarding the effects of recreational harvest slots, DM_{rec} reductions, and the benefit of total removals-based quota accounting on attaining the diverse management objectives for GOM red snapper will likely provide insight to managers of similar marine fish stocks. For example, GOM gray triggerfish; U.S. Gulf of Maine Atlantic cod and Atlantic haddock (*Melanogrammus aeglefinus*); Mid-Atlantic summer flounder, scup (*Stenotomus chrysops*), and black sea bass; Area 2A (California, Oregon, and Washington) Pacific halibut (*Hippoglossus stenolepis*); and California halibut (*Paralichthys californicus*) share many similarities to GOM red snapper. Common fishery and management characteristics include 1) recreational fishers account for a considerable portion of annual landings, 2) discarding is high in the recreational fishery, 3) recreational discard mortality rates may be underestimated and fishers may be able to reduce discard mortality using improved practices or technology such as descender devices, and 4) recreational fishers are currently managed with a combination of minimum size regulations, bag limits, and fishing seasons but not with maximum size limits or harvest slots (Maunder, 2011; Northeast Fisheries Science Center, 2015, 2017, 2019; SEDAR, 2015; Brownscombe et al., 2017; Erikson and Tran, 2020; NOAA Fisheries, 2020; NOAA Office of Science and Technology, 2020). The implications of landings- versus total removals-based quota allocation approaches is a pertinent issue to these fisheries, as well. Although some fisheries (e.g., Gulf of Maine Atlantic cod and haddock, and mid-Atlantic scup) already rely on a total removals-based quota allocation approach, the sector allocations of mid-Atlantic summer flounder and black sea bass are still based on landings only and managers are considering shifting to a total removals-based approach (Mid-Atlantic Fishery Management Council and Atlantic States Marine Fisheries Commission, 2020).

The GOM red snapper fishery provides an interesting case study that would likely be applicable to other marine fish stocks. In contrast to freshwater fisheries for which most studies on harvest slots have occurred, larger and older red snapper are distributed farther offshore, making them less accessible to the fisheries resulting in dome-shaped selectivity with age for both recreational and commercial sectors (SEDAR, 2018; Fig. 5*a*). Thus, the impact of implementing recreational harvest slots is not as intuitive for the red snapper case study due to multiple fishery sectors with steep decreasing limbs in the associated selectivity function, whereas typical freshwater applications assume that large fish are fully vulnerable to the fishery. As a result, shifting the recreational fishery towards younger fish by means of a smaller maximum size limit decreases the number of fish that are vulnerable to capture for both sectors (Fig. 5*b–c*). As would be expected, the average age of fish in the recreational sector (landings and dead discards) decreases as regulations prohibit fishers from keeping fish above the maximum size limit (Fig. 5*d*). Conversely, commercial catch average age concurrently increases slightly towards older fish, because there are fewer younger fish available to fulfill the quota (Fig. 5*e*). Although not directly explored, differences in selectivity at age between the commercial and recreational sectors, such as the more steeply descending portion of the selectivity at age relationship for the commercial red snapper fleets, likely influence the effectiveness of recreational harvest slots. The impacts of selectivity could be more influential in marine

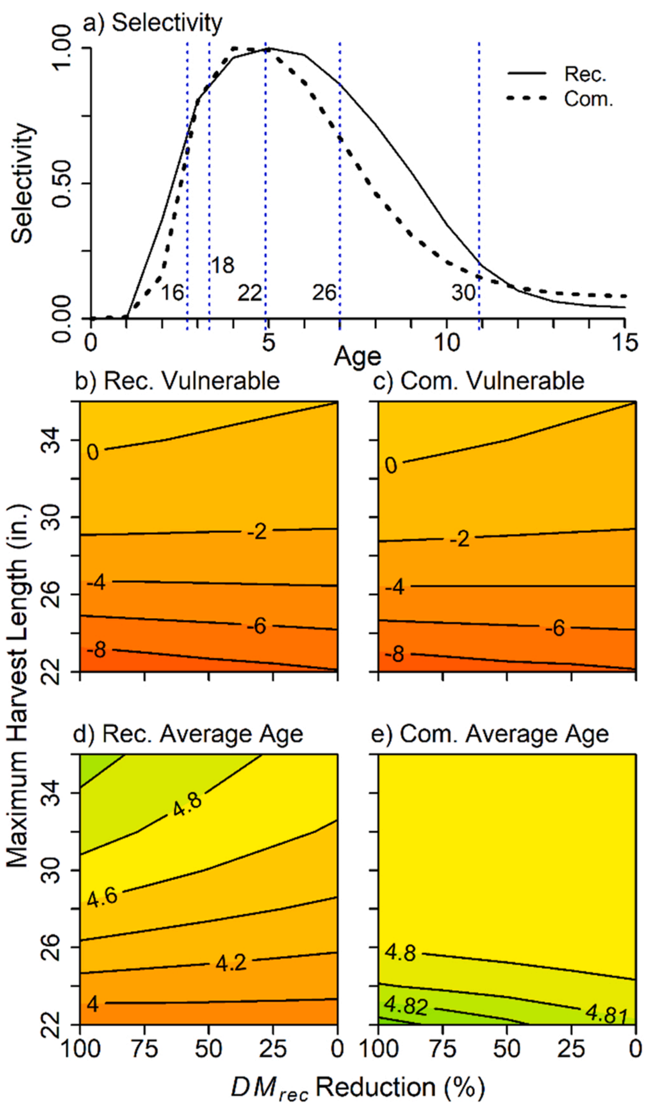

Fig. 5. Age-dependent selectivity for the GOM recreational (rec.) and commercial (com.) sectors (a), relative percent change in abundance of the capture-vulnerable population (b–c), and average age in years of total removals (d–e) for each sector. Selectivity is calculated as the maximum selectivity at age across all recreational fleets and for the commercial sector is based on the handline fleets only, which account for the majority of annual landings. Ages at length are noted by broken blue lines for minimum harvest lengths = 16 and 18 in. TL and maximum harvest lengths = 22, 26, and 30 in. TL. For (b–e), minimum harvest length is 16 in. TL, maximum harvest length ranges from 22 to 34 in. TL and no maximum (top) on the y-axis, and relative reductions of recreational discard mortality rate (DM_{rec}) in the projection years are shown on the x-axis. Assessment DM_{rec} = SEDAR 52 values and the landings-based quota accounting approach is assumed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fisheries where selectivity differences between the sectors are more pronounced. Future work comparing the efficacy of harvest slots under assumptions of both asymptotic and dome-shaped selectivity would better elucidate the potential non-intuitive interactions between harvest slots, selectivity, and retention.

Most examples of decision support analyses have focused on evaluating trade-offs among harvest and conservation objectives (Walker et al., 1983, Robb and Peterman 1998; Azadivar et al., 2009; Connors et al., 2020). There are fewer examples addressing the trade-offs among recreational objectives (Peterson and Evans, 2003; van Poorten and MacKenzie, 2019) or between recreational and commercial sectors within a single fishery (Keeney, 1977). The rising importance of recreational fisheries, increased opportunities for conflict among diversified stakeholders, and shifting emphasis towards ecosystem-based fisheries management (Ihde et al., 2011; NOAA, 2016; Hyder et al., 2018) will require increasingly complex decision analyses that take into account multiple harvest, recreational, and conservation based management objectives. A greater number of management objectives and a growing toolbox of potential management actions brings new challenges for communicating the results of a decision analysis to managers (Punt, 2017). We demonstrated the use of single-dimension *SMs* to reduce multiple performance measures to a single quantity as an approach to illustrate trade-offs among the competing interests observed in our simulation analysis. However, integrating a utility function within a prescriptive framework for direct decision making in fisheries management can hold many pitfalls. Assigning weighting coefficients to each *PM* would undoubtedly be a challenge, as decision makers and stakeholders may be reluctant or unable to agree upon such values (Punt, 2017). In addition, over-simplifying the results of decision support analyses to facilitate communication to managers and stakeholders undermines opportunities for open discussion of trade-offs among performance measures and alternate management scenarios (Punt and Hilborn, 1997). When practical, decision-makers should focus on a subset of potential management scenarios, with the trade-offs between management objectives (and often stakeholders) visualized with a combination of summary metrics and multi-axis plots, in order to adequately address the variety of learning styles that exist (Goethel et al., 2019). Ideally, decision support should incorporate stakeholders into the development of management actions and performance metrics (e.g., as is done with full MSE frameworks; Goethel et al., 2019). Work is currently underway to develop an MSE for GOM red snapper that will integrate our simulation framework into an MSE (see Zhang et al., 2018), which will enhance understanding of the implications of harvest slots and total removals-based quotas for achieving management and stakeholder objectives.

We necessarily made simplifying assumptions regarding the management and population dynamics of GOM red snapper to match the available data and structural complexity of the SEDAR 52 stock assessment model. First, we applied uncertainties in past DM_{rec} and future management actions uniformly across the recreational sector. For the purpose of management and quota accounting only (i.e., not included in the fleet structure in the SEDAR 52 assessment model), the GOM red snapper recreational fishery was subdivided by managers into private and for-hire components in 2015 (GMFMC and NOAA, 2014), and the private recreational fishery was further divided between each of the five GOM states in 2017 (Federal Register, 2020). Unfortunately, landings and effort data matching these subdivisions are not available and are not incorporated into the SEDAR 52 assessment model. Second, estimates of private recreational fisher effort and catch in the U.S. were revised in 2018, greatly increasing the magnitude of recreational fisheries landings and discards for many fish stocks, especially in the Southeast U.S. (Shertzer et al., 2019). These revised estimates, which are 1.1–2.6 times higher for annual GOM red snapper landings between 1981 and 2016 (NOAA Office of Science and Technology, 2020), post-date the SEDAR 52 assessment model and have not been evaluated by the regional stock assessment review process for red snapper. Our analysis showed if historic recreational removals were biased low due to DM_{rec} being underestimated in the assessment model, then the effects of future reductions in DM_{rec} and the implementation of recreational harvest slots would be amplified. Hence, we expect underestimates of recreational red snapper catch would have a similar effect and the potential impacts of harvest slots and DM_{rec} reductions would be greater than demonstrated for the SEDAR 52 scenarios used in the current analysis.

A particularly strong assumption we used in the SS projection analyses was the relative distribution of fishing mortality was unidirectional among fleets within an allocation group, allowing for positive correlation between fishing mortality in open and closed season recreational fleets. By directly linking the fleets in this manner, the model was able to incorporate dynamic changes in fishing mortality in the projections under the assumption that increases in system fishing mortality would be shared across all fleets. When calculating future catch quotas, the SEDAR 52 red snapper assessment projections assume constant fishing mortality for closed season recreational, non-directed commercial, and shrimp trawl bycatch fleets (SEDAR, 2018). Neither approach is optimal, as recreational closed season discards are likely to be inversely proportional to open season effort, commercial discards due to lack of IFQ likely change depending on the amount of quota available, and shrimp bycatch varies with shrimp effort. Developing submodels to adjust the fishing effort for each of the discard or bycatch fleets based on functional relationships with the associated directed fleets could greatly improve the current modeling but would require empirical data that are currently not available. Similarly, integrating models of human behavior to account for the distribution of fishing effort between open and closed fishing seasons could improve the decision making process. For instance, the number of fishers who choose to fish each day (which influences daily catch rates and season length) is driven by factors such as the number and size of fish that fishers expect to catch, availability of other opportunities to catch fish (e.g., season length or regulations of other target species), and fisher attitudes on the importance of harvesting fish (Walters and Cox, 1999; Murphy et al., 2019). Better quantification of each of these processes would improve the predictive power of our simulation approach. Finally, the spawning stock of GOM red snapper is divided between the east and west subareas and the majority of the spawning stock is in the west subarea (SEDAR, 2018). Our results reflect DM_{rec} reductions and harvest slots applied evenly to both the east and west subareas in the model. Hence, we expect diminished effects on recreational season length and proportion of older fish in the eastern part of the GOM red snapper stock compared to impacts on the stock as a whole.

The SEDAR 52 population dynamics model does not account for temporal variation in key demographic processes such as natural mortality, growth, and sexual maturation. Fish size at age is highly variable in many marine fish species, including GOM red snapper (SEDAR, 2018). Fishers often selectively harvest the largest fish, which has been shown to favor fish that reproduce at smaller sizes, but invest less energy into growing large and surviving to older ages, resulting in population-wide shifts in these life history traits (Cooke and Cowx, 2006; Heino et al., 2015). This type of fishing-induced evolution has likely occurred in red snapper populations, given that the GOM reef fish fishery has operated continuously since the mid-1800s (SEDAR, 2018). We expect harvest slots, if combined with sufficiently low DM_{rec}, could lead to increased somatic growth and delayed age at sexual maturity, because a maximum size limit would favor individuals that grow quickly through the harvest slot at the cost of delaying reproduction to larger sizes. Several coupled population dynamics-life history models support this expectation (Ayllón et al., 2018; Law and Plank, 2018), and we believe the interactions of fisheries regulations, including size limits, and fisheries-induced evolution present an interesting topic for future investigation.

Moving towards a more holistic management regime that includes total removals-based quotas with recreational harvest slots for red snapper (or any similar marine fishery with multiple fishing sectors) could further incentivize the recreational sector to increase use of descender devices and, thereby, further reduce discard mortality and increase recreational fishing opportunities. Reef fish managers in the GOM have been increasingly active in encouraging recreational fishers to reduce discard mortality (Gulf of Mexico Fishery Management Council, 2018b). The findings of a number of recent studies suggest many recreational fishers, though unfamiliar with descender devices, are supportive of using the devices or other methods (such as venting) to decrease mortality of released fish (Crandall et al., 2018; Curtis et al., 2019; Bohaboy et al., 2020). Discards are a challenging management issue in recreational fisheries because most discards, especially those on small, private fishing boats, are unobserved, rendering estimates of discards extremely difficult (Cooke and Cowx, 2006). Unfortunately, total removals-based quotas may also incentivize misreporting the number or condition of discards (Condie et al., 2014). There is a clear need to better 'legitimize' recreational fisheries by developing methods to improve reporting and discard estimation similar to commercial fisheries (Cooke and Cowx, 2006; MacKenzie and Cox, 2013). Legitimization approaches would be greatly aided by methods to better document recreational effort through both common (e.g., fishing licenses, mail surveys, and telephone surveys; Ryan et al., 2016) and alternative approaches (e.g., harvest tags, electronic monitoring of recreational fishing boats or ports, and digital reporting through smart phone applications; Jackson et al., 2016; Venturelli et al., 2017; Hartill et al., 2020).

As impacts of recreational angling on marine fisheries gain increased recognition, managers are realizing the need to implement measures to effectively limit recreational fishing effort, while also explicitly dealing with allocation of quotas among recreational and commercial stakeholders (Kearney, 2001; Cooke and Cowx, 2004; Eero et al., 2014; Hyder et al., 2018). With the expansion of stakeholder dimensionality and associated desired benefits from the resource, we expect increased use of simulation-based decision analyses to better quantify the implications and trade-offs of management decisions and more effectively communicate results to managers and stakeholders. Ultimately, no panacea exists for fisheries management. Our results suggest even relatively simple management measures, such as harvest slots, can have complex and non-intuitive impacts, especially in multi-sector fisheries. However, considered together, harvest slots, discard mortality mitigation efforts, and total removals-based quota accounting present viable options for achieving diverse stakeholder and conservation objectives, while helping incentivize rational resource utilization.

CRediT authorship contribution statement

Erin C. Bohaboy: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Daniel R. Goethel**: Methodology, Software, Writing – original draft, Writing – review & editing. **Shannon L. Cass-Calay**: Conceptualization, Resources, Writing – review & editing, Funding acquisition. **William F. Patterson III**: Conceptualization, Resources, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106268.

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