UNITS 1+2 REDFISH MANAGEMENT STRATEGY EVALUATION

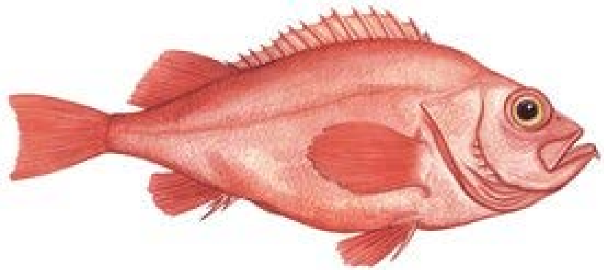

Figure 1. Units 1 and 2 Redfish stock management areas. The (grey) area, where Northwest Atlantic Fisheries Organization (NAFO) Subdivisions 3Pn and 4Vn are located, indicates the seasonal common area (January to May, Unit 1 and June to December, Unit 2).

Context:

*The Unit 1+2 redfish fishery targets two similar species, the Acadian Redfish (*Sebastes fasciatus*) and Deepwater Redfish (*Sebastes mentella*). Landings data represent aggregate catch with survey sampling used to infer the species composition of those catches. Past and present uncertainty in the attribution of catches to each species is high. Redfish experience long periods of low recruitment interspersed with periods of strong year classes that may support the fishery for many years.*

The redfish fishery experienced three periods of high exploitation since the 1950s followed by strong declines in landings in the mid-1990s. In 1993, the fishery was also divided into management Units 1, 2 and 3 with Units 1 and 2 considered to comprise the same stock. Unit 1 was placed under moratorium in 1995, with an index fishery permitted since 1998 while Unit 2 continued to support a commercial fishery. An assessment by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2010) identified S. mentella *in Units 1+2 as endangered, and* S. fasciatus *as threatened. More recently, survey data indicate the presence of three strong year classes (2011-2013, largely* S. mentella*) that are expected to recruit to the fishery beginning in 2018.*

The failure to adopt an assessment model for redfish in 2015, recent doubts cast on the veracity of historical catch reporting statistics uncertainty with regards to key aspects of redfish biology, highly variable recruitment dynamics and varied objectives in the stakeholder group given the new strong year classes provided the impetus for embarking on a Management Strategy Evaluation (MSE) approach in 2016-2018. The MSE was focused exclusively on Unit 1+2 S. mentella *and* S. fasciatus*. The impacts on other species of trophic interactions involving redfish and broader ecosystem effects of the fishery* *via bycatch of other species or interactions with seafloor habitats were explicitly not considered in the MSE. This Science Advisory Report is from the April 25-26, 2018 Unit 1+2 Redfish Management Strategy Evaluation. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.*

SUMMARY

- A Management Strategy Evaluation (MSE) was initiated for Unit 1+2 Redfish in December 2016 by DFO Resource Management and Science in collaboration with the Unit 1+2 Redfish Rebuilding Plan Working Group (the WG). The WG developed and refined a final list of 7 objectives, 12 performance metrics and 18 operating models (OMs) representing key areas of uncertainty.
- Five candidate Management Procedures (MPs) of an initial 21 were selected for further consideration by the WG in March 2018. All candidate MPs used the same Harvest Control Rule (HCR), but differed in the year in which the HCR was first implemented, limits on the magnitude of interannual changes in total allowable catch (TAC) and with respect to the presence or absence of: maximum TAC caps, adjustment of HCR catch limits (TACs) by a factor of 0.8 and the use of fixed TACs in early years.
- The spawning stock biomass (SSB) of the two redfish populations in Units 1+2 is growing. Presently, modelled estimates of SSB from the base OM suggest that the *Sebastes mentella* and *S. fasciatus* populations are respectively in the Healthy and Cautious zones of the Precautionary Approach, based on reference points estimated as part of the MSE.
- The strong 2011-2013 cohorts resulted in small differences in performance of candidate MPs in the simulations. However, under base OM conditions, there was a trade-off between average annual catches retained 10-20 years in the future and the duration of high TACs, interannual TAC stability, years during which the redfish Small Fish Protocol is met and the abundance of large fish in the catch.
- The presence or absence of maximum caps and HCR TAC adjustments mattered more to candidate MP performance than the year in which the HCR was first implemented. Projected median TACs in the next five years from most MP were sufficiently low as to constitute low conservation risk to the stocks.
- Stock conservation objectives that aim to reach in 10 years and then maintain the SSB of both species in the Healthy Zone were met with a high probability in all tested MPs. Under OMs assuming catch splits favouring *S. mentella*, only one MP failed to maintain sustainable exploitation rates for *S. fasciatus* with 50% probability.
- The abundant small fish associated with the 2011-2013 cohorts results in predicted catches from all candidate MPs will fail to meet the Small Fish Protocol in 2018 and 2019. Small fish (< 22 cm) are expected to remain abundant in the catch until 2020. Nonetheless, the MSE concluded that these predicted outcomes would not compromise the achievement of the other conservation objectives. However, adequate monitoring of small fish removals is required to ensure full accounting of fishing mortality for the stocks.
- Exploratory analysis indicates that the performance of MPs with respect to three conservation objectives was improved and total allowable catches were increased in simulations that assumed that the two species of redfish were perfectly distinguished in fishery catches, enabling species-specific TACs. The implementation of fishery sampling

aimed at estimating the species composition of redfish catches should be a high monitoring priority.

- An implementation period of up to five years is recommended for this MSE, following which a retrospective analysis should take place in which the actual performance of the MP in the fishery are evaluated, and any updates to MP design, OMs, simulations, objectives, and exceptional circumstances are re-evaluated in a new MSE process.

BACKGROUND

Biology

Redfish (the Acadian Redfish, *Sebastes fasciatus,* and the Deepwater Redfish, *S. mentella*) are slow-growing and long-lived live-bearing groundfish, with males maturing at 7-9 years (20-23 cm) and females at 9-10 years (24-25 cm). The two species are very similar in appearance but can be distinguished genetically and to a lesser extent morphologically (*S. fasciatus* typically has 7 or fewer soft anal rays and a gas bladder attachment to ribs 3 and 4, while *S. mentella* typically has 8 or more soft anal rays and a gas bladder attachment to ribs 2 and 3). Landings data in Units 1 and 2 represent aggregate redfish catch (*Sebastes* sp.), and survey and limited commercial sampling (using anal fin ray counts) is currently used as a cost-effective way to separate the catch into estimates of landings by species.

Redfish inhabit cold waters along the slopes of banks, and deep channels (100 to 700 m). In the Gulf of St. Lawrence and Laurentian Channel, *S. mentella* predominates in the main channels at depths ranging from 200 to 500 m. In contrast, *S. fasciatus* dominates at depths of less than 250 m, along the slopes of channels and on the banks, except in the Laurentian Fan where it inhabits deeper waters. Redfish generally live near the bottom but migrate vertically at night to follow prey. Juvenile redfish feed mainly on crustaceans, including several species of shrimp, while the adult redfish diet is more diversified and includes fish.

Mating occurs in the fall (September-December) and larvae are extruded in the spring (April-July). Larvae develop in surface waters and progress to deeper waters as development progresses. Recruitment for redfish is spasmodic, with long periods of low recruitment coupled with sporadic instances of strong year classes that may be spaced several years or even decades apart. Catch-at-length data from the survey indices and commercial fishery point to the prevalence of a few strong year classes that support the fishery for years to decades. For example, from 1999-2015, the Unit 1 index fishery is believed to have primarily operated on the 1980 *S. mentella* year class (Brassard et al. 2017).

When assessed in 2016, both species of redfish were at very low levels of biomass (DFO 2016) and in the Critical Zone of DFO's Precautionary Approach Framework (DFO 2009). An assessment by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2010) identified redfish in Unit 1 and 2 as endangered (*S. mentella*) and threatened (*S. fasciatus*). However, more recent survey data indicate that three strong year classes (2011-2013, comprising largely *S. mentella*, are recruiting to the fishery beginning in 2018 (DFO 2016). Thus, the outlook for the Unit 1+2 redfish stock is currently positive (DFO 2018).

Fishery

A fishery for redfish began in the Gulf of St. Lawrence and the Laurentian Channel in the 1950s (DFO 2016). The fishery in Units 1 and 2 has historically been prosecuted by different fleets, gear classes and vessel classes, the composition of which has varied over time. Until 1993, the fishery was managed as three NAFO divisions, 4RST, 3P and 4VWX. However, in 1993 the fishery was divided into the newly created management units 1, 2 and 3 in response to a new understanding of stock structure and winter migration of redfish from the Gulf to the Cabot Strait area. Units 1 and 2 are considered to comprise the same stock (Kulka and Atkinson 2016; Figure 1) residing in two management units. Unit 1 consists of NAFO divisions 4RST, as well as 3Pn4Vn from January to May. Unit 2 consists of NAFO subdivisions 3Ps4Vs, 4Wfgj, and the subdivision 3Pn4Vn from June to December.

The Unit 1+2 redfish fishery underwent three periods of high exploitation (1954-1956, 1965-1976, and 1987-1992), after which landings dropped precipitously in 1993-1994 (Brassard et al. 2017). Landings and Total Allowable Catches (TAC) for the Unit 1+2 redfish fishery continued to decline after 1993, when TAC was set at 60,000 t and 28,000 t in the newly created Units 1 and 2 respectively. Unit 1 has been under commercial moratorium since 1995. An index fishery was introduced in 1998 with a TAC of 2,000 t since 1999. Unit 2 continues to support a commercial fishery, with a TAC of 8,500 t since 2010.

Redfish are managed mainly by an annual TAC. Additional conservation measures include the application of a Small Fish Protocol (fish <22 cm must remain < 15% of catch by numbers), 100% dockside verification, mandatory hail-out and hail-in, observer coverage at sea and the application of a bycatch protocol. Closure periods have also been introduced: 1) to protect mating (fall) and larval extrusion (spring) periods, 2) to minimize the harvest of Unit 1 redfish migrating into Subdivisions 3Pn4Vn in late fall and winter, and 3) to protect cod reproduction (Div. 4RS). In addition, since the introduction of the index fishery in 1998, fishing is permitted only between longitudes 59° and 65° (W) at depths greater than 182 m (> 100 fathoms) and an area in NAFO Div. 4T has been closed since August 2009 to avoid incidental catch of Greenland halibut.

Management Strategy Evaluation

Management strategy evaluation (MSE) is a structured decision-making process for testing management options and choosing which options provide acceptable outcomes relative to explicit conservation and fishery objectives (e.g., DFO 2011). A range of candidate management procedures (MP) are developed that can be expected to perform acceptably under a range of credible scenarios for the future dynamics of the fish stock. This represents a shift away from the traditional stock assessment approach in fisheries, where the focus is on the development of a single best-fitting assessment model. MSE is a collaborative process with significant involvement by stakeholders at all stages, particularly in the development of objectives. Objectives for the fishery are typically developed by a working group comprising fishery stakeholders, scientists and fisheries managers, and typically include stock and conservation objectives, as well as fishery objectives relating to the economic value and stability of the fishery in the future.

MPs are developed by working group participants that include specifications for which data are to be collected, and how the data are to be used in controlling future harvests in the form of a Harvest Control Rule (HCR). For each objective, performance metrics or indicators are defined that quantify how well the candidate MPs are able to meet different MSE objectives.

Computer simulation models are developed to project the possible consequences of the future implementation of candidate MPs, accounting for imperfections in the data collected in future years which are used in HCRs that specify particular total allowable catches (TACs) given the results from the data. A number of different operating models (OMs) are formulated that represent different plausible hypotheses for how the fish populations and fishery will behave in the future. A desirable attribute for a MP is for its performance to be acceptable across all of the

OMs considered. If there is a subset of MPs that have acceptable performance across all OMs and all performance metrics, then a single MP can be proposed by stakeholders and fishery managers. Once selected, a MP is implemented for a set period of time before the MSE process, including an evaluation of actual MP performance and the refinement of objectives, performance metrics, OMs and MPs.

Rationale for MSE for Unit 1+2 Redfish

There have been several attempts at developing stock assessment models for Unit 1+2 redfish since 2011 but it has proven difficult to fit a single assessment model to trawl survey stock biomass and survey and fishery length composition data. Aggregate catch data must be split by species, and there is the potential for inaccuracies in estimates of abundance or productivity of the stock if there are systemic biases in catch splitting methods (leading to between species contamination). Recent work suggests that there have been periods of the past with considerable discarding of undersized redfish (Duplisea 2016). The ephemeral presence of large numbers of juvenile *S. fasciatus* from the Grand Banks (3LNO) redfish stock in Units 1+2 has led to periodic issues with stock contamination of trawl survey indices. Catches of adult *S. fasciatus* in Unit 2 can include fish from the 3LNO stock. Furthermore, the catchabilities for the trawl survey indices of abundance obtained from model fitting have been inexplicably large, especially for the trawl survey index of abundance from Unit 2. A MSE was initiated for Unit 1+2 redfish by fisheries managers given these areas of uncertainty, a 2015 competing-model approach that failed to yield an accepted assessment model for redfish, and the new cohorts recruiting to the fishery.

The MSE for Unit 1+2 redfish was focused exclusively on Unit 1+2 *S. mentella* and *S. fasciatus*. The impacts on other species of trophic interactions involving redfish and broader ecosystem effects of the fishery via bycatch of other species or interactions with seafloor habitats were explicitly not considered in the MSE.

Record of Stakeholder Consultation

A Working Group to support the development of a Rebuilding Plan for Unit 1+2 redfish was initiated in 2014, in accordance with DFO's Precautionary Approach Framework guidelines for stocks in the Critical Zone. The working group consists of stakeholders from industry, indigenous communities, provincial and federal government representatives, and observers from environmental non-government organizations. The Working Group agreed to the proposal of a Management Strategy Evaluation in December 2016. Feedback into MSE objectives, performance metrics, MPs and considerations to be included in the development of OMs were provided over several in-person Working Group meetings (in March, October and December 2017 and March 2018). An additional five technical meetings (May, September, October and December 2017, and February 2018) were held to support the development of MSE models and model inputs.

ANALYSIS

MSE Objectives and Performance Metrics

Stock and fishery objectives, along with performance metrics and pass-fail criteria, where identified, were initially formulated in consultation with redfish stakeholders and fishery managers. The list was revised to remove redundant and/or non-informative objectives and metrics in March 2018, resulting in a final set of 3 stock and 4 fishery objectives, and a total of 12 performance metrics (Table 1).

Table 1. Objectives and performance metrics for the Unit 1+2 Redfish MSE process. An additional fishery objective (objective 5) initially retained by the working group was dropped later in the MSE process. The original numbering is retained here as it was used throughout the MSE process for specific objectives.

Type	Objective	Performance Metrics
Stock	1. Increase spawning stock biomass (SSB) of each species (SSB_x) above the lower reference point (LRP) and into the Healthy Zone in 10 years (95% probability)	a) P(simulations SSB_x > LRP_x in 10 years). b) P(simulations SSB_x > USR_x in 10 years).
	2. Once in Healthy Zone, maintain SSB of each species (SSB_x) above the Critical Zone (95% probability) and in Healthy Zone (75% probability)	a) P(simulations SSB_x > LRP_x after 10 years). b) P(simulations SSB_x > USR_x after 10 years).
	3. Maintain exploitation rate U of each species below Umsy (50% probability)	P(years U_x:$Umsy_x$ < 1)
Fishery	4. Maximize number of years where fish < 22 cm represent < 15% of catch (Small Fish Protocol; 85% probability).	Mean years fish < 22 cm < 15% of catch.
	6. Maximize duration of high annual catch.	a) Average annual catches in i) 10-20 years ii) 10-40 years b) P(simulations TAC ≥ 40 kt by 2028) c) Mean years TAC ≥ 40 kt 2028-2057
	7. Maximize catch of large fish (>27 cm)	P(years fish > 27 cm > 80% of catch)
	8. Maintain stability of the fishery	P(years where TAC < 15% between years)

Operating Models (OMs)

Within MSE, key sources of uncertainty in stock and fishery dynamics are identified and represented as best possible in different OMs (Table 2). OMs are used within an MSE context to test the robustness of candidate MPs to credible sources of uncertainty in the fishery (Edwards 2016). MP performance is assessed under the range of OMs, with the aim of identifying MPs that can perform acceptably under a wide variety of hypothesized conditions (i.e., to identify MPs that have suitable robustness to uncertainty). A suite of OMs (completed separately for each species) were formulated for the Unit 1+2 Redfish MSE in consultation with stakeholders and fishery managers.

In keeping with other recent MSE exercises (e.g., for Western Component (4Xopqrs5) Pollock; DFO 2011), OMs were grouped into two categories: core models (including the base case or reference model) and stress-test models (Table 2). Within the core model set, the base model was considered the most credible of all formulations and in some cases was used to derive additional information. Additional models were developed as sensitivity tests (i.e., OM19 and OM20, testing alternative prior values for historical strong cohorts, and OM13, alternative values for offsets in the median age of fish killed to fish retained), but such models were not retained as stress tests.

- **Core Models**: OMs that represent credible alternative hypotheses for how the fishery and stocks have behaved or will behave (from the standpoint of science and stakeholders) and are considered to represent the most important axes of uncertainty. Candidate MPs must perform acceptably against all core models. The base case model is the core model used to derive the most extensive set of diagnostics and auxiliary stock or management procedure performance information.

- **Stress-Test Models**: OMs that are considered to be plausible alternative representations of fishery and stock behaviours but have less scientific credibility than the core and base case models. Such models have relatively little research available on possible mechanisms and lack sufficient data to guide the detailed development of the model component. It is desirable that candidate MPs that perform acceptably under the core models will also perform acceptably against the stress-test models (i.e., demonstrate robustness); if they do not, this must be noted.

Table 2. Operating models (core and stress-test) for the Unit 1+2 Redfish MSE process. The OMs are numbered based on the complete list of OMs that were tested, but no necessarily retained.

Model	Description	Details
CORE		
1	Base Case	Fisheries selectivity is logistic. Change in selectivity and offset over time is in two time blocks (early years – 1993, 1994 – present). Catch killed:retained ratio is 1.2 (early years – 1985), 2 (1986-1993), and 1.1 (1994-present). Future recruitment simulated with a non-parametric bootstrap of recruitment events from historical timeseries. In projections, catch killed = 1.1*TAC from HCR and the catch biomass retained is assumed to be very similar to the TAC.
6	Reduced future recruitment	No strong cohorts for next 20 years.
8	Alternative *M*	Lorenzen *M* (natural mortality *M* varies with fish size and is higher for smaller fish)
9	Alternative recruitment simulation method	Parametric bootstrap of historical recruitment, with variance and autocorrelation coefficient estimated for recruitment events since 1970.
10	Alternative catch split	Assume more *S. mentella*
11	Alternative catch split	Assume more *S. fasciatus*
STRESS-TEST		
2	Alternative fishery selectivity	Assumes fisheries selectivity is dome-shaped or double-logistic for both species (selectivity decreases for both large and small fish)
3	High future *M*	Future *M* is doubled for both species for the next 20 years.
4	Reduced future growth	Reduce Linf for both species to 2/3 the value in the von Bertalanffy growth equation for the next 20 years.
5	Reduced future recruitment	No strong cohorts for next 40 years.
14	Alternative catch killed:retained ratio	Adjust ratio of catch killed:retained, a) -0.5, b) + 0.5
15	Alternative *M*	Reduce historic and future *M* by a factor of 0.75 (both species)
16	Alternative *M*	Increase historic and future *M* by a factor of 1.25 (both species)
17	Alternative steepness	Assume steepness of stock-recruit relationship is higher by a factor of 1.25
18	Alternative steepness	Assume steepness of stock-recruit relationship is lower by a factor of 0.75
22	Alternative fisheries selectivity	Assume that fisheries selectivity reverts to earlier pattern (early years – 1993) for next five years only.
23	High discarding rates 2018-2020 under OM1	Using model 1, assume ratio of catch killed:retained in 2018-2020 is 2 and then returns to 1.1 for 2021-2057. The catch biomass retained in future years is assumed to be very close to the TAC.
24	High discarding rates 2018-2020 under OM3	Using the stress test model 3 (natural mortality rate doubles for next 20 years), assume the ratio of catch biomass killed to catch biomass retained in 2018-

Model	Description	Details
		2020 is 2 and then returns to 1.1 for 2021-2057. The catch biomass retained in future years is assumed to be very close to the TAC.

Sources of Uncertainty Addressed by the MSE

The key sources of uncertainty relating to available data or model assumptions, and uncertainties related to projections of future stock states, were identified and where possible were addressed as described below.

Unit 1+2 Redfish data treatment, population model assumptions, key uncertainties and robustness testing

1. **Species composition in commercial fishery catches**: Unit 1+2 redfish landings represent aggregate catch across two species. The estimates of species composition from Unit 1 trawl survey records have been applied in the past to predict the species composition of historical catch biomass and length composition records. However, this has been problematic due to seasonal differences in the timing of the survey and of the fishery and potential seasonal differences in species composition in the locations surveyed. In the MSE, this uncertainty was addressed by three core OMs that made different assumptions about catch splits (OM1, OM10 and OM11)
2. **NAFO 3LNO Grand Banks cohorts**: survey length composition data from Unit 1, and genetic analyses show that there may be occasional contamination of survey data by young 3LNO redfish (specifically, *S. fasciatus*) in Unit 1 and possibly Unit 2. It appears that cohorts from the 3LNO stock occasionally use Unit 1 as a nursery area, appearing in Unit 1 survey data at young ages, but migrate out of the area (disappear from the data) before they recruit to harvestable sizes. In the MSE, these cohorts were removed from survey abundance and length composition data.
3. **Historical fishery selectivity**: The trawl gear used in the commercial fishery has changed considerably over the past several decades. In some years, mid-water trawls were more commonly used than bottom trawls. In the last few decades bottom trawls were most commonly used. Observer records suggest that the size distribution of fish retained has changed significantly over time. Stress test model OM2 explored dome-shaped fisheries selectivity, while stress test model OM22 simulated fisheries selectivity that reverted back to patterns observed prior to 1993 for 2018-2022 only.
4. **Spatial structure**: Following the stock decline in the early 1990s, Unit 1 was subject to a moratorium and index fishery, and the remaining commercial activity has concentrated in Unit 2. It is possible that age, stock and species composition differed between the two units, but insufficient data were available to formulate a spatially structured model of the two redfish species in this MSE process.
5. **Multiple fleets**: More than one fleet have operated in Units 1 and 2; the fishery uses both smaller vessels that tend to fish nearer to shore, and larger vessels comprising the offshore fleet. There were insufficient data to disaggregate the landings data by fleet in this MSE process.
6. **Discarding**: Discarding is known to have occurred prior to the 1995 banning of discarding of redfish (Duplisea 2016). Uncertainty over historical discarding creates uncertainty over estimates of historical fishing mortality rates, and historical and current stock abundance and stock productivity. Discarding uncertainty was addressed by varying ratios of catch

killed to catch retained in stress test model OM14 (historically), and in future projections in stress test models OM23 and OM24.

7. **Historical records of strong cohorts**: There are recorded observations of large cohorts in the early years of the Gulf of St. Lawrence redfish fishery. The years in which the cohorts originated can be identified, however there are no length composition data from the earliest years of the fishery to provide estimates of cohort strength. Assumptions about cohort strength in the early years of the fishery can affect estimates of stock productivity. In the MSE, sensitivity tests (OM19 and OM20) were attempted assuming both lower and higher prior means for strong historical cohorts, however the results obtained demonstrated a lack of sensitivity to the prior specification.
8. **Future recruitment**: In the past, large cohorts have occurred approximately four times in four decades for both species, but with a gap of as much as 30 years. The potential mechanisms that favour strong cohorts are poorly understood and thus years of good recruitment are unpredictable. The occurrence of large cohorts is the main source of biomass production for the stock. Due to the low rates of natural mortality, the rate of decline in the predicted redfish biomass resulting from the recent strong cohorts will depend on whether additional strong cohorts appear within the next 5 to 10 year. In the MSE, stress test model OM5 and core models OM6 and OM9 explored alternative assumptions regarding future recruitment.
9. **Catch splits**: The lack of direct measures of species composition of catches in the past creates a scaling problem for the size and productivity of each of the two stocks, not only in the past but for projections into the future. Estimates of cohort strength and current stock biomass of the two redfish species are strongly determined by values assumed for the species split of the catch in past and recent years. Alternative catch splits were represented in the MSE by core models OM10 and OM11.
10. **Life history attributes**: Due to difficulties with obtaining reliable age data, estimates of natural mortality (*M*) of the two redfish species are uncertain. Alternative *M* values were explored in the MSE in stress test models OM3, OM15 and OM16. It is unknown whether *M* can vary systematically with age, or whether it it varies inversely with body size (OM8). Individual growth estimates also remain uncertain as analysis of trawl survey records suggested a smaller theoretical maximum length (length infinity, Linf) von Bertalanffy growth parameter than estimates for redfish in other parts of the North Atlantic which were supported in the base model fitting to the historical survey length composition records. There also remains uncertainty over whether there could be future density dependent changes in growth and in *M* in strong cohorts, which was simulated in stress test models OM3 and OM4.
11. **Recruitment compensation**. Uncertainty over steepness (an index of recruitment compensation) has often been found to be one of the most influential types of uncertainty affecting OM predictions. The values assumed for the steepness parameter has for example strongly determined the ranking of MPs and the extent of the trade-offs between fishery catch objectives and stock conservation objectives in other MSE processes (Edwards 2016). However, with Unit 1+2 redfish, base model fittings suggest that recruitment compensation may be fairly low for both species, although slightly higher for *S. fasciatus*; however variability in projected recruitment is largely determined by the likelihood of future strong cohorts. Different assumptions regarding steepness were explored in stress test models OM17 and OM18.

Reference Points

In order to evaluate Objectives 1-3, reference points were developed. The proposed Limit Reference Point (LRP) and Upper Stock Reference (USR) are 40% and 80%, respectively, of the model-estimated survey mean spawning stock biomass (B_{ref}). B_{ref} is estimated in the core OM and corresponds to the average of 1984-1990 and 1984-1992 biomass for *S. mentella* and *S fasciatus*, respectively, divided by their respective estimated catchability coefficient for the Unit 1 survey. The time periods chosen for each species are considered productive periods based on survey indices. U_{msy} (exploitation rate at maximum sustainable yield) was also calculated for each species. While performance of MPs was evaluated against reference points generated within each model, and reference points were updated each year in the simulations, values for the base operating model (and U_{msy}) are presented in Table 3, and the trajectory of the stock with respect to the reference points is shown in Figure 2.

Table 3. Reference Points and values of B_{ref} and estimated survey SSB in 2017 ($B_{2017,}$ with standard deviation in parentheses) from the base operating model for S. mentella and S. fasciatus.

Reference Point	*S. mentella*	*S. fasciatus*
B_{ref}	371 kt	329 kt
B_{2017} (S.D.)	401 (55.1) kt	172 (20.1) kt
LRP (0.4xB_{ref})	148 kt	132 kt
USR (0.8x B_{ref})	297 kt	263 kt
U_{msy}	0.041	0.094

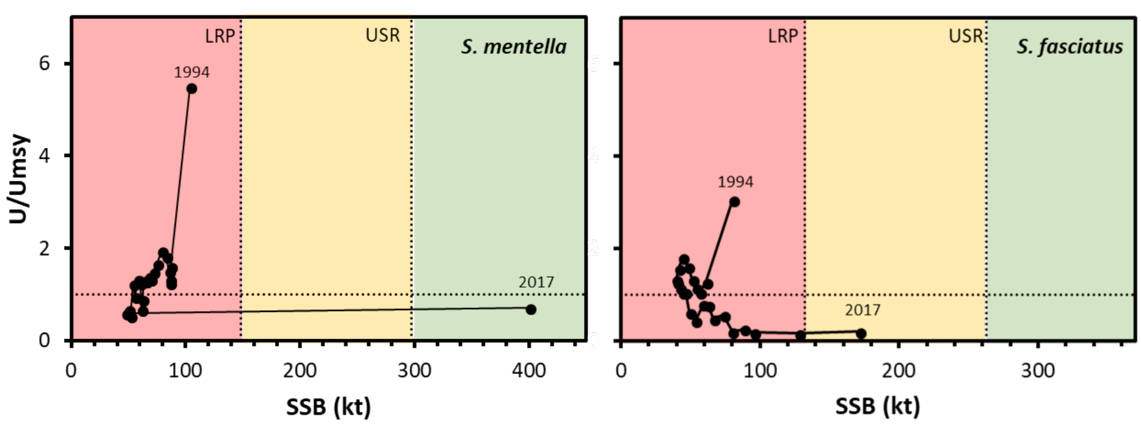

Figure 2. Estimated stock trajectories with respect to the reference points from the base operating model since 1994 for S. mentella and S. fasciatus. The horizontal dashed lines represent a value of 1 for U/U_{msy}.

Harvest Control Rule (HCR)

HCRs are key ingredients of MPs in MSE. Such rules set recommended catch limits, or TACs, based on some data input relating to stock status.

Similar to previous MSE process (DFO 2011), the HCR used in each MP is applied to each redfish species separately, and uses a recommended TAC for the given year, y, that is calculated from the following equation:

$$TAC_y = a + b\,(J_y - J_0) - \text{penalty, where penalty} = \begin{cases} 0 \text{ when } J_y > J_0 \\ c(J_y - J_0)^2 \text{ when } J_y \le J_0 \end{cases}$$

J_y is the ratio of the 3 year trailing average Unit 1 survey biomass index of large fish (>29 cm for *S. fasciatus* or > 30 cm for *S. mentella*) to the values for the index from the reference period 1984-2017. For example, for a TAC for 2018, J_{2018} would be the mean of Unit 1 survey index values for 2015, 2016, and 2017, divided by the average value for 1984-2017. The body size thresholds were chosen to reflect the commercial desirable size ranges of redfish and are about the size of full maturity for females. The choice of these size thresholds, which are larger than the current legal size in the fishery, also reduces much of variability in the index caused by large recruitment events at smaller sizes. Both the recent and reference means are calculated using the geometric mean to dampen the effects of extreme survey values Other parameters in Eq. 1 determine the relationship between the TAC and J_y. The parameters a and b are parameters that set the scale of the TAC. The parameter J_0 determines (1) TAC reductions to prevent overfishing at small stock sizes (as $J_y - J_0$ becomes small and eventually negative) and (2) the point on the J_y axis at which the TAC is set to zero as survey index values and therefore J_y decline.

The parameter values of a, b, c and J_0 (5, 1.5, 4 and 1.5) were set so that the TACs specified by the resulting HCR would: drop to zero at values for J_y slightly less than the historical minimum value for J_y (around 0.3; Figure 3A); give TACs less than retained catch biomass values in years with the highest J_y (Figure 3B); and, give median values for harvest rates no more than about 75% of the U_{msy} for both species over a 40-year simulation when applied in the base case operating model. HCRs were tuned such that the U_{msy} values would be rarely exceeded in the base model fitting and thus HCR for a particular Jy are less than catches actually taken.

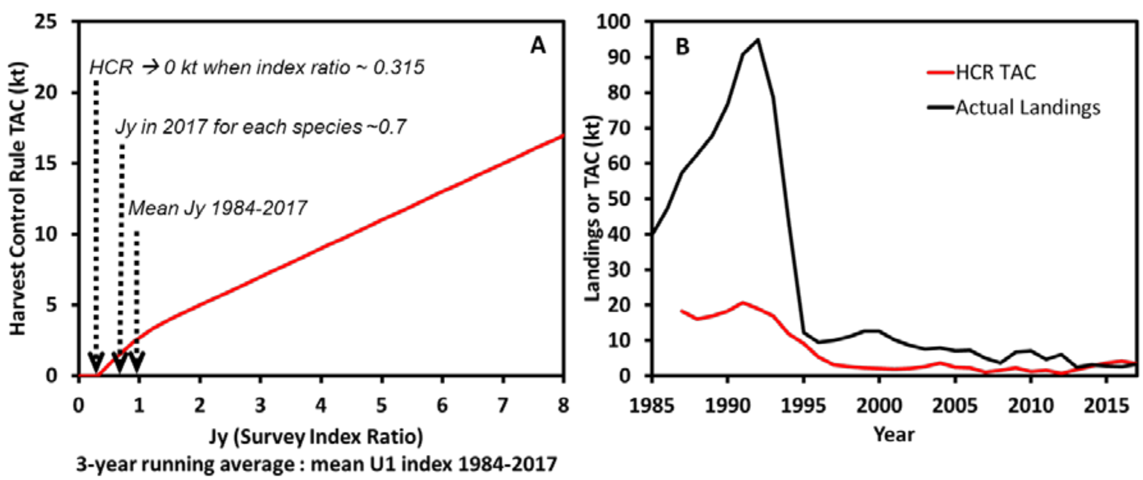

Figure 3. A) Harvest control rule. B) Retrospective calculation of Jy and the corresponding total allowable catch (TAC) recommended from the harvest control rule from 1987-2017, contrasted against actual landings from Unit 1+2.

Formulation of Management Procedures (MPs)

MPs included at least one of four possible components.

1. A HCR that specifies a TAC for each species of redfish from a 3-year trailing average of Unit 1 trawl survey biomass estimates of large redfish. The TAC for the two species are combined to yield a single total TAC per year.
2. A pre-specified maximum cap to possible total TACs in particular years. The lower of the two values (TAC or cap) would apply in each year.
3. An assumption of a status quo period of management before the year in which the HCR is first implemented (with status quo defined as the average retained catches from 2015-2017, of 2,838 t, during which period TAC has been 10,500 t, unless otherwise stated).
4. A maximum allowed change in TACs between years

Evaluating MP performance

For each OM, 1,000 draws were taken from the approximation of the joint posterior density function of OM parameters for that OM. The parameters were vetted by projecting the model from past to present and used only if the stock survived to the present year. The OMs were projected 40 years into the future, i.e., from 2018 to 2057. To improve the calculation of differences in performance metrics between candidate MPs, the same 1,000 sets of recruitment deviates and draws of operating model parameters were applied within each OM to compute performance metrics for the candidate MPs.

Selection of MPs

Eighteen candidate MPs were initially formulated by stakeholders and fisheries managers. In March 2018, the working group selected five candidate MPs for further consideration (Table 4).

Table 4. The five candidate MPs proposed and selected for further consideration by the working group.

MP	Description
1	Capped. Ramp caps starting in 2020 at 14.5 kt to a maximum 40 kt in 2027 and thereafter.
14	Capped. Ramp caps starting in 2020 at 14.5 kt to a maximum 40 kt in 2027 and thereafter. A maximum allowed change of 15% in TACs between years.
43	Uncapped. From 2018-2021, fixed TACs of 7.5, 10, 15, 20 kt are applied, and from 2022 onward TAC is derived from HCR*80%.
44	Uncapped. From 2018-2019, fixed TACs of 5 kt are applied, and from 2020 onward TAC is derived from HCR*80%.
45	Uncapped. From 2018-2021, fixed TACs of 5 kt are applied, and from 2022 onward TAC is derived from HCR*100%.

Performance of MPs Against Objectives

Conservation Objectives

All five MPs passed objectives 1 and 2, regarding both species reaching the Healthy Zone in 10 years and then remaining in the Healthy Zone, under all core and stress-test models (probability of 0.99-1.0; data not shown). Proposed catches during the implementation phase (i.e., next 5 years) of the MSE were sufficiently low as to constitute little conservation risk to the stocks in all core and stress-test OMs.

Four of five MPs passed objective 3, relating to exploitation rates (U) that remain below U_{msy} with 50% probability (Figure 4A-4B). MP45 failed to pass this objective for *S. fasciatus* on core model OM10, which assumed an alternative historical catch split method favouring more *S. mentella* than in the base model.

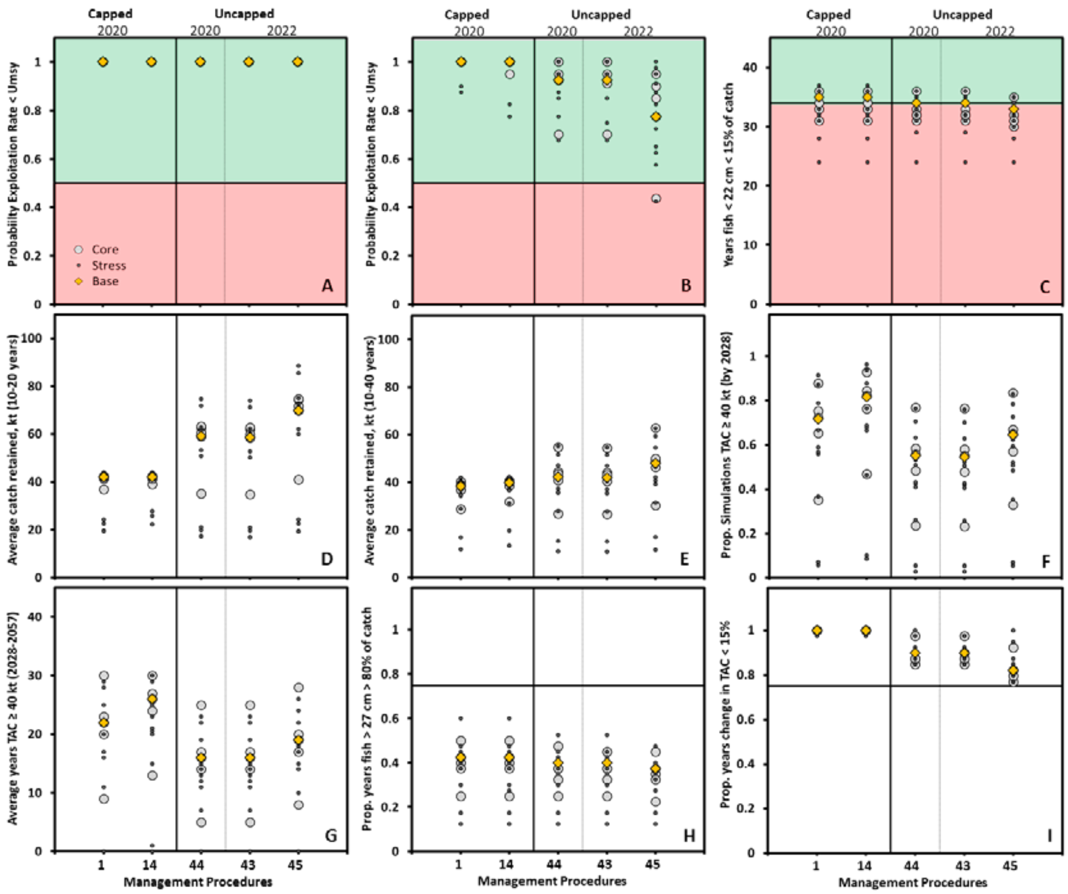

*Figure 4. Median performance (n = 1,000 simulations) of MPs in different performance metrics. Scores are differentiated by the base model OM1 (yellow diamonds), core models (light grey circles), and stress-test models (dark grey points) and the labels at the top of the figure indicate the year in which the HRC were implemented. A) Objective 3 (*S. mentella*). B) Objective 3 (*S. fasciatus*). C) Objective 4. D-G) Objective 6. H) Objective 7. I) Objective 8. Horizontal lines indicate pass-fail thresholds set by fisheries management (A-C; green = pass, red = fail) or suggested for fishery objectives (H,I).*

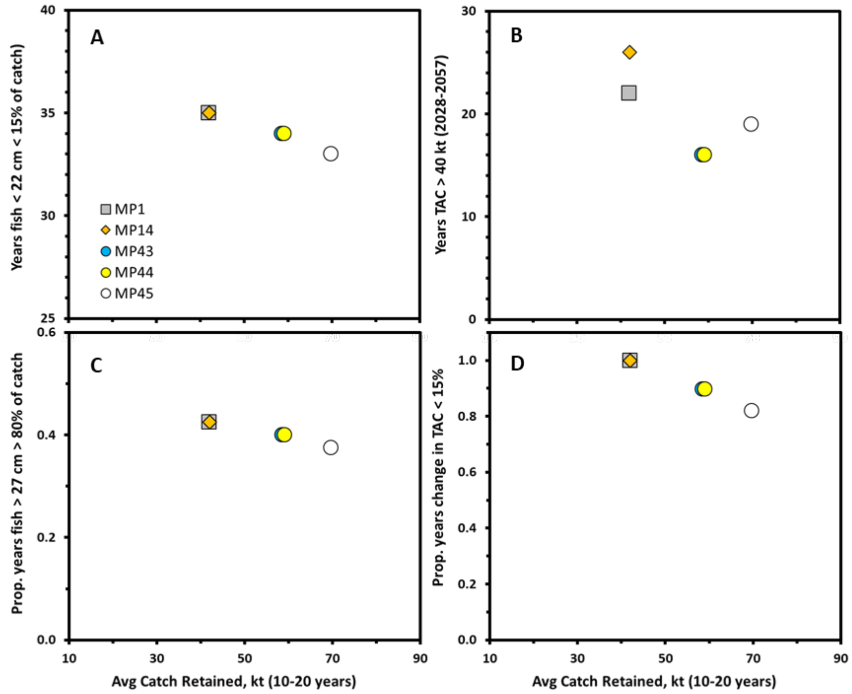

Figure 5. Trade-offs in median performance (n = 1,000 simulations) of MPs in catches retained over 10-20 years (Objective 6, X axis) against other objectives under the base model OM1. A: Objective 4, years in which the Small Fish Protocol is met. B: Objective 6, duration of high annual TACs (≥ 40 kt) over 30 years. C: Objective 7, high abundance of large fish (>27 cm) in the catch. D: Objective 8, stability of TACs between years.

Fishery Objectives

All five MPs failed to pass Objective 4 regarding the Small Fish Protocol (Figure 4C), for which the passing threshold was 85% of years. Catches killed failed to meet the Small Fish Protocol (fish < 22 cm < 15% of catch) in 2018 and 2019 in 100% of the simulations across all models for all MPs. High numbers of small fish in the catch persisted in simulations through 2020 (Table 5).

Table 5. The estimated proportion of fish <22 cm (by numbers) from the base model (median and lower and upper 90% confidence intervals), for both redfish species for 2018-2022.

Year	*S. mentella*			*S. fasciatus*		
	Median	Lower	Upper	Median	Lower	Upper
2018	0.227	0.224	0.228	0.332	0.310	0.311
2019	0.066	0.054	0.095	0.178	0.148	0.203
2020	0.019	0.012	0.035	0.085	0.068	0.107
2021	0.005	0.003	0.010	0.034	0.026	0.049
2022	0.002	0.001	0.005	0.021	0.011	0.054

Uncapped MPs were generally associated with higher predicted retained catches than capped MPs (Figure 4D-4E), while capped MPs were somewhat more likely to reach TACs of 40 kt or above by 2028, and remain there through 2057 (Figure 4F-4G). However, scores of the performance metrics for catches retained were sensitive to model assumptions. All five MPs exhibited similar scores for the abundance of large fish in the catch (Figure 4H), falling below the suggested performance threshold of 75% of years; and capped MPs were more conservative than uncapped MPs when examining the stability of TACs between years (Figure 4I). The MP performance regarding predicted catches retained traded off, to a limited extent, against other objectives regarding fish size, the duration of high TACs, and the stability of TACs between years. Examples of trade-offs in performance under the base model OM1 are shown below (Figure 5); however, the magnitude of trade-offs varied under different operating models. Overall, the performances of MP1 and MP14 were similar, as were MP43 and MP44.

In many circumstances the performance of certain MPs decreased and the total landings/TACs of redfish were constrained by the uncertainty in simulated catch of *S. fasciatus*, the less abundant of the two species. Additional exploratory OMs that assumed that catches could be accurately and perfectly ascribed to each of the two species by the fishery had improved performance and resulted in total catches that were about 40-90% higher than OMs that assumed that species were not distinguished.

Predicted Total Allowable Catches

Examples of median projected possible TACs from 2018-2028 under the base and core operating models for each of the five MPs are shown in Figure 6. Note that in projections, the HCR generates the recommended TAC, and total catch killed = 1.1*TAC.

Except for MP43, all MPs produced projected median TACs less than the 2017 TAC until about 2022. MP43 had a more aggressive set of fixed TACs for the next four years reaching 20 kt by 2021 (Figure 6). TAC increased gradually from 2022-2027 until reaching the TAC maximum cap of 40 kt for MPs 1 and 14. The uncapped MPs (43, 44, and 45) gave a more rapid TAC increase between 2022 to 2026 levelling out at between 60 and 80 kt by 2028. Capped MP TACs were robust over the core set of OMs while the uncapped MPs were sensitive to OM specifications in both the speed of TAC increase from 2022 and 2028 and the maximum TAC levels between the various core OMs.

CONCLUSIONS AND ADVICE

Performance of the five candidate MPs showed few differences. This may be attributed to the effect of the strong 2011-2013 cohorts now entering the redfish fishery. The presence or absence of maximum caps (MP1 and 14, vs. MP43-45) or of adjustment of HCR TACs by 0.8 (MP43 and 44 vs. MP45) mattered more to candidate MP performance than the year in which the HCR was first implemented. Differences in MP performance related to some trade-offs in average annual catches retained (10-20 years in the future) against duration of high TACs (≥ 40 kt), TAC stability (annual changes in TAC < 15%), years where the redfish Small Fish Protocol is met (fish < 22 cm < 15% of catch), and the abundance of large fish in the catch (fish > 27 cm > 80% of catch). However, the strength of these trade-offs depends on the operating model examined.

While the stock conservation objective to reach and maintain the SSB of both species in the Healthy Zone was met in all tested MPs, MP45 failed to maintain exploitation rates (U) below Umsy for *S. fasciatus* with 50% probability in all core and base operating models.

The abundant small fish associated with the 2011-2013 cohorts results in predictions that catches from all candidate MPs will fail to meet the Small Fish Protocol in 2018 and 2019, and there are expected to be abundant small fish (< 22 cm) in the catch until 2020. Even with proportion of small fish in fishery catches greater than those currently allowed under the small fish protocol, the MSE concluded that this would not compromise the achievement of other conservation objectives.

OTHER CONSIDERATIONS

Implementation Period of MSE

Once a MP is chosen, this MP must be adhered to in setting catch limits (TACs) for a fixed number of years (typically not more than five). At the end of the initial implementation phase, a retrospective analysis should take place in which the actual performance of the MP in the fishery are evaluated, and any updates to MP design, OMs, simulations, objectives, and exceptional circumstances among other items are re-evaluated in a new MSE process.

An implementation period of a maximum five years is strongly recommended. This duration was chosen to balance the period of time required to phase in the MP, and the collection of sufficient fishery and survey data to assess its performance. Assuming the present MSE is initiated in 2018, a second MSE process should be initiated in 2022, which may result in a new or revised MP to be implemented starting in 2023.

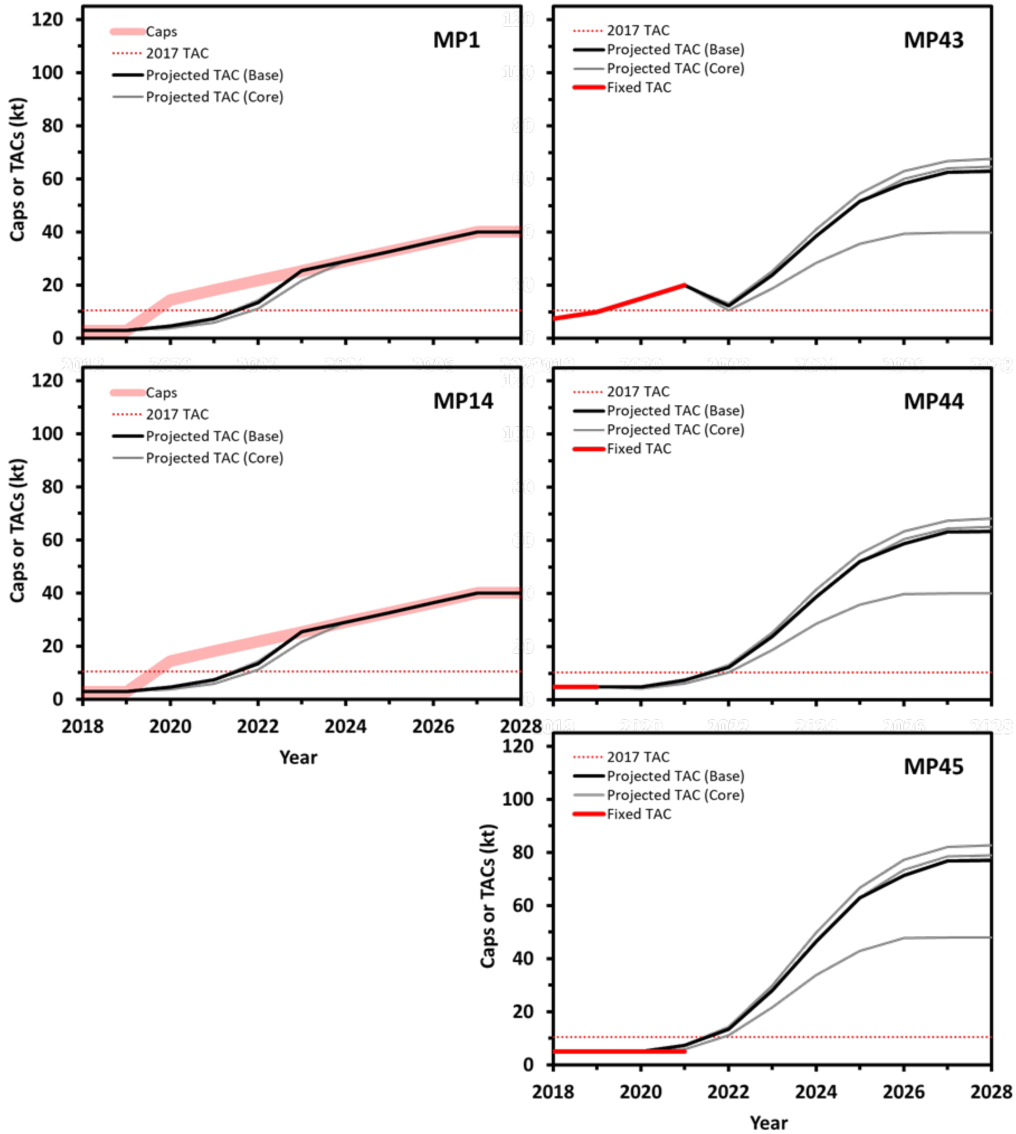

Figure 6. Projected median TACs (over n = 1,000 simulations) for each MP are shown for the base operating model (OM1; black) and the core operating models (OM6, OM8, OM9, OM10, and OM11; all grey). Pale red lines indicate the presence of caps. Solid red lines indicate fixed TACs included as part of the MP design. The dotted red line indicates the 2017 TAC of 10.5 kt for Units 1 and 2 combined.

Exceptional Circumstances Protocol

Exceptional circumstances are commonly defined in the MSE process, where a decision could be taken for the implementation of a MP to stop before the pre-determined implementation period comes to an end. These circumstances describe events that are sufficiently outside the range for which the MP in use has been tested against in simulation, such that confidence in MP performance may be reduced. Such circumstances include:

Survey Index Ratio

- Beginning in 2019, if the survey index ratio (Jy) for either *S. mentella* or *S. fasciatus* falls below 0.35 (i.e., lowest historical value) or is outside the 90% confidence interval for which the survey index ratio is projected to lie for core operating models (Table 6).

Table 6. Estimated lower and upper 90% confidence interval for the survey index ratio from the core operating models for both redfish species for 2019-2028.

Year	*S. mentella*		*S. fasciatus*	
	Lower	Upper	Lower	Upper
2019	0.379	0.715	0.574	1.241
2020	0.397	1.152	0.486	1.756
2021	0.656	2.994	0.415	2.369
2022	1.624	8.378	0.49	3.125
2023	3.783	21.259	0.667	4.493
2024	6.609	37.644	0.895	6.518
2025	8.439	51.087	1.124	8.679
2026	9.092	60.334	1.234	10.01
2027	9.587	65.968	1.233	11.137
2028	9.267	65.724	1.11	11.393

Survey Data

- If the Unit 1 or Unit 2 mature survey biomass indices for either *S. mentella* or *S. fasciatus* fall below their historical lowest values (Unit 1: 1984-2017; Unit 2: 2000-2016), for two consecutive surveys.
- If the Unit 1 survey, which provides the survey index ratio (J_y) for the HCR, has either not taken place or has been substantially curtailed or changed for two consecutive years. While the Unit 2 survey data are used to evaluate mature survey biomass (above) and length composition (below), they are not used in the annual application of HCR and there is therefore no exceptional circumstance for failure to complete that survey as planned.

Length Composition

- An important and unanticipated change in the catch length composition structure of the fishery or survey for either *S. mentella* or *S. fasciatus* in either Unit 1 or 2 (either truncated, or spread out). This could result from a significant change in fishery or survey selectivity, density-dependent effects, emigration events or the presence of a previously unknown strong cohort. What constitutes a significant change needs to be defined during the first year of implementation of the MSE.

Operating Model Assumptions

- An important change in the understanding of the life history or stock parameter assumptions in the core operating models in the MSE affecting management procedure performance. These may include:

- Parameters significantly different from the ranges tested in the operating models or sensitivity tests.
- A stress-test model becomes more credible than the core models, and the management procedure has not performed acceptably under this model.
- No operating models have been developed that adequately address the specific biological change observed (e.g., significant spatio-temporal differences in stock distribution).

Catches

- Evidence of landings, discarding or unreported catches significantly higher than in the tested model assumptions for the MP

If an exceptional circumstance arises, the evaluation of impacts will be reported by DFO Science (see below) and the management of the fishery including the implementation of the MP may need to be reconsidered and re-evaluated before new management actions could be taken, including the development of a new MP that performs acceptably under the updated circumstances of the stock and fishery.

Information Support Requirements

The implementation of the MSE requires annual updates of key information to inform the HCR and to evaluate whether the Exceptional Circumstances Protocol should be invoked. The necessary information is:

1. The biomass index for *S. mentella* (>30 cm) and *S. fasciatus* (>29 cm) from the annual Unit 1 bottom trawl survey.
2. Data on length composition of catches in the surveys and in the fishery in Units 1 and 2, and the mature survey biomass of both redfish species in the Units 1 and 2 surveys, to evaluate the necessity to invoke the exceptional circumstances protocol.

Annual review and reporting

The information required annually for the implementation of the MSE, as regards the HCR and Exceptional Circumstances Protocol need to be peer reviewed to ensure its accuracy and then published to ensure scientific integrity and transparency of the process. Annual Canadian Science Advisory Secretariat Science Responses, or an equivalent process, are recommended as the means by which to achieve annual review and reporting.

Research Recommendations

Implementing the collection of representative species composition data in fishery catch sampling is a high priority. Data on species composition will improve the fidelity of subsequent MSE processes in the future (i.e., their ability to correctly simulate stock and fishery dynamics) and would contribute to enhancing the sustainable management of *S. fasciatus*, while potentially allowing for higher overall catches of redfish if the species composition of catches can be estimated with high accuracy and precision and if the commercial fishery can reliably target *S. mentella*.

A number of uncertainties concerning important life history parameters were identified in the MSE and were represented using stress-test models. Research aimed at reducing these uncertainties would improve the fidelity of the MSE process. Notably, this includes data on the natural mortality (*M*) and growth rate of *S. fasciatus* and *S. mentella*. Furthermore, the underlying equation used to model recruitment in the MSE was a Beverton-Holt stock-recruitment function. Given strong evidence of cannibalism in redfish, a Ricker stock-recruitment model could be considered for the 5-year review of the present MSE

Preliminary analyses undertaken outside the MSE process based on both Unit 1 and Unit 2 surveys (2000-2017) suggest the possibility that Unit 2 densities could remain elevated even at lower stock levels and that as abundance increases, densities increase rapidly in Unit 1. This phenomenon, termed hyper-expansion, would result in a disproportionate increase in the Unit 1 survey index as abundance increases, leading to a risk of setting catch levels under the HCR that are biologically too high. Conversely, abundance declines would result in a disproportionate decrease in the Unit 1 survey index (hyper-depletion), resulting in catch levels under the HCR that cause foregone yield. Such a hypothesis was not simulated in the present MSE. Further research into the spatial distribution and dynamics of redfish prior to the evaluation phase of the present MSE is highly recommended. To support this research, and in anticipation of possible modified MSE process following the five-year implementation period, the biennial Unit 2 survey should continue and ideally be made annual.

Given the importance of OM10 and OM11, which address uncertainties in the historic catch species-split uncertainty, further research into the feasibility of alternative methods to address the historic species-split in the commercial catches should be explored.

SOURCES OF INFORMATION

This Science Advisory Report is from the April 25-26, 2018 Unit 1+2 Redfish Management Strategy Evaluation. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Brassard, C., Bourdages, H., Duplisea, D., Gauthier, J., and Valentin, A. 2017. The status of the redfish stocks (*Sebastes fasciatus* and *S. mentella*) in Unit 1 (Gulf of St. Lawrence) in 2015. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/023. ix + 53 p.

COSEWIC. 2010. COSEWIC Assessment and Status Report on the Deepwater Redfish/Acadian Redfish complex *Sebastes mentella* and *Sebastes fasciatus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. x + 80 pp.

DFO. 2009. A Fishery Decision-Making Framework Incorporating the Precautionary Approach. Last updated 2009-03-23.

DFO. 2011. Western Component (4Xopqrs5) Pollock Management Strategy Evaluation. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/054.

DFO. 2016. Assessment of Redfish Stocks (*Sebastes fasciatus* and *S. mentella*) in Units 1 and 2 in 2015. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2016/047.

DFO. 2018 Assessment of Redfish Stocks (*Sebastes fasciatus* and *S. mentella*) in Units 1 and 2 in 2017. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/032.

Duplisea, D.E. 2016. Context and interpretation of reported redfish catch in Unit 1+2 in the 1980s and 1990s based on interviews with industry participants. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/103. v + 11 p.

Edwards, C.T.T. 2016. Feedback control and adaptive management in fisheries. pp 16-38. In: Management Science in Fisheries: An introduction to simulation-based methods. Edwards, C.T.T. and Dankel, D.J. (eds.). Routledge: New York. 460 pp.

Kulka, D.W., and Atkinson, D.B. 2016. Redfish Catch Results from the Summer 2009, 2011 and 2014 Surveys in Unit 2. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/019. v + 32 p.

THIS REPORT IS AVAILABLE FROM THE:

Center for Science Advice (CSA)
Quebec Region
Fisheries and Oceans Canad
Maurice Lamontagne Institute
850 route de la Mer
P.O. Box 1000
Mont-Joli (Quebec)
Canada G5H 3Z4

Telephone: (418) 775-0825
E-Mail: bras@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2018. Units 1+2 Redfish Management Strategy Evaluation. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/033.

Aussi disponible en français :

MPO. 2018. Évaluation des stratégies de gestion du sébaste des unités 1 et 2. Secr. can. de consult. sci. du MPO, Avis. Sci. 2018/033.