Supplementary Materials for:

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

Quang C. Huynh[1], Adrian R. Hordyk[1], Robyn Forrest[2], Clay E. Porch[3], Sean C. Anderson[2], Thomas R. Carruthers[1]

[1] Institute for the Oceans and Fisheries, The University of British Columbia, 2202 Main Mall, Vancouver BC V6T 1Z4

[2] Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Rd, Nanaimo BC V9T 6N7

[3] National Marine Fisheries Service, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, FL, 33149

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A. Illustration of the interim management procedure

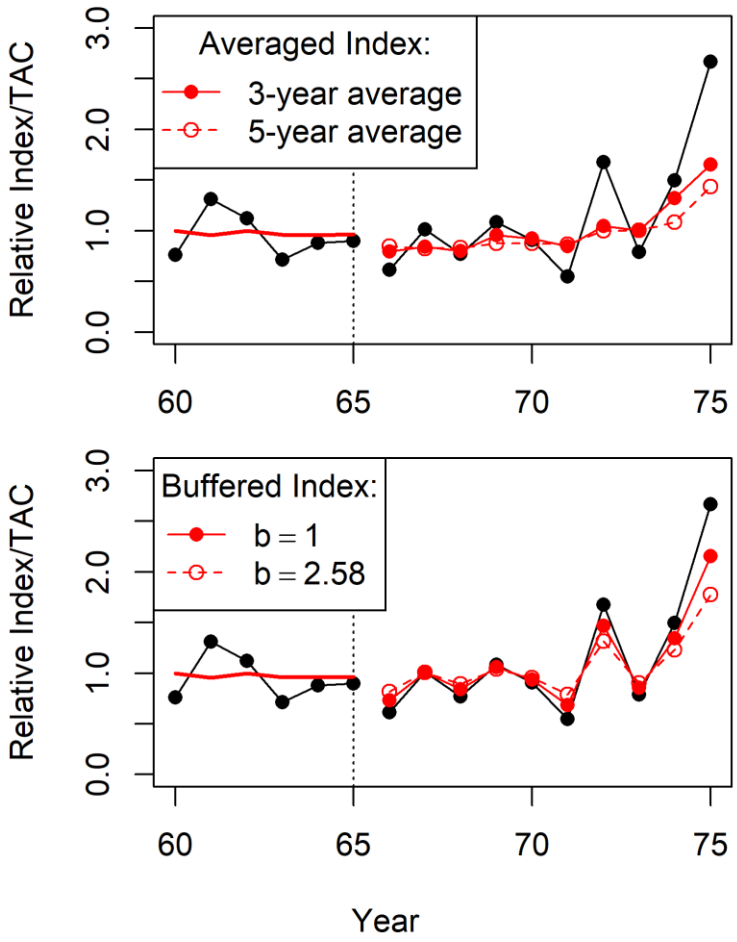

Figure A.1. Demonstration of the interim MPs. Black points and lines indicate index values from a survey. The red lines prior to year 65 are predicted values from an assessment performed in year 65 and a TAC subsequently proposed. The TAC and index are scaled to equal to one in Year 65. After year 65, either future observed index values (black) or moving averages of the index can be used to update the TAC (connected red circles). Top: In the Averaged Index MP, the relative change in TAC is proportional to either a 3-year or 5-year moving average of the index. Bottom: In the Buffered Index MP, the magnitude of the proposed change in TAC is first calculated to be proportional to the observed index but reduced by the buffer in Equation 7 of the main text. Either MP can be tuned so that the relative change in TAC is smaller than that in the index by different magnitudes based on one's risk tolerance. For example, in Year 75, the observed index has tripled since Year 65, but the change in catch advice between those years is smaller than that in the index.

B. Description of the operating models

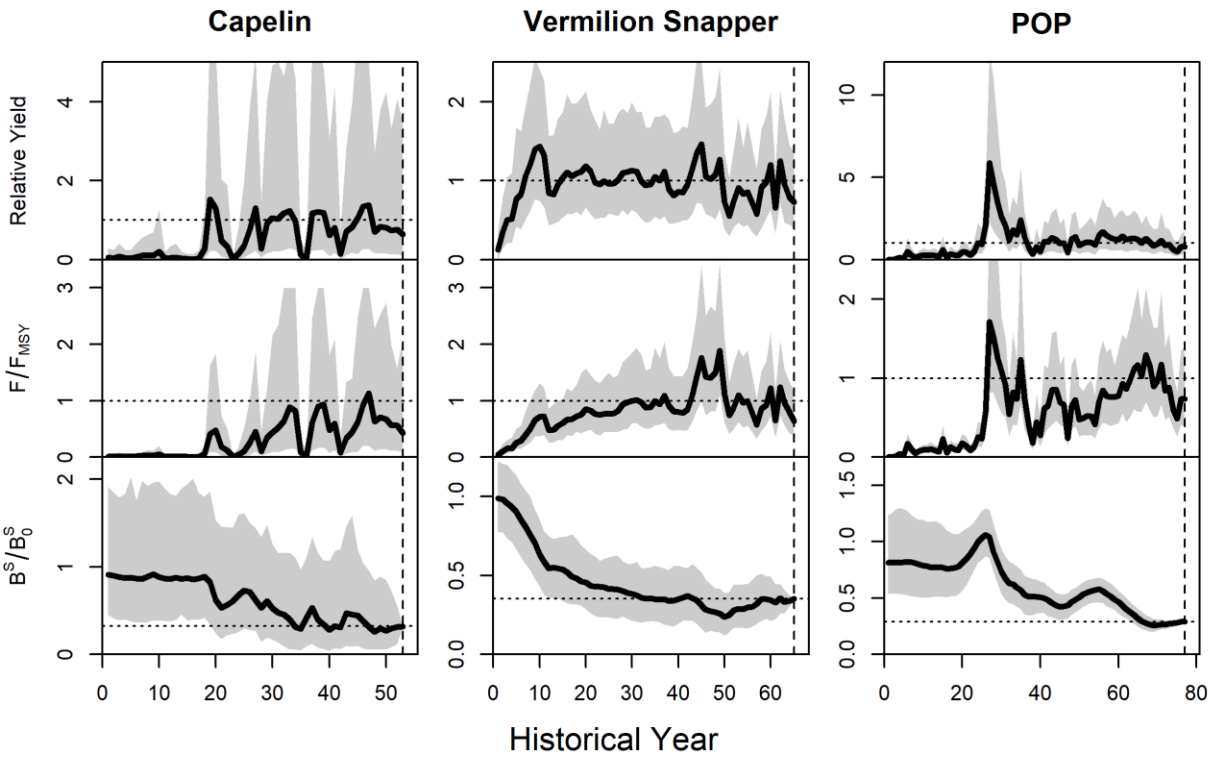

Figure B.1. Historical fishing and stock dynamics (relative yield, relative fishing mortality F/F_{MSY}, and spawning depletion B/B_0) of the three operating models. The relative yield is the ratio of the catch to the reference yield, defined in the Methods section of the main text. Black lines indicate the median trajectory and grey shades cover the 95% range of the respective values. The dashed, vertical line indicates the end of the historical period and the dotted horizontal line indicates B^S_{MSY}/B^S_0 in the bottom row and a value of 1 for all other rows.

C. Description of the Statistical Catch-at-Age (SCA) assessment model

The population abundance $N_{y,a}$ of age a at the beginning of year y is

$$N_{y,a} =$$

$$\begin{cases} R_y & a = 1 \\ N_{y-1,a-1}\left(1 - v_{a-1}U_{y-1}\right)\exp(-M_{a-1}) & a = 2,..,A-1 \\ N_{y-1,A-1}\left(1 - v_{A-1}U_{y-1}\right)\exp(-M_{A-1}) + N_{y-1,A}\left(1 - v_A U_{y-1}\right)\exp(-M_A) & a = A \end{cases}$$

, (C.1)

where R_y is the recruitment of age 1, v_a is the vulnerability at age, U_y is the harvest rate, and M_a is the instantaneous natural mortality rate, and A is the maximum age (as a plus-group).

The vulnerability, assuming a logistic function, is

$$v_a = \left\{1 + \exp\left[-\ln(19) \times \left(\frac{a - a_{50}}{a_{95} - a_{50}}\right)\right]\right\}^{-1}, \quad \text{(C.2)}$$

where a_{50} and a_{95} are the ages of 50% and 95% vulnerability, respectively.

The vulnerability, assuming a double-Gaussian function, is

$$v_a = \begin{cases} \exp\left[-0.5\left(\frac{a-\mu}{\omega^{asc}}\right)^2\right] & , \quad a \le \mu \\ \exp\left[-0.5\left(\frac{a-\mu}{\omega^{des}}\right)^2\right] & , \quad a > \mu \end{cases}, \quad \text{(C.3)}$$

where μ is the age of full vulnerability, and ω^{asc} and ω^{des} are parameters that control the width of the ascending and descending limbs (referenced by superscript asc and des, respectively) of the vulnerability function.

From a time series of observed catch C_y (in weight), the harvest rate U_y is

$$U_y = C_y / B_y^V, \quad \text{(C.4)}$$

with the vulnerable biomass B_y^V calculated as

$$B_y^V = \sum_{a=1}^{A} v_a w_a N_{y,a} e^{-0.5M_a}, \quad \text{(C.5)}$$

where w_a is the weight-at-age schedule. Pope's approximation is used so that the harvest rate is conditional on the catch taken at the midpoint of the year.

With a Beverton-Holt stock-recruit function, the recruitment (at age-1) in year y is

$$R_y = \frac{4hR_0 B_{y-1}^S}{(1-h)B_0^S + (5h-1)B_{y-1}^S} \exp(\delta_y - 0.5\tau^2), \tag{C.6}$$

where R_0 is the unfished recruitment, h is steepness, δ_y are normally-distributed deviates with standard deviation τ, and B_0^S is the unfished spawning biomass derived from R_0 and other life history parameters. The spawning biomass B_y^S is calculated as

$$B_y^S = \sum_{a=1}^{A} m_a w_a N_{y,a}, \tag{C.7}$$

where m_a is the maturity-at-age schedule.

The model estimates R_0, vulnerability parameters, and recruitment deviates, with steepness fixed to the assumed value from the observation model.

The log-likelihood L^I of the observed index I_y is

$$L^I = -n^I \ln \hat{\sigma} - \frac{1}{2\hat{\sigma}^2} \sum_y \left(\ln\left[I_y\right] - \ln\left[\hat{q}\, \hat{B}_y^V\right]\right)^2, \tag{C.8}$$

where n^I is the number of years with index values, $\hat{q}$ is an estimated coefficient that scales the vulnerable biomass to index values (with the circumflex [^] denoting an estimate) and $\hat{\sigma}$ is the estimated standard deviation of the index.

The log-likelihood L^X of the catch-at-age matrix $X_{y,a}$ is

$$L^X = \sum_y \sum_a O_{y,a} \ln[\hat{p}_{y,a}], \tag{C.9}$$

where $O_{y,a}$ is the assumed sample size of the age composition, and $\hat{p}_{y,a}$ is the estimated catch-at-age composition, calculated as

$$\hat{p}_{y,a} = \frac{\hat{v}_a \hat{U}_y \hat{N}_{y,a} \exp(-0.5M_a)}{\sum_a \hat{v}_a \hat{U}_y \hat{N}_{y,a} \exp(-0.5M_a)}. \tag{C.10}$$

The log-likelihood L^{δ} of annual recruitment deviates $\hat{\delta}_y$, estimated as penalized parameters, is

$$L^{\delta} = -n^{\delta} \ln \tau - \frac{1}{2\tau^2} \sum_y \hat{\delta}_y{}^2. \tag{C.11}$$

where n^{δ} is the number of estimated recruitment deviates and τ is the standard deviation of recruitment deviates.

The total log-likelihood Λ of the model is

$$\Lambda = L^I + L^X + L^{\delta}. \tag{C.12}$$

From the fitted model, estimates of terminal-year vulnerable biomass and MSY reference points can be derived for the management procedures.

D. Evaluation on the number of simulations

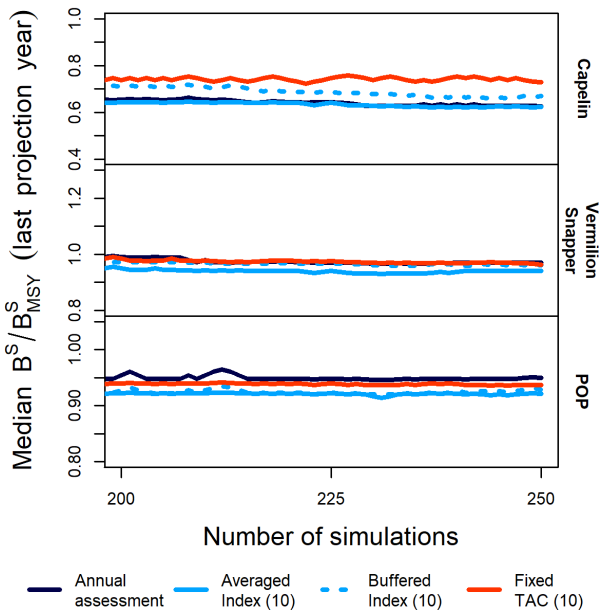

Figure D.1. The median B^S_{MSY}/B^S_0 in the terminal year of the projection period for annual assessment MP and other MPs with a 10-year assessment interval. Stability in the median is used to evaluate whether enough simulations have been run.

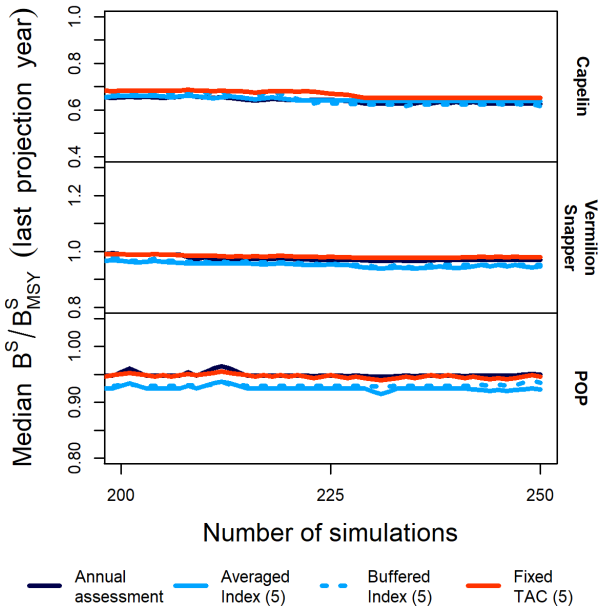

Figure D.2. The median B^S_{MSY}/B^S_0 in the terminal year of the projection period for annual assessment MP and other MPs with a 5-year assessment interval. Stability in the median is used to evaluate whether enough simulations have been run.

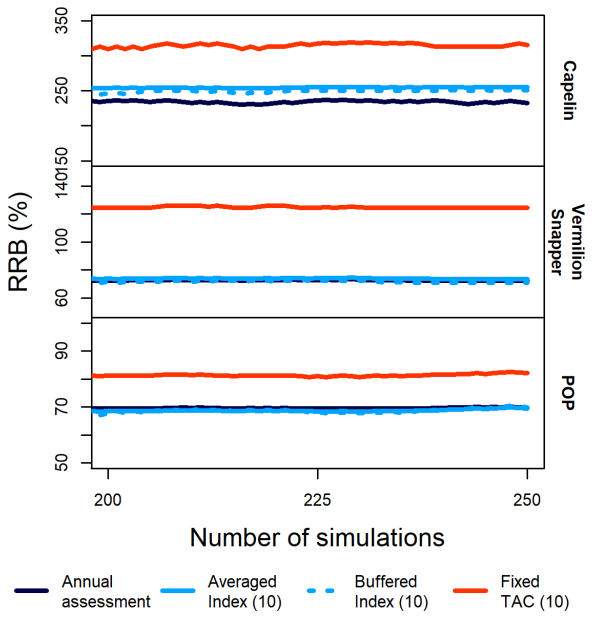

Figure D.3. The median *RRB* (relative range in biomass) during the projection period for annual assessment MP and other MPs with a 10-year assessment interval. Stability in the median is used to evaluate whether enough simulations have been run.

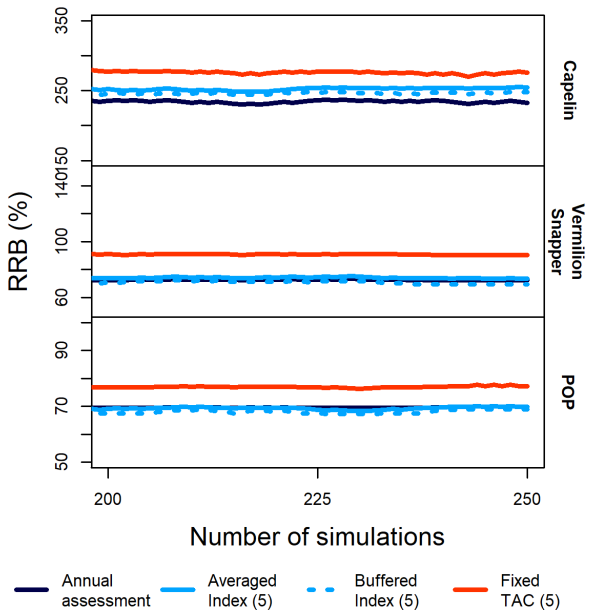

Figure D.4. The median *RRB* (relative range in biomass) during the projection period for annual assessment MP and other MPs with a 5-year assessment interval.

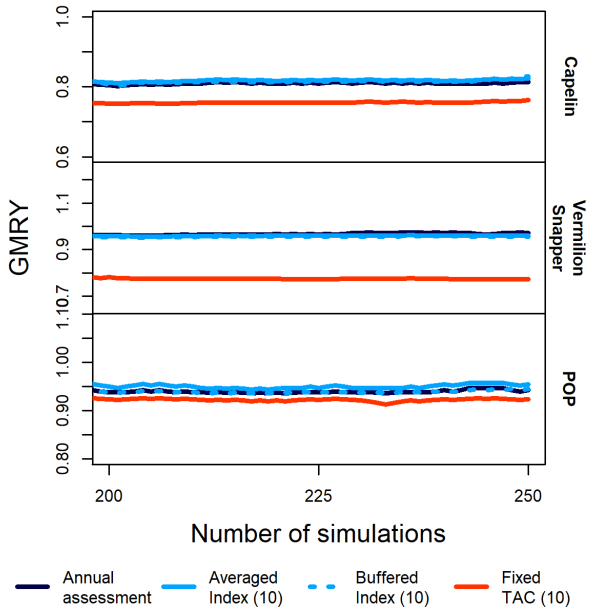

Figure D.5. The median $GMRY$ (geometric mean of the relative yield) during the projection period for annual assessment MP and other MPs with a 10-year assessment interval. Stability in the median is used to evaluate whether enough simulations have been run.

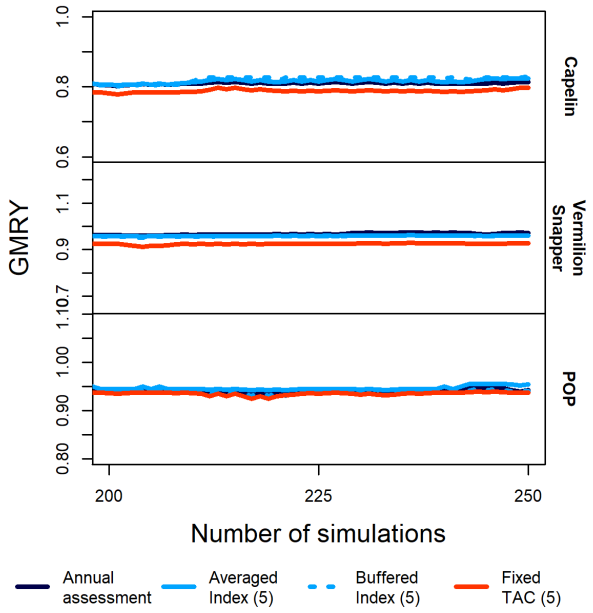

Figure D.6. The median $GMRY$ (geometric mean of the relative yield) during the projection period for annual assessment MP and other MPs with a 10-year assessment interval.

E. Interim MPs and Fixed TAC MPs with 5-year assessment intervals

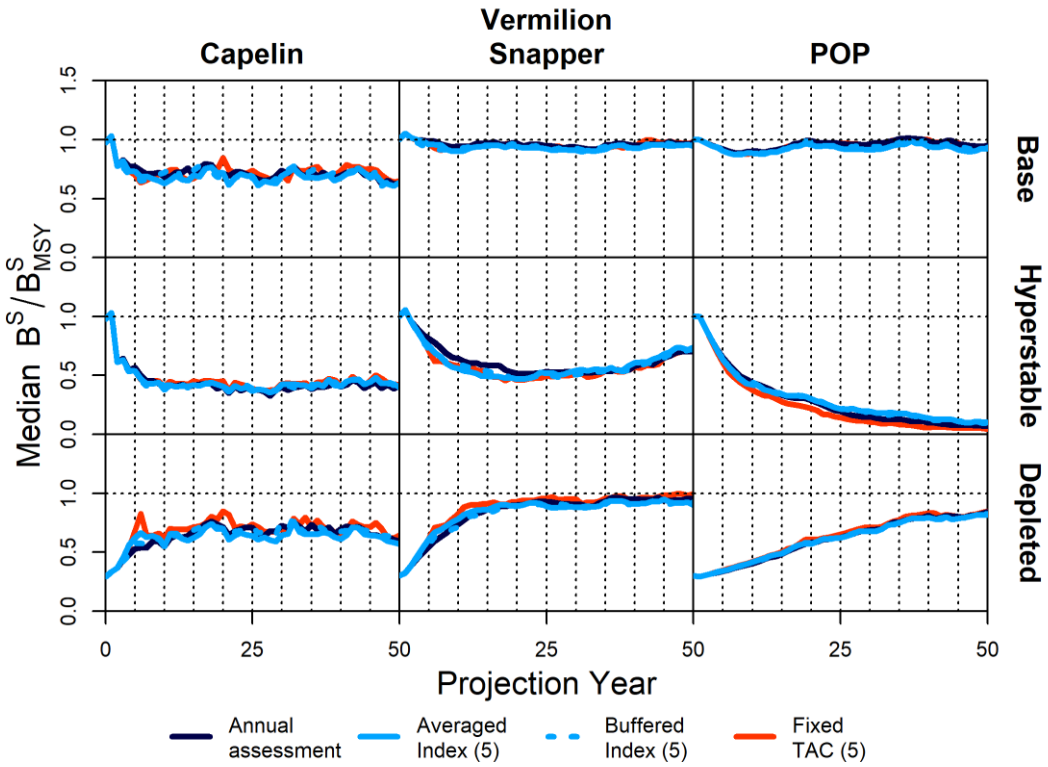

Figure E.1. Annual median B^S/B^S_{MSY} from 250 simulations for each species (columns) and scenario (rows). Colored lines correspond to the four MPs. Dotted horizontal lines represent a value of 1. Dotted vertical lines indicate timing of the assessment of the Averaged Index, Buffered Index, and Fixed TAC MPs (not shown for Annual assessments). Parentheses in the legend indicate the assessment interval.

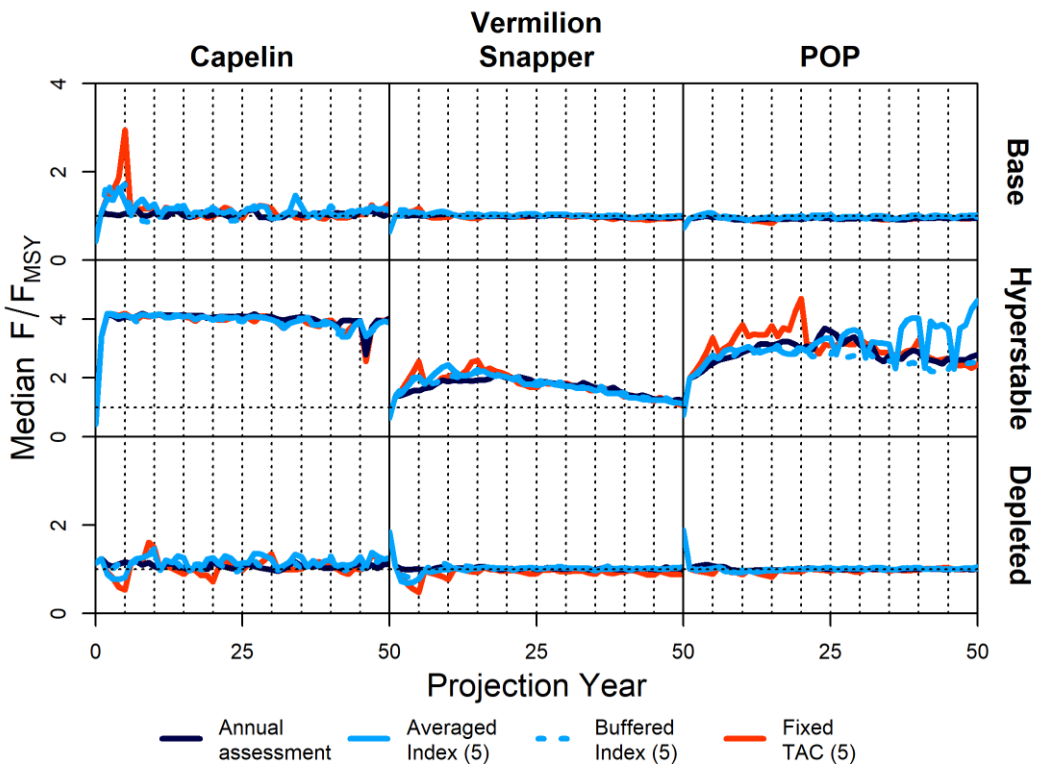

Figure E.2. Annual median F/F_{MSY} from 250 simulations for each species (columns) and scenario (rows). Colored lines correspond to the four MPs. Dotted horizontal lines represent a value of 1. Dotted vertical lines indicate timing of assessment of the Averaged Index, Buffered Index, and Fixed TAC MPs (not shown for Annual assessments). Parentheses in the legend indicate the assessment interval.

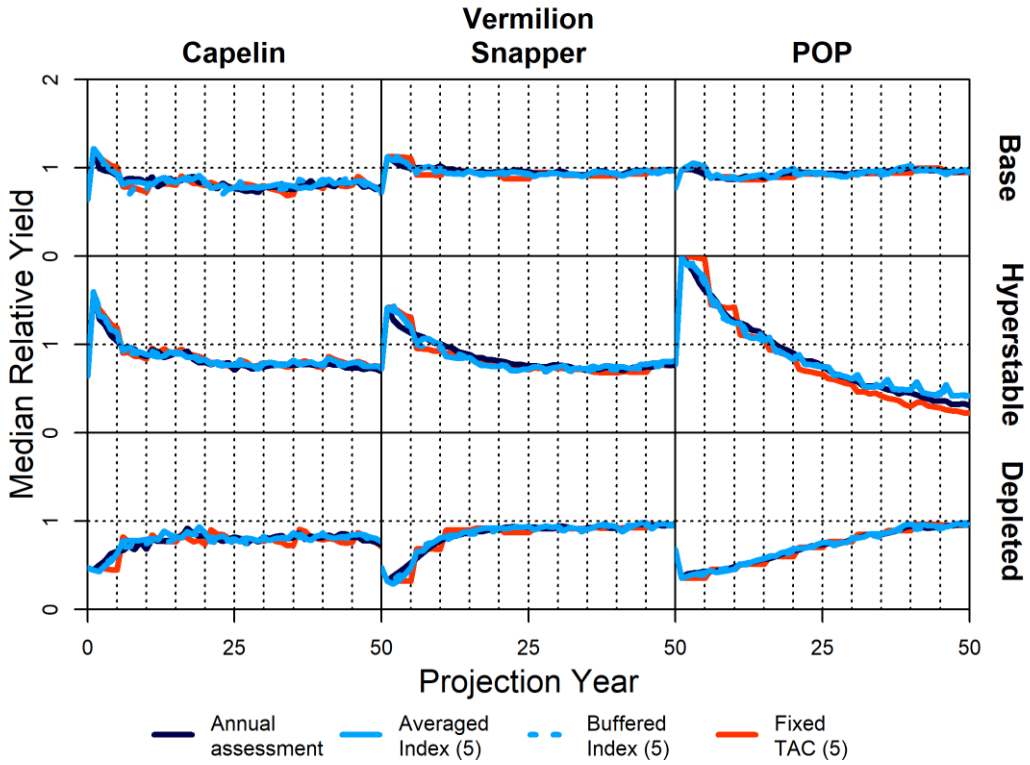

Figure E.3. Annual medians of relative yield from 250 simulations for each species (columns) and scenario (rows). The relative yield is the ratio of the catch to the reference yield. Colored lines correspond to the four MPs. Dotted horizontal lines represent a value of 1. Dotted vertical lines indicate timing of assessment of the Averaged Index, Buffered Index, and Fixed TAC MPs (not shown for Annual assessments). Parentheses in the legend indicate the assessment interval.