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The interim management procedure approach for assessed stocks: Responsive management advice and lower assessment frequency

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Abstract

Stock assessments are often used to provide management advice, such as a total allowable catch (TAC), to fishery managers. Many stocks are not assessed annually, and the TAC from the previous assessment is often maintained in years between assessments. We developed two interim management procedures (MPs) that update the estimate of current vulnerable biomass from a surveyed index of abundance to adjust the TAC from a previous assessment. These MPs differ in how they handle uncertainty in observed indices. Using closed-loop simulation, we evaluated the two interim MPs (with 10- and 5-year assessment intervals) against several "status quo" approaches: (1) an annual assessment, and (2) a stock assessment every 5 or 10 years with (a) fixed TACs or (b) projections between assessments. We evaluated performance across three life-history types and six operating model scenarios. The interim MPs performed similarly to annual assessments in terms of trends in biomass and yield, regardless of the assessment interval of the interim MPs. The interim MPs often produced more yield than the Fixed TAC MP with 10-year assessment intervals, for example, in depleted scenarios. The Fixed TAC MP performed more similarly to interim MPs when the assessment interval for the Fixed TAC MP was decreased to five years. The interim MPs can also perform well when circumstances arise that are not accounted for in the Projection MP. Our results show that interim MPs should be considered for infrequently assessed stocks or rebuilding stocks, and highlight potential cost savings of interim MPs over annual assessments.

KEYWORDS

fisheries management, management strategy evaluation, simulation, stock assessment, total allowable catch

1 | INTRODUCTION

For many fished stocks, management recommendations for harvest levels are prescribed in terms of a catch limit, commonly referred to as a total allowable catch (TAC). In output-controlled fisheries where explicit catch limits must be provided, a stock assessment model, such as a statistical catch-at-age model (Methot & Wetzel, 2012) or a surplus production model (Pedersen & Berg, 2017; Prager, 1994), is used to provide TAC recommendations to fishery managers. Important estimates from assessments include current vulnerable biomass and reference points, such as the fishing mortality (F) that produces the maximum sustainable yield (F_{MSY}).

If stock assessment outputs were the only tools for setting annual catch limits, then annual assessments would be required to ensure regular, up-to-date management advice. Management bodies and fishing industry organizations often prioritize frequent assessments for high-value and high-volume fisheries. In the United States and Canada, annual assessments are conducted for important stocks such as Pacific halibut (*Hippoglossus stenolepis*, Pleuronectidae; Stewart & Hicks, 2018), Pacific hake (*Merluccius productus*, Merlucciidae; Edwards, Taylor, Grandin, & Berger, 2018) and Pacific herring (*Clupea pallasii*, Clupeidae; DFO, 2018). Many stocks under the purview of the International Council for the Exploration of the Sea (ICES), such as Norwegian spring-spawning herring, are also assessed on an annual basis (Zimmermann & Enberg, 2017).

However, the practice of annual assessments tends to be the exception rather than the norm. In many cases, annual assessments are not feasible due to cost limitations, time constraints, data limitations or insufficient scientific capacity. Instead, assessments are typically conducted periodically, with varying frequency. For example, socio-economically important stocks such as Gulf of Mexico Red Snapper may be assessed every 3–4 years (SEDAR, 2018), while other species such as Gulf of Mexico Vermilion Snapper (SEDAR, 2016), Gulf of Mexico Cobia (SEDAR, 2013) and many Canadian Pacific stocks managed under the Integrated Fisheries Management Plan for Groundfish (DFO, 2019) are assessed less frequently, with 5- to 10-year assessment intervals or longer.

Several approaches have been used to provide TAC recommendations in the interim period between assessments. One approach is to project the vulnerable biomass from the most recent assessment to generate a TAC recommendation for each interim year (e.g. Gulf of Mexico Red Snapper; Cass-Calay et al., 2015). However, this approach requires specific assumptions about future levels of recruitment, natural mortality and fishing behaviour that can be difficult to forecast. A common alternative is to fix the TAC at a constant level until the next assessment is adopted. For example, TACs for most assessed Canadian Pacific groundfish stocks are based on the target fishing mortality rate applied to the biomass at the end of the latest assessment and often stay static, with some exceptions, until advice from new assessments is received (e.g. DFO, 2019).

Ideally, TACs should be updated in response to changing fishing pressure and fish population size. For example, if the fish population is decreasing, the catch prescribed by a fixed TAC will correspond to increasingly higher exploitation rates as the population gets smaller (Harford & Carruthers, 2017). On the other hand, foregone yield can occur where a fixed TAC corresponds to a lower exploitation rate for an increasing fish population. Low TACs for an increasing fish population may also lead to higher discard rates due to high encounter rates and lack of available quota.

Assessment intervals have generally not been considered in a strategic context for managing fisheries, even though they can be crucial for successful fisheries management (Hutniczak, Lipton, Wiedenmann, & Wilberg, 2019; Wiedenmann, Wilberg, Sylvia, & Miller, 2017). Fixed TACs over long intervals amount to static management, which has been found to have poorer performance than adaptive management procedures (Harford & Carruthers, 2017; Sagarese et al., 2018; Shertzer & Prager, 2007). Static management also has implications for other exploited stocks in multispecies fisheries. For example, low TACs of "choke" species in fully monitored multispecies fisheries, such as British Columbia's groundfish fishery, can limit fishing of other commercially desirable species (DFO, 2012).

Assessment frequency is often constrained by scientific capacity, but data collection programmes may contain valuable information to support decision-making during the interim period between assessments. Increases in biomass could be inferred from fishery-independent surveys or by the appearance of a strong cohort in age-composition data. Such information could provide a basis for updated management advice, but in cases where there are long intervals between assessments, these data generally remain unused until the next scheduled assessment.

Management procedures (MPs) for setting annual TACs based on surveyed indices of abundance have been proposed and applied (Geromont & Butterworth, 2015; Geromont, De Oliveira, Johnston, & Cunningham, 1999; ICES, 2014). Such MPs follow a general formula: after setting an initial TAC, the catch advice in subsequent years either increases or decreases in accordance with the population biomass, as indicated by the index. Control parameters can constrain the rate of change in TAC from one year to the next and scale the overall magnitude of the catch. For example, the magnitude of catch shortly after implementation of such MPs is strongly influenced by the magnitude of the initial

TAC. For un-assessed stocks, initial TACs may be set empirically, for example, using historical catch (Geromont & Butterworth, 2015), or be based on consensus by managers and stakeholders (Geromont et al., 1999). In some cases, such MPs have been found to perform as well as those using conventional assessment models (Carruthers et al., 2016).

In this study, we describe a similar approach, whereby the TAC is set by an assessment model at periodic intervals and by an index-based rule in the interim period between assessments. During an assessment year, we set TACs based on maximum sustainable yield (MSY) targets. In years without an assessment, the interim MPs update the TAC every year based on an updated estimate of current vulnerable biomass inferred from survey indices (calibrated from the most recent assessment), while keeping the target fishing mortality rate of F_{MSY} that was estimated in the most recent assessment. In effect, the assessment model informs some of the control parameters, for example, the initial TAC, for the index-based rule.

This approach has two potential benefits for assessed stocks. First, for species currently assessed on an annual basis, there is the potential to increase cost efficiency if advice can be robustly updated with less frequent stock assessments. Second, for species with infrequent stock assessments that are currently managed with constant or near-constant TACs, a robust approach to setting interim TACs may reduce risk of over- or under-exploitation and, as a more responsive form of advice, improve management performance with respect to both conservation and economic objectives. These interim MPs could also be improvements over cases where multiyear catch advice is based on multiyear model projections, which assume average conditions going forward and do not incorporate current information from the system that would be provided by survey data.

In this study, we proposed two interim MPs that differ in how they handle uncertainty in index values. We then compared the two interim MPs to: (i) an annual assessment MP, (ii) an MP that fixes the TAC between assessments and (iii) an MP that uses projections to set the TAC between assessments. We also evaluated the relative performance of the two interim MPs, fixed TAC MP, projection MP with varying frequencies of assessments.

We evaluated the performance of the alternative MPs using closed-loop simulation, in which a simulated population is updated over time, based on successive applications of MPs that use simulated data generated from an operating model (OM), subject to observation error and biases (Butterworth & Punt, 1999; Cochrane, Butterworth, De Oliveira, & Roel, 1998). The study addresses three questions:

1. How well do the interim MPs perform compared to annual assessments?
2. How well do the interim MPs perform compared to the fixed TAC and projection MPs?
3. How does assessment frequency affect the relative performance of interim MPs, fixed TAC MP and projection MP?

2 | METHODS

2.1 | Management procedures (MPs)

In year y, a typical procedure for setting the TAC of an assessed stock in the following year $y + 1$ is

$$\mathrm{TAC}_{y+1} = F_{\mathrm{target}} B_{\mathrm{ref}}, \tag{1}$$

where F_{target} is the target fishing mortality rate, and B_{ref} is the reference biomass used as the basis for setting the TAC. We use a simple policy based on MSY to set $F_{\mathrm{target}} = \hat{F}_{\mathrm{MSY}}$, where the circumflex ^ denotes estimates from the assessment model, and B_{ref} is the vulnerable biomass in year $y + 1$ either estimated or projected from the assessment, that is, $B_{\mathrm{ref}} = \hat{B}^{V}_{y+1}$ (where superscript V denotes vulnerable biomass). If the TAC is held constant between periodic assessments, then Equation (1) is updated to be

$$TAC_{y+1} = \begin{cases} F_{\mathrm{target}} B_{\mathrm{ref}}, & \text{if } y \text{ is an assessment year} \\ TAC_y, & \text{otherwise} \end{cases}. \tag{2}$$

We propose an alternative approach for empirically updating the TAC in the interim years between assessments. First, assume that there is a survey I_y, used to index the biomass vulnerable to the fishery in year y,

$$I_y = qB^{V}_{y}, \tag{3}$$

where q is the catchability coefficient. Equation (3) shows that, with a catchability coefficient, the vulnerable biomass can be updated in the interim from observed index values to provide a catch recommendation,

$$TAC_{y+1} = \begin{cases} F_{\mathrm{target}} B_{\mathrm{ref}}, & y \text{ is an assessment year} \\ F_{\mathrm{target}} I_y / \hat{q}, & \text{otherwise} \end{cases}, \tag{4}$$

where $\hat{q}$ is the estimated coefficient from the most recent assessment to scale the index values to absolute vulnerable biomass. Equation (4) forms the basis for an interim MP.

2.2 | Uncertainty in the index

Annual estimates of I_y are subject to multiple sources of error, for example, insufficient sample sizes, hyperstability and insufficient coverage of stock range by sampling gear. Ideally, adjustments to the TAC should only be made to the degree that the index reflects true changes in the underlying biomass.

For setting the interim TAC, we propose two ways to modify Equation (4) to accommodate error in the index. First, a simple method of smoothing, such as a moving average, dampens the effects of high inter-annual variability in the index and penalizes fluctuations in the index over time ("Averaged Index"). We use a three-year moving average of the index in the interim,

$$TAC_{y+1} = \begin{cases} F_{target} B_{ref}, & \text{if } y \text{ is an assessment year} \\ F_{target} \tilde{I}_y / \hat{q}, & \text{otherwise} \end{cases}, \quad (5)$$

where $\tilde{I}_y = \frac{1}{3}\sum_{k=y-2}^{y} I_k$. A moving average with a larger time window, for example, 5 years, could be used if one had a lower tolerance for changing the catch advice (see Supplementary Material A).

Second, the change in catch advice from an assessment can be buffered (reduced) proportional to the uncertainty in the index ("Buffered Index"). To begin with, Equation (4) is re-written as

$$TAC_{y+1} = \begin{cases} C_{ref}, & \text{if } y \text{ is an assessment year} \\ C_{ref} \frac{I_y}{I_{ref}}, & \text{otherwise} \end{cases}, \quad (6)$$

where $C_{ref} = F_{target} B_{ref}$ is the reference catch, and $I_{ref} = \hat{q} B_{ref}$ is the reference index. Equation (6) shows that the interim approach descred by Equation (4) is equivalent to adjusting the reference catch by the ratio of the observed index and the reference index. The TAC increases if the observed index is larger than the reference index and vice versa. Equation (6) follows a similar format to MPs that have been proposed for data-limited fisheries where the reference quantities are determined empirically, for example, using historical catch, rather than through an assessment model (Geromont & Butterworth, 2015; ICES, 2014).

Changes in the catch advice can then be buffered by adjusting Equation (6) as follows,

$$TAC_{y+1} = \begin{cases} C_{ref}, & \text{if } y \text{ is an assessment year} \\ C_{ref} \frac{I_y + b\hat{\sigma}}{I_{ref} + b\hat{\sigma}}, & \text{otherwise} \end{cases}, \quad (7)$$

where $\hat{\sigma}$ is the estimated standard deviation of the index, and b is an additional non-negative scaling factor that is inversely proportional to one's risk tolerance for changing the catch advice under uncertainty. Large values of either σ or b penalize changes in the catch advice. Equation (7) has the desirable properties of converging to Equations (4) and (6) as either b or σ approaches zero. As b or σ approaches infinity, the TAC becomes fixed until an assessment year.

We calculated σ as the standard deviation of index values from a de-trended time series, for example, the standard deviation of the residuals from the assessment model's fit to the index values. In doing so, one quantifies the uncertainty of the index, incorporating observation and process errors, based on the fit in the assessment. For selecting the value of b, some guidance could be taken from statistical hypothesis testing. With a standard normal distribution for a null hypothesis, critical values of 1 and 2.58 correspond to significance levels of 0.31 and 0.01, respectively, and represent relatively moderate and low tolerance, respectively, for rejecting a null hypothesis. Therefore, values of b = 1 and b = 2.58 imply moderate and low tolerance, respectively, for changing the catch advice with Equation (7).

2.3 | Closed-loop simulation study

We evaluated the performance of the MPs using closed-loop simulation, in which alternative methods of setting TACs are applied over time in a simulated fishery system. We used the R package DLMtool (version 5.3.1). Pertinent features of the software are described here, with the full description available in Carruthers and Hordyk (2018). The operating model (OM) is an age-structured model in which the user specifies parameters that define the fish stock, fishing fleet, observations and management implementation dynamics of the system. After the historical dynamics of the stock are generated ("historical period"), candidate MPs are applied successively over time ("management period"). During the management period, annual catches are removed from the OM population according to the TAC prescribed from the selected MP, and data are generated by the OM and used to generate the TAC at the next time step. A 50-year management period was used in the study.

We developed operating models for three species (Table 1; Figure 1) to evaluate the MPs:

1. Capelin (*Mallotus villosus*, Osmeridae)—a short-lifespan forage species. The OM was developed from an assessment using a stochastic stock-reduction analysis (Walters, Martell, & Korman, 2006) based on data available for the Gulf of St. Lawrence stock in Canada (Carruthers, 2017; MPO, 2013);
2. Vermilion Snapper (*Rhomboplites aurorubens*, Lutjanidae)—a moderate-lifespan reef species, with dome-shaped vulnerability to the fishery and low recruitment variability. The OM was based on the Gulf of Mexico stock in the U.S. (Carruthers, 2018a; SEDAR, 2016);
3. Pacific Ocean Perch (POP) (*Sebastes alutus*, Sebastidae)—a long-lifespan rockfish species. The OM was based on the Queen Charlotte Sound stock in Canada (Carruthers, 2018b; DFO, 2017).

Process error was incorporated in the OMs with lognormal deviations in annual recruitment among simulation replicates. For the historical period, the fishing mortality was taken from the most recent assessment and re-scaled by the multiplier that produced the specified biomass at the beginning of the management period (Table 1; Supplementary Material B). The OMs were designed to provide insight into the performance of different MPs among contrasting life histories and fleet dynamics and were not intended to fully describe the assessed stocks.

The observation model incorporated variables that control random and persistent error in the generated data, including the following: (1) hyperstability/hyperdepletion in the index of abundance (i.e. whether trends in the index over time are linearly proportional to changes in biomass); (2) bias (i.e. persistent under-estimates or over-estimates within a simulation) in catch and

TABLE 1 Range in operating model parameters for the three species

Parameter	Capelin	Vermilion Snapper	Pacific Ocean Perch (POP)
Maximum age (years)	8	15	60
Historical years of fishing	53	65	77
Spawning depletion at MSY (B^S_{MSY}/B^S_0)	0.32	0.35	0.29
Fishing mortality at MSY (F_{MSY}) (year^{-1})	1.00	0.34	0.08
Natural mortality (M) (year^{-1})	0.80	0.25	0.06
von Bertalanffy asymptotic growth coefficient (K) (year^{-1})	0.55	0.33	0.16
von Bertalanffy asymptotic length (L_∞) (cm)	19.0	34.4	44.2
von Bertalanffy location parameter (t_0) (year)	−0.50	−0.80	−0.65
Beverton–Holt stock–recruit steepness (h)	0.60	0.60	0.70
Mean generation time (year)	2.9	5.0	23.9
Recruitment variability standard deviation (lognormal distribution)	0.48–1.00	0.20–0.39	0.65–0.96

Notes: Additional life history (growth and maturity) and vulnerability schedules are shown in Figure 1. Parameters do not vary among simulations except for the standard deviation of recruitment, which is drawn from a uniform distribution for a given simulation iteration. Parameters were based on the most recently available stock assessment for each species (see Methods).

life-history parameters (maturity, growth, natural mortality and steepness of the stock–recruit relationship); and (3) annual, random sampling error in the index, catch and age compositions. A full description of the distributions of observation model parameters is provided in Table 2.

The observed index $\acute{I}_{i,y}$ and catch (in weight) $\acute{C}_{i,y}$ in simulation i and year y is

$$\acute{I}_{i,y} = q_i \left(B^V_{i,y}\right)^{\beta_i} \exp\left(\varepsilon^I_{i,y}\right) \tag{8a}$$

and

$$\acute{C}_{i,y} = C_{i,y} \exp\left(\gamma^C_i\right) \exp\left(\varepsilon^C_{i,y}\right), \tag{8b}$$

respectively, where the acute accent (´) denotes the simulated observation of the corresponding variable in the operating model, q_i represents the scaling parameter for the index, β_i represents the hyperstability exponent of the simulated index, $\varepsilon^C_{i,y}$ and $\varepsilon^I_{i,y}$ represent independent, normally distributed deviates in the simulated data "observed" from the operating model, the superscript references the data type (I is index and C is catch), and γ^C_i represents independent, normally distributed deviates among simulations that parameterize bias in observed catches (among simulations, observed catches are unbiased). Sampled deviates are bias-corrected for the lognormal distribution. Age compositions were sampled from the catch-at-age matrix from a multinomial distribution with an assumed sample size (Table 2). The annual observed age-composition vectors $\acute{\boldsymbol{X}}_{i,y}$ were sampled from the catch-at-age proportions $\acute{\boldsymbol{p}}_{i,y}$ as a multinomial random variable,

$$\acute{\boldsymbol{X}}_{i,y} \sim \text{Multinomial}\left(O_i, \boldsymbol{p}_{i,y}\right), \tag{8c}$$

where O_i is the assumed sample size (Table 2).

For life-history parameters such as the Beverton–Holt steepness of the stock–recruit function (h, Mace & Doonan, 1988), the i-th simulated observation $\acute{h}$ is similarly parameterized as

$$\acute{h}_i = h \exp\left(\gamma^h_i\right), \tag{9}$$

where γ^h_i are deviates of observed steepness among simulations (Table 2).

The generated data were then passed to the assessment model. The assessment model was a single-fleet statistical catch-at-age (SCA) model from the MSEtool R package version 1.3.0 (Huynh, Hordyk, & Carruthers, 2019; Supplementary Material C). From the assessment, the TAC was generated through the following MPs:

1. "Annual assessment"—the TAC was set via Equation (1) with an assessment performed every year.

TABLE 2 Observation model parameters common to the operating models for the three species. Subscripts indicate whether values are varied among simulations i, years y, or both

Parameter	Symbol	Distribution
Index hyperstability exponent[a]	β_i	Hyperstable: $U(0.33,0.67)$ Hyperdeplete: $U(1.5,3)$ Base and Other Scenarios: $U(0.67,1.5)$
Annual observation error in the index[a]	$\varepsilon^{I}_{i,y}$	$\varepsilon^{I}_{i,y} \sim N\left(-0.5\left[\sigma^{C}_{i}\right]^2, \left[\sigma^{C}_{i}\right]^2\right)$, where $\sigma^{I}_{i} \sim U(0.10,0.25)$
Annual observation error in the catch[b]	$\varepsilon^{C}_{i,y}$	$\varepsilon^{C}_{i,y} \sim N\left(-0.5\left[\sigma^{I}_{i}\right]^2, \left[\sigma^{I}_{i}\right]^2\right)$, where $\sigma^{C}_{i} \sim U(0.1,0.2)$
Age-composition sample size [multinomial sampling]	O_i	$O_i \sim U(50,100)$
Bias in observed catch [among simulations] [b]	γ^{C}_{i}	$\gamma^{C}_{i} \sim N(-0.001,0.05^2)$
Bias in observed steepness (h)[c]	γ^{h}_{i}	$\gamma^{h}_{i} \sim N(-0.005,0.10^2)$
Bias in observed natural mortality (M), ages of 50% and 9% maturity (m_{50} and m_{95}, respectively), and von Bertalanffy growth parameters (L_∞, K, and t_0)[d]	$\gamma^{M}_{i}, \gamma^{m_{50}}_{i}, \gamma^{m_{95}}_{i}, \gamma^{L_\infty}_{i}, \gamma^{K}_{i}, \gamma^{t_0}_{i}$	$N(-0.001,0.05^2)$

[a]See Equation (8a)

[b]See Equation (8b).

[c]See Equation (9).

[d]Similar to Equation (9).

2. Interim MP with index averaging ("Averaged Index")—the TAC was set by Equation (5) with a 3-year moving average of the observed index.
3. Interim MP with buffering ("Buffered Index")—the TAC was set by Equation (7) with b = 1 and σ calculated from the standard deviation of the index residuals in the most recent assessment.
4. "Fixed TAC"—the TAC was set via Equation (2) and remained static until the next assessment.
5. "Projection"—the TAC was set by Equation (1) with periodic assessments. Between assessment years, projections were used to update B_{ref}.

The estimated values of F_{MSY} and B^{V}_{y+1} from the most recent available assessment were used as F_{target} and B_{ref}, respectively. For Averaged Index, Buffered Index and Fixed TAC MPs, assessments were conducted every 10 years, with an additional run that evaluated these MPs with a shorter assessment frequency of 5 years. The TACs were implemented without error in the simulation. Pope's approximation (Pope, 1972) was used to remove the TAC from the population at the midpoint of the year, with a maximum apical fishing mortality set to 3 to prevent unrealistically high levels of fishing effort.

For each species, there were six operating model scenarios (Table 3):

- Base—the spawning biomass is at B^{S}_{MSY}, where superscript S denotes spawning biomass, and the index on average follows changes in the underlying biomass. The following scenarios diverge from the Base scenario as described.
- Hyperstable—evaluated the MPs when the indices used for the assessments and interim TAC calculations were hyperstable, that is, $\beta << 1$. In our simulation runs, the hyperstable index had a disproportionately smaller change in index values over time compared to an index that is directly proportional to the biomass of the simulated population. Hyperstability masks depletion trends and arises from factors such as spatial aggregation behaviour of fish (Walters, 2003; Walters & Martell, 2004). This scenario evaluates the cost, relative to the Base scenario, of misidentifying an index as proportionate to population size.
- Hyperdeplete—the complement of Hyperstable. In this scenario, the index shows disproportionately larger changes than one directly proportional to surveyed biomass.
- Depleted—evaluated performance of the MPs when the stock is at a lower biomass level at the start of the management period (30% B^{S}_{MSY}) compared to the Base scenario. This evaluates how well each of the MPs performs for rebuilding stocks.
- Lightly fished—the complement of Depleted. This scenario, the stock is at a higher biomass level at the start of the management period (250% B^{S}_{MSY}).
- Episodic M—evaluated the MPs when the operating model diverges from the assumptions of the assessment model and projections during the management period. Environmental conditions can reduce population abundance through episodic events, for example, die-offs (Anderson, Branch, Cooper, & Dulvy, 2017; Harford et al., 2018). Here, we model die-offs through episodic increases in natural mortality. In the operating model, natural mortality in year y of the management period is

TABLE 3 Summary of operating model scenarios

Name	Description
Base	Parameters in Tables 1, 2 and Figure 2, spawning biomass is B^S_{MSY} at the beginning of the management period
Hyperstable	Same as Base, but $\beta_i \sim U\,(0.33, 0.67)$ (Table 2)
Hyperdeplete	Same as Base, but $\beta_i \sim U\,(1.5, 3)$ (Table 2)
Depleted	Same as Base, but spawning biomass is 30% B^S_{MSY} at the beginning of the management period
Lightly fished	Same as Base, but spawning biomass is 250% B^S_{MSY} at the beginning of the management period
Episodic M	Same as Base, but with occasional increases in natural mortality during the management period (Equation 10)

$$M_y = \begin{cases} M^{\text{hist}} & \text{if } \eta_y = 0 \\ M^{\text{hist}}(1+\theta_y) & \text{if } \eta_y = 1 \end{cases}, \quad (10)$$

where M^{hist} is the historical M (Table 1), $\eta_y \sim \text{Be}\,(p = 0.1)$ is a Bernoulli random variable indicating a 10% annual probability for the occurrence of an episodic event, and $\theta_y \sim \text{Lognormal}\,(1,2)$ is a lognormal deviate with median of 1, log-scale standard deviation of 2, and truncated to a maximum value of 4 that indicates the increase in natural mortality during the episodic event. The management procedures did not incorporate increased natural mortality in the assessment model, reference points and projections.

2.4 | MP evaluation

We evaluated the performance of the MPs in three ways. First, we calculated annual means in relative spawning biomass (B^S/B^S_{MSY}) and relative yield (ratio of catch to MSY) to highlight their behaviours under the different MPs during the management period. Annual means can be used to describe whether changes in biomass or yield may occur more quickly for one MP over another.

The second metric evaluated how the MPs changed the biomass over time by calculating the coefficient of variation in spawning biomass (CVB) during the management period. It is expected that CVB will vary among MPs and assessment intervals. For example, if a fish population were at B^S_{MSY}, a fixed TAC that is lower than MSY would, on average, increase the size of the population over time, whereas an annually adaptive TAC would be more likely to keep the population stable. In many management settings, it is also desirable to avoid high inter-annual variability in catch and the risk of stock collapse, both of which could occur with high variance in biomass.

Third, we calculated the geometric mean of the relative yield (GMRY) over the entire management period to evaluate the magnitude of catches achieved after implementation of the MPs. The GMRY in simulation i over n_y management years is

$$\text{GMRY}_i = \left(\prod_y C_{i,y}/\text{MSY} \right)^{1/n_y}, \quad (11)$$

where the relative yield is the ratio of catch to MSY. A GMRY value greater than one implies that the geometric mean of the catches is greater than MSY. The ratio in geometric mean catch between two MPs is given by the ratio of their GMRY. The GMRY has similar properties to the sum of the logarithm of yield utility function for comparing time series of catch among MPs (Walters & Martell, 2004). The geometric mean penalizes MPs that produce any years with very low catches and, compared to the arithmetic mean, reduces the influence of individual years with very high catches.

We carried out a total of 250 replicate simulations for each OM-MP combination. We checked the stability of the mean B^S/B^S_{MSY} in the last year of the projection period, mean CVB, and mean GMRY to evaluate whether enough simulations had been carried out. Mean values of all three were stable with 250 simulations (Supplementary Material D).

3 | RESULTS

This section is organized into three subsections for each question posed in the Introduction:

1. How well do the interim MPs perform compared to annual assessments?
2. How well do the interim MPs perform compared to the fixed TAC and projection MPs?
3. How does assessment frequency affect the relative performance of the interim MPs and fixed TAC MPs?

For the first two subsections, we present results for the interim MPs, Fixed TAC MPs and Projection MP with a 10-year assessment interval. The third subsection presents results comparing these MPs with 5-year assessment intervals (Figure 1).

3.1 | How well do interim MPs perform compared to annual assessments?

In all six scenarios, the trajectory of mean biomass and mean relative yield associated with the interim MPs (Averaged Index and Buffered Index MPs) with 10-year assessment intervals was similar to those from the annual assessment MP (Figures 2 and 3). Despite their large differences in assessment frequency, the interim MPs and Annual Assessment MP produced relatively stable biomass with lower median CVB compared to the other MPs in each corresponding life-history and scenario combination (Figure 4). Additionally, similar annual yields were achieved between the interim MPs and the Annual Assessment MP based on nearly identical median GMRY for the majority of scenarios (Figure 5). Inter-annual variability in biomass was correlated with life history, with highest variability in a short-lived Capelin and lower variability in Vermilion Snapper and POP (Figures 2 and 4). Below, trends common to both the interim MP and Annual Assessment MP are reported unless otherwise noted.

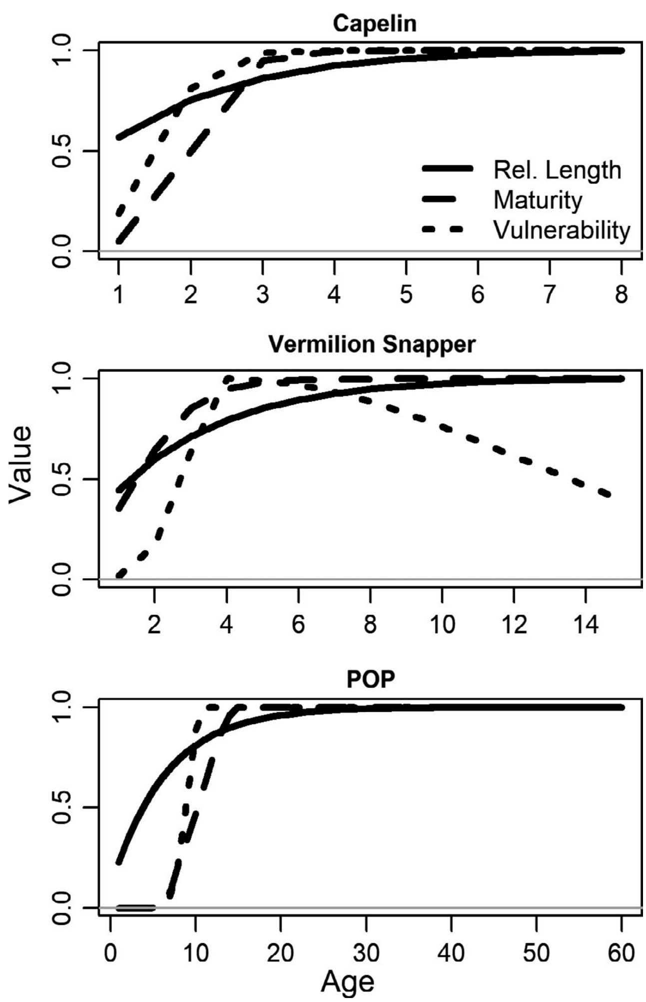

FIGURE 1 Life history (growth and maturity) and vulnerability schedules at age used in the operating models for Capelin, Vermilion Snapper and POP. Growth is expressed as mean length-at-age relative to that at the maximum age

In the Base scenario, the trajectory of mean biomass was stable near B^S_{MSY} and mean relative yield near MSY for all three species (Figures 2 and 3, first row). Although the median CVB was higher with the interim MPs than in the Annual Assessment MP for Capelin, this appeared to have little effect on GMRY.

The Hyperstable scenario is characterized by large declines in biomass during the first decade of the management period in both the interim MP and Annual Assessment MP (Figure 2). The mean biomass of Capelin and Vermilion Snapper declined to around 50% B^S_{MSY} and stabilized at this level (Figure 2, second row). Dome selectivity in Vermilion Snapper appeared to limit the decline in biomass, while the low productivity of POP reduced biomass persistently to very low levels (≪50% B^S_{MSY}). The pattern in yield was characterized by initially large increases that could not be sustained over time (Figure 3, second row). This results in higher median CVB and lower median GMRY than in the Base scenario for Vermilion Snapper and POP (Capelin had similar GMRY in the Hyperstable scenario). For POP, the Averaged Index MP generated ~10%–13% more catch annually than the other two MPs, based on median GMRY ratios.

In the Hyperdeplete scenario, catches were more precautious with reductions at the start of the start of the management period (Figure 3, third row). Differences in mean biomass and relative yield between the Base and Hyperdeplete scenarios for most of the management period were modest for Capelin and Vermilion Snapper, with mean biomass slightly higher than B^S_{MSY}. For these two species, the Annual Assessment MP did generate slightly more yield (2%–13% annually) compared to the two interim MPs (Figure 5, third row). On the other hand, the perception of POP was that of a depleted stocks with low yields prescribed to increase biomass to higher levels. Yield for POP was nearly identical, with 2%–3% difference, among the MPs.

In the Depleted scenario, the biomass of all three species increased to higher stock levels under all MPs (Figure 2, fourth row). Yields were reduced at the start of the management period and gradually increased as biomass increased (Figure 3, fourth row). Recovery was fastest for Capelin and slowest for POP. For POP, the mean biomass still had not reached B^S_{MSY} by the end of the management period, owing to its long generation time. Identical yield was achieved among the MPs based on median GMRY (Figure 5, fourth row).

Large windfalls in catch in the Lightly fished scenario brings the biomass Capelin and Vermilion Snapper to B^S_{MSY} (Figures 2 and 3, fifth row). For POP, the trend was more gradual, with the mean biomass still above B^S_{MSY} due to its long generation time. In all three life histories, both interim MPs (Averaged Index and Buffered Index MPs) brought the stock biomass down more quickly. This may be expected since the interim MPs were designed to respond more slowly than the index, although faster rebuilding rates was not observed with the interim MPs in the Depleted scenario. Relatively small differences in yield, that is up to 5% annually, were observed between the interim MPs and Annual Assessment MPs (Figure 5, fourth row).

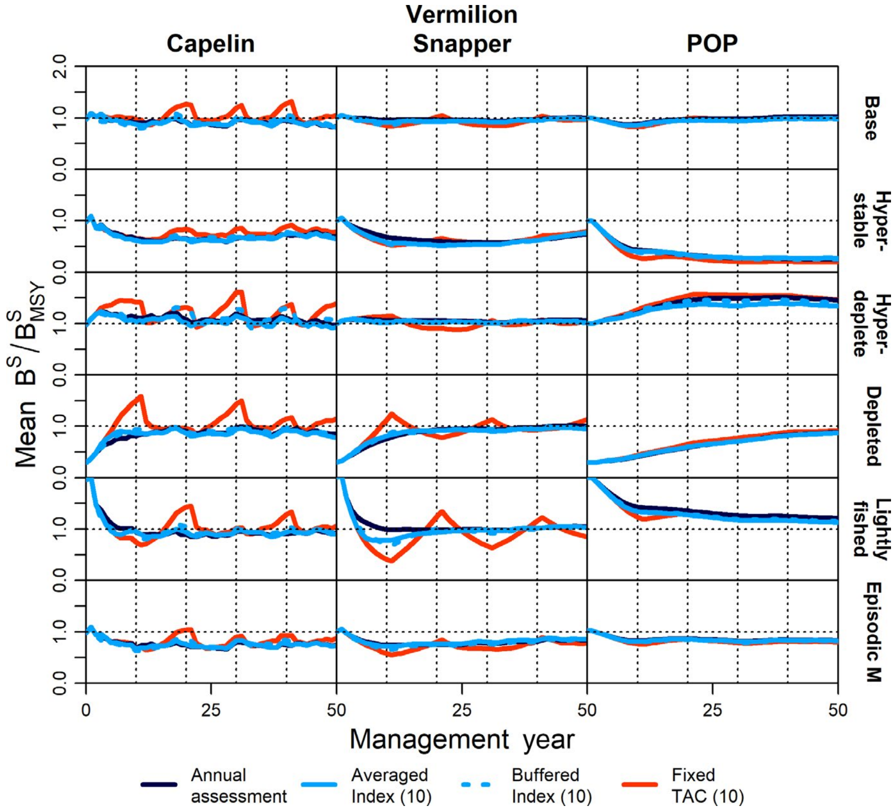

FIGURE 2 Annual mean B^S/B^S_{MSY} from 250 simulations for each species (columns) and scenario (rows). Coloured lines correspond to the four MPs. Dotted horizontal lines represent a value of 1. Dotted vertical lines indicate timing of the assessment of the Averaged Index, Buffered Index, and Fixed TAC MPs (not shown for the Annual assessment MP). Parentheses in the legend indicate the assessment interval. Means for MPs with 5-year assessment intervals are shown in Supplementary Material. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

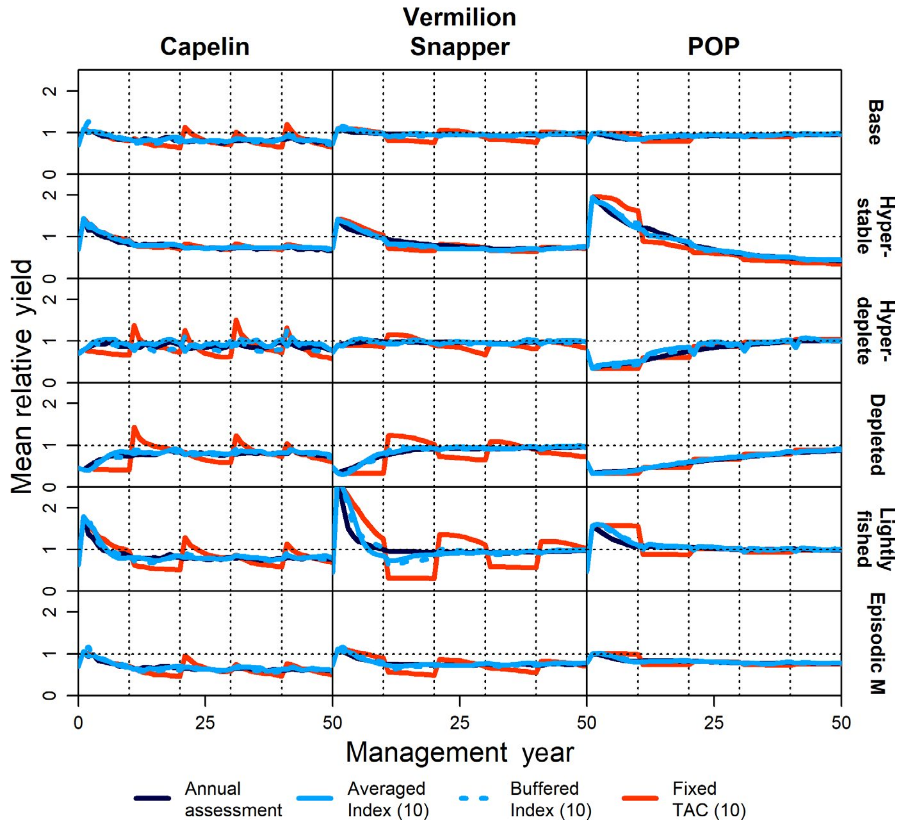

FIGURE 3 Annual mean of relative yield from 250 simulations for each species (columns) and scenario (rows). The relative yield is the ratio of the catch to MSY. Coloured lines correspond to the four MPs. Dotted horizontal lines represent a value of 1. Dotted vertical lines indicate timing of assessment of the Averaged Index, Buffered Index and Fixed TAC MPs (not shown for the Annual assessment MP). Parentheses in the legend indicate the assessment interval. Means for MPs with 5-year assessment intervals are in Supplementary Material. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

In the Episodic M scenario, the mortality events eventually decrease the mean biomass and mean relative yield, to values lower than those in the Base scenario for all three species (Figures 2, 3, sixth row). The historical B^S_{MSY} and MSY reference points used here do not consider increased mortality (and cannot be realized) in the management period, but are used to provide comparable

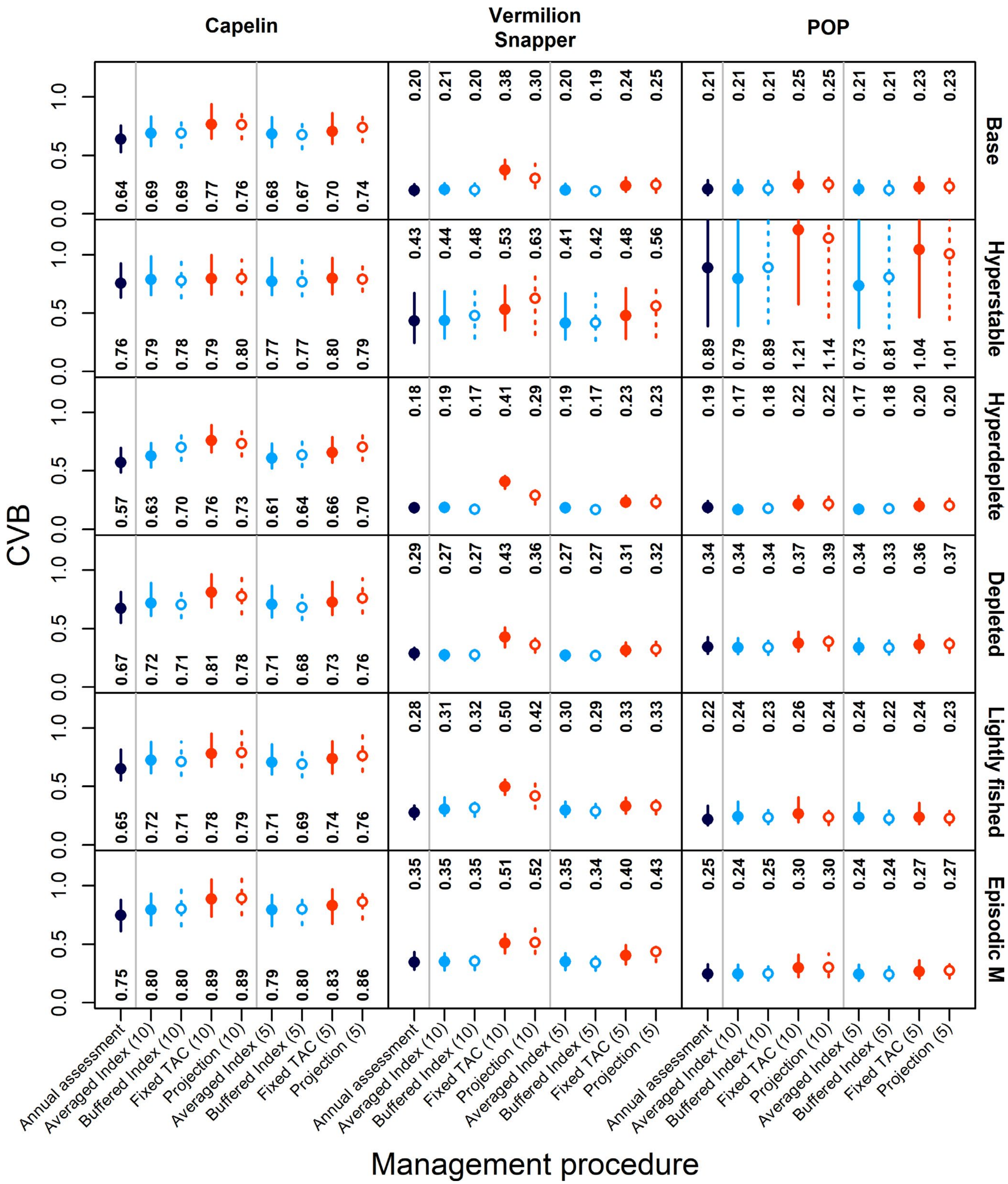

FIGURE 4 Dot-and-whisker plots of *CVB* (coefficient of variation in biomass) for each species (columns) and scenario (rows). For each MP, dots and numbers indicate the median from 250 simulations, and whiskers span the interquartile range. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

scaling of biomass and yield alongside the other scenarios. Compared to the Base scenario, more variability in biomass arises (Figure 4, sixth row) and lower yield is achieved (Figure 5, sixth row). The interim MPs and Annual Assessment MP both behave similarly in the Episodic M scenario with identical median GMRY (Figure 5).

3.2 | How well do interim MPs perform compared to the fixed TAC and projection MPs?

Compared to the interim MPs, the Fixed TAC MP produced larger oscillations and occasionally extreme values in mean biomass and mean relative yield for all species and scenarios (Figures 2 and 3, red lines). The oscillation periods coincided with the 10-year intervals between assessments for the Fixed TAC MP, and often generated more extreme values in mean biomass and yield for all three species compared to the interim MPs (Figures 2 and 3, second and third columns). The Fixed TAC MP also produced higher median CVB and lower median GMRY relative to both interim MPs (Figures 4 and 5). In many scenarios, the behaviour of biomass and yield Projection MP better approximated those of the interim MPs (Figures 6 and 7). Yields with the Projection MP often improved compared to those from the Fixed TAC MP, although the interim MPs generally produced the lowest median CVB and highest median GMRY (Figures 4 and 5).

In the Base scenario, the oscillations in mean biomass and mean yield were most notable for Vermilion Snapper followed by Capelin, and least notable for POP under the Fixed TAC MP, whereas mean biomass and yield trajectories were stable with the interim MPs and Projection MP (Figures 2 and 6). This is corroborated by the highest median CVB for the Fixed TAC MP compared to the other MPs for all three species (Figure 4, first row). The Fixed TAC MP produced the lowest yields. The largest reduction was in Vermilion Snapper where ratio of median GMRY was 82% between the Fixed TAC MP and interim MPs, with smaller reductions for Capelin and POP (Figure 5, first row).

Low biomass and low yield are achieved with the Fixed TAC MP in the Hyperstable scenario, also similar to levels observed for the interim MPs (Figures 2 and 3, second row). The most variation among MPs were seen in POP. With the Fixed TAC MP, mean yield was initially higher with the Fixed TAC MP (Figure 3), but resulted in much lower biomass later on and lower yield overall (30%–40% reductions based on median GMRY) compared to the interim MPs (Figure 5). The interim MPs still outperform the Projection MP in terms of median CVB and median GMRY. The differences in CVB and GMRY are smaller for Vermilion Snapper and trivial for Capelin (Figures 4 and 5).

In the Hyperdeplete scenario, mean biomass was often higher for POP with the Fixed TAC MP compared to the interim MPs (Figure 2, third row). For Capelin and Vermilion Snapper, the Fixed TAC MP generated mean biomass and mean yield fluctuations at values higher and lower than those of the interim MPs. The corresponding median GMRY ratio ranged from 73% (for Vermilion Snapper) to 92% (for POP) with the Fixed TAC MP relative to the two interim MPs (Figure 5). The Projection MP appeared to remove the large fluctuations in mean biomass and yield associated with the Fixed TAC MP, resulting in higher GMRY for the former (Figure 5). The Projection MP was able to generate up to 18% higher yield than the interim MPs for Capelin, and similar catches in Vermilion Snapper and POP.

The relative performance of the MPs in the Depleted scenario was similar to that in the Hyperdeplete scenario, due to similar perceptions of the stock status from the assessment model (whether true or not). All MPs recovered the biomass to higher stock levels (Figures 2 and 6, fourth row). Median yield initially stayed low under the Fixed TAC MP until the next assessment and was followed by either oscillations for Capelin and Vermilion Snapper or stepwise increases for POP (Figure 3; fourth row). Under the interim MPs and Projection MP, the yield gradually increased in the first decade and subsequently stabilized for all three species (Figures 3 and 7; fourth row). The interim MPs produced slightly more yield than the Fixed TAC MP during the management period for Capelin and POP, while a substantial 30% increase was seen for Vermilion Snapper (Figure 5). By accounting for increases in biomass between assessments, the Projection MP produced similar yield (95%–105%) to the interim MPs (Figure 5).

For the Lightly fished scenario, large increases in yield were initially prescribed by all MPs at the beginning of the management period (Figures 3 and 4; fifth row). The Projection MP and interim MPs decrease yield within the first decade as the stock approaches B^S_{MSY}. High yields with the Fixed TAC leads to alternating periods of high and low biomass and yield later in the management period, which leads to poorer yields compared to the interim MPs and Projection MP (Figures 4 and 5, fifth row). The relative performance of the MPs with regard to CVB and GMRY are similar to that in the previous two scenarios (Figures 4 and 5, fifth row).

The Episodic M scenario generates periods of higher and lower biomass and yield in the Fixed TAC MP compared to the interim MPs, similar to previous scenario (Figures 2 and 3, sixth row). The Projection MP, which does not account for higher mortality events between assessments, produced lower mean biomass in Capelin and Vermilion Snapper over time compared to the interim MPs (Figure 6, sixth row). Yields are lower overall in this scenario, with interim MPs among those producing the highest annual yield (Figure 5, sixth row). The Projection MP and Fixed TAC MP produced 90%–100% and 79%–97%, respectively, of the yield produced by the interim MP. Median CVB is lowest with the interim MPs for all three species (Figure 4, sixth row), suggesting that they adjust better to changes in biomass while realizing the same catch as the other two MPs.

3.3 | Assessment frequency

When the assessment frequency was increased from 10-year to 5-year intervals, the performance of the interim MPs and the Projection MP did not appreciably change in terms of mean trajectories, CVB and GMRY (Supplementary Material E; Figures 4 and 5). On the other hand, for the Fixed TAC MP, the trajectories of biomass and yield more closely approximated those of all other MPs considered (Supplementary Material E). With an increased assessment frequency, the extremes in the Fixed TAC trajectories were greatly reduced, with the trajectories more closely matching those of the other MPs (Supplementary Material E). For the Fixed TAC MP, the

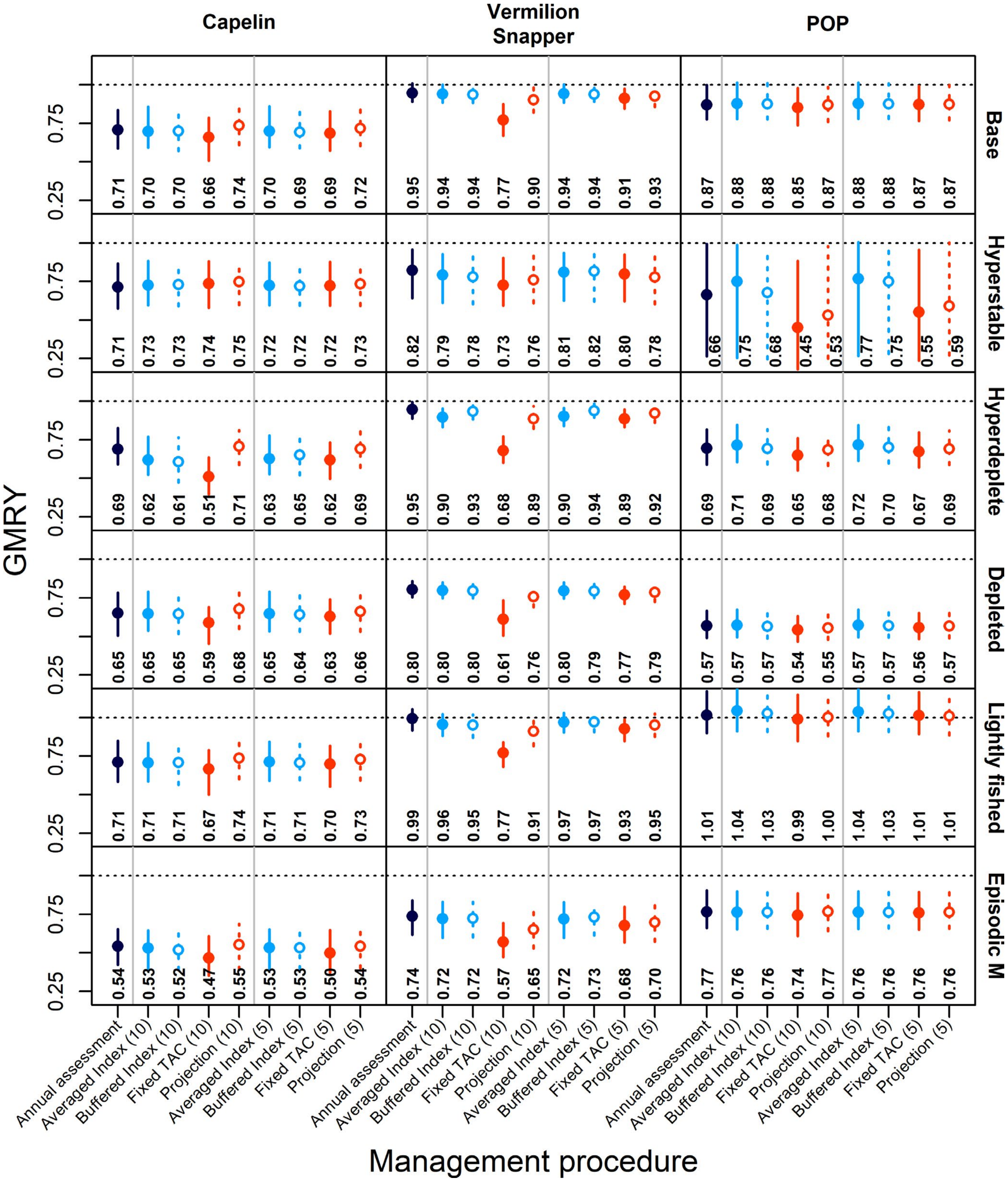

FIGURE 5 Dot-and-whisker plots of *GMRY* (geometric mean of relative yield) for each species (columns) and scenario (rows). For each MP, dots and numbers indicate the median from 250 simulations, and whiskers span the interquartile range. Dotted, horizontal lines indicate a value of 1. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

median CVB also decreased and the median GMRY increased with the shorter assessment interval (Figures 4 and 5). Larger reductions in median CVB corresponded to larger increases in median GMRY. This was most apparent in the median GMRY, which increased to 95%–100% of that of the interim MPs, of Vermilion Snapper (Figure 5, second column).

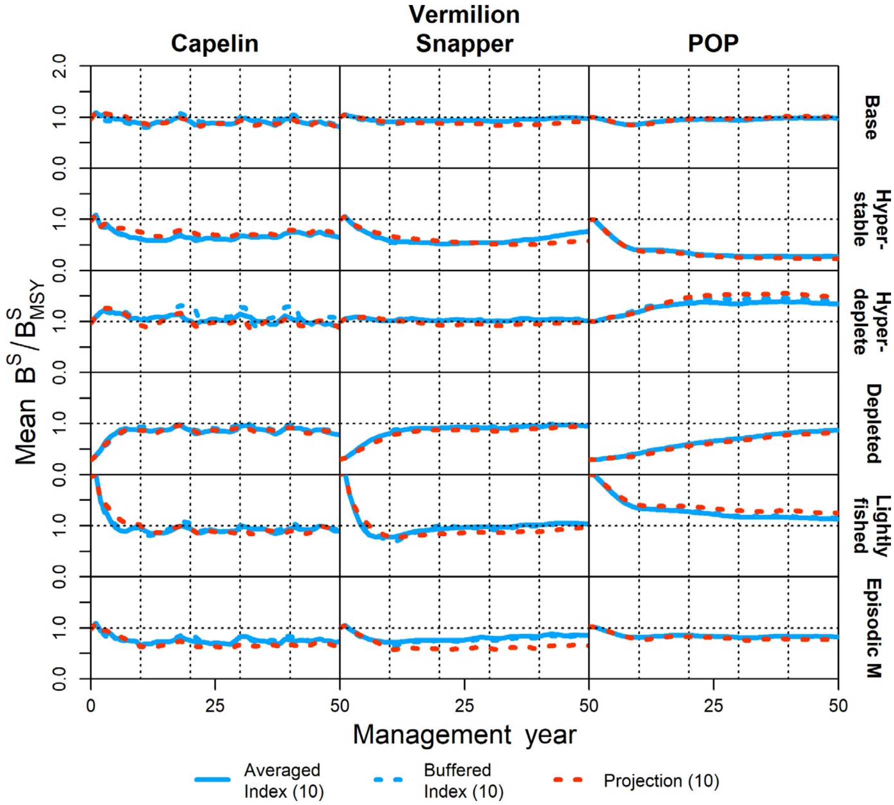

FIGURE 6 Annual mean B^S/B^S_{MSY} from 250 simulations for each species (columns) and scenario (rows) comparing the Averaged Index, Buffered Index and Projection MPs. Trajectories for the Averaged Index overlap that for the Buffered Index. Means for MPs with 5-year assessment intervals are shown in Supplementary Material. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

In this study, we presented interim MPs for updating catch advice between stock assessments and highlighted their performance relative to annual assessments, fixed TACs and projections in three life-history archetypes and six OM scenarios. The ability to update the catch advice more frequently was important in many scenarios. For example, under Lightly fished scenario, fewer extreme values of mean biomass and yield were observed when either: (1) the assessment frequency with the Fixed TAC MP was reduced; or (2) an interim MP or Projection MP was used instead of the Fixed TAC MP. Under the Depleted scenario, foregone yield occurred when the population recovered during periods of low TAC under the Fixed TAC MP with 10-year assessment intervals. Interim MPs are more cost-effective means of providing robust TAC advice than either annual assessments or more frequent assessments with fixed TACs, due to the lower required assessment frequency. Finally, interim MPs also performed well in circumstances that projections do not foresee, as demonstrated by the Episodic M scenario. Die-offs are reflected in the index which would trigger an immediate reduction in TAC in the interim MP. Immediate responses to changes in conditions can also lend credibility to management to address stakeholder concerns regarding the stock.

The Hyperstable and Hyperdeplete scenarios evaluated situations when no proportional index exists. No major differences in the mean biomass at the end of the management period were observed among the MPs, which indicates that the quality of the index is still important for the performance of the assessment model and management procedure. In a situation where it is recognized that no proportional index exists, non-index-based approaches could be evaluated for providing management advice (Geromont & Butterworth, 2015; Klaer, Wayte, & Fay, 2012; Thorson & Cope, 2015). Closed-loop simulation comparison of such methods with assessment-based MPs and other index-based MPs would quantify the value of developing a better survey for the stock.

From this study, we recommend routine evaluation of the assessment interval when testing MPs for assessed stocks (Hutniczak et al., 2019; Wiedenmann et al., 2017). While Zimmerman and Enberg (2017) have reported only minor loss in precision in the performance of stock assessment models with less frequent assessments, they only evaluated annual versus biennial assessments and did not evaluate situations where the assumptions of the estimation model were violated, such as the proportionality of the index to the underlying population. Their study also did not account for feedback between the system dynamics and management advice using closed-loop simulation.

4.1 | Interim MP implementation

Interim MPs could be tuned to meet specific management goals. For example, we tested the interim MPs here with a simple MSY-based control rule ($F_{target} = F_{MSY}$), but if management desires to avoid overfishing (Restrepo & Powers, 1999), it would be prudent to choose a more precautionary F_{target} that is less than F_{MSY}. A ramped harvest control rule, such as the 40–10 control rule, could be implemented

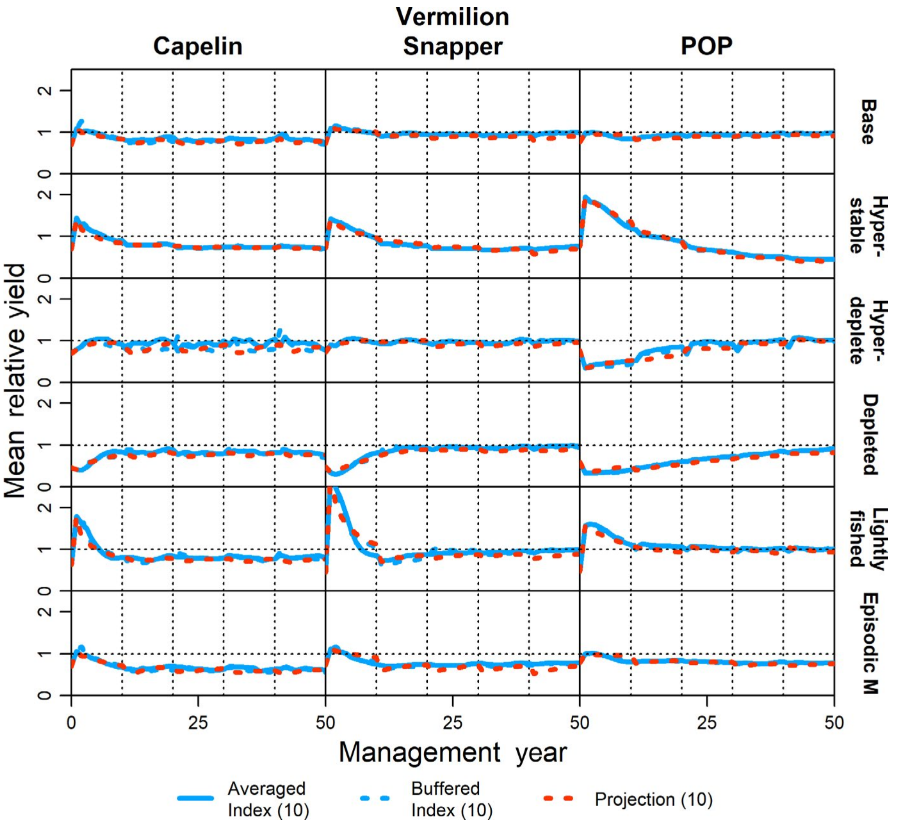

FIGURE 7 Annual mean relative yield from 250 simulations for each species (columns) and scenario (rows) comparing the Averaged Index, Buffered Index and Projection MPs. Trajectories for the Averaged Index overlap that for the Buffered Index. Means for MPs with 5-year assessment intervals are shown in Supplementary Material. The coloured figure is available in the online version only [Colour figure can be viewed at wileyonlinelibrary.com]

such that F_{target} is linearly reduced from its maximum value if the reference biomass, for example spawning biomass, is below the upper reference point (Deroba & Bence, 2008). In an interim MP with such a harvest control rule, an increasing index could be used to update the biomass estimate and increase F_{target} towards the upper threshold reference point.

Additionally, reference points based on MSY can be imprecise, largely due to uncertainty in the steepness of the stock–recruit relationship (Forrest, Holt, & Kronlund, 2018; Haltuch, Punt, & Dorn, 2009). Alternative reference points based on quantities such as the spawning potential ratio (SPR; Clark, 1991, 2002), or average estimated historical biomass (Forrest et al., 2018) may be substituted if they can be shown to improve performance. Benchmark performance metrics could be calculated to identify whether the configuration and implementation of the interim MPs meet pre-specified management thresholds.

Many management systems require rebuilding plans in order to increase depleted population levels within a specified timeframe (e.g. DFO, 2009; PFMC, 2016). Assuming a fixed fishing mortality rate, recovery time will be driven by life history (Carruthers & Agnew, 2016). For example, we found that while fishing at F_{MSY}, the mean spawning biomass of POP in the Depleted scenario still did not reach B^{S}_{MSY} during the 50-year management period, due to the relatively long generation time (Table 2). Rebuilding time can be decreased by decreasing F_{target} in the interim MPs, which will necessitate further decreases in short-term yield for faster recovery. Specific performance metrics, such as the probability of rebuilding within a certain timeframe, can be developed in order to evaluate potential F_{target} values and the trade-off between rebuilding time and short-term yield (Wetzel & Punt, 2016).

There are differences in how perceived uncertainty is addressed in deriving the catch advice between our Buffered Index and Averaged Index MPs. The moving average in the Averaged Index MP is intended to reduce annual changes in the catch advice despite sometimes large inter-annual variability in the index. In contrast, annual changes in the TAC from the Buffered Index MP were primarily determined by the fit of the assessment to the simulated data, that is, when the assessment fit the data well, the catch advice predominantly followed the change in the index. In this study, we tuned the Averaged Index and Buffered Index MPs to allow for moderate changes in the catch advice. Although both performed similarly in this study, there is no straightforward way to tune the two interim MPs such that they handle uncertainty equivalently. Empirical testing via simulation could be used to evaluate outcomes under alternative tuning options, for example, length of moving average and magnitude of the risk buffer for the Averaged Index and Buffered Index MPs, respectively. Catches would more closely track variability in surveyed abundance with shorter moving averages, and lower risk buffers, respectively.

Data availability can influence the success of an assessment-based MP. Here, we assumed that for an assessment, data were available from the current year (end of season), and assessment and TAC advice were generated for the next year. Time lags between data availability and assessment can lead to an improper match between the information from an assessment and conditions at the time of implementation of the catch advice (Hutniczak et al., 2019; Kell et al., 2005). This can be important for short-lived stocks or for fisheries that target young cohorts not accounted for from the most recent assessment. Further evaluation of the interim MPs will need to account for the time lags in the management system. Additionally, greater efficiencies in personnel time may be possible if there are systematic analytical and reporting mechanisms for survey data (Anderson, Keppel, & Edwards, 2019) for the interim MPs as part of a strategy to streamline assessment processes.

The interim MPs presented here are conditional on the state of knowledge assumed in the most recent assessment. In management settings such as the Federal fisheries in the United States, there are often two types of stock assessments: benchmark and update assessments. The benchmark assessment considers all available information and potentially revises the structure and assumptions of the assessment model (SEDAR, 2018). Update assessments, on the other hand, use the same structural assessment model as the benchmark, but can add any new time-series data produced since the last benchmark assessment (Cass-Calay et al., 2015). This study did not consider cases in which a benchmark assessment significantly revises the structure and information from the previous assessment. New assessments are occasionally required in cases where new life-history information becomes available—for example when a new growth study informs changes in the asymptotic length or size of maturity, or systemic changes in the fishery have occurred with a change in sizes of vulnerability or retention due to management regulations or market demands. Alternatively, changes in environmental conditions may require revision of reference points to recognize changes in stock productivity. These scenarios all affect the appropriate fishing mortality rate, and new assessments may be needed in response to these changes. Sensitivity explorations can evaluate how misspecification of assessment models affects performance of interim MPs.

For the interim MPs, we also assumed that the survey vulnerability matches that of the fishery. This occurs in cases where fishery catch-per-unit-effort is used to index the population or if the survey uses the same gear as the fishery. Future case-studies can evaluate how interim MPs perform if survey and fishery vulnerability are substantially different.

4.2 | Strategic management

The development and application of quantitative stock assessments and their subsequent updating to produce catch advice over time require considerable resources which are not available for all stocks (Newman, Berkson, & Suatoni, 2015). This study demonstrated the strategic advantages of using an interim MP over Annual Assessment and Fixed TAC MPs in the assessment and management of exploited stocks. First, our interim MPs performed similarly to an Annual Assessment MP. A reduction of the assessment frequency from an annual interval to as much as a 10-year interval gave similar performance, in terms of the stock dynamics and achieved yield. This would substantially reduce the scientific capacity needed to support management. It is also especially important for rebuilding stocks, for which the TAC advice can quickly become outdated as the population size increases.

Second, if the assessment interval cannot be decreased, then it would be preferable to adopt an interim MP rather than simply fixing the TAC. Performance of the Fixed TAC MP was improved by reducing the assessment interval from 10 to 5 years. As more time passes between assessments, the catch advice from the Fixed TAC became further detached from current biomass levels. In both cases, an older assessment that would be perceived as outdated under a fixed TAC management approach remains relevant in an interim approach so long as major departures from the assumptions in the assessment have not occurred.

Third, the interim MP approach can alleviate the time and resources needed to produce assessments as frequently, and the time can be focused on assessing other managed stocks. For example, despite periodic stock assessments for most stocks in the United States, the number of updated assessments tends to be low relative to the number of managed stocks. Reducing the frequency of stock assessment by using the interim approach could allow additional resources to focus on the approximately 70% of U.S. federal fisheries that are managed by data-limited approaches (Neubauer, Thorson, Melnychuk, Methot, & Blackhart, 2018; Newman et al., 2015). Similar benefits could exist for other regions around the world where frequent stock assessments are costly and time-consuming.

Finally, stakeholders often have more confidence in MPs that respond to signals on time scales comparable to what they witness while fishing or diving. Whereas full assessments can be two or three years out of date by the time regulations are implemented, the interim MPs described here can be applied immediately after the survey data are processed. Accordingly, managers can quickly adjust catches in response to unexpected pulses in recruitment or mortality. Stakeholders are more likely to gain more trust in the process if management actions respond appropriately to their real-time observations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this manuscript.

DATA AVAILABILITY STATEMENT

The R code that supports this study is available at: https://doi.org/10.5281/zenodo.3601687

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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