Mathematical descriptions for CMPs

Contents

BR CMPs (UTC)

Authors: Butterworth and Rademeyer
Documents: SCRS/2021/152

The CMP is empirical, based on inputs related to abundance indices which are first standardised for magnitude, then aggregated by way of a weighted average of all indices available for the East and the West areas, and finally smoothed over years to reduce observation error variability effects. TACs are then set based on the concept of taking a fixed proportion of the abundance present, as indicated by these aggregated and smoothed abundance indices. The details are set out below.

Aggregate abundance indices

An aggregate abundance index is developed for each of the East and the West areas by first standardising each index available for that area to an average value of 1 over the past years for which the index appeared reasonably stable[1], and then taking a weighted average of the results for each index, where the weight is inversely proportional to the variance of the residuals used to generate future values of that index in the future modified to take into account the loss of information content as a result of autocorrelation. The mathematical details are as follows.

$J_y^{E/W}$ is an average index over *n* series (*n*=5 for the East area and *n*=5 for the West area) [2]:

$$J_y^{E/W} = \frac{\sum_i^n w_i \times I_y^{i*}}{\sum_i^n w_i} \tag{A1}$$

where

$w_i = \frac{1}{(\sigma^i)^2}$ for the west and i.e. inverse effective variance weighting)

$w_i = \frac{1}{\sqrt{\sigma^i}}$ for the east (i.e. inverse effective variance to the power ¼ weighting).

and where the standardised index for each index series (i) is:

$$I_y^{i*} = {I_y^i}\Big/{Average\ of\ historical\ I_y^i}$$

(A2)

σ^i is computed as

$$\sigma^i = \frac{SD^i}{1 - AC^i}$$

where SD^i is the standard deviation of the residuals in log space and AC^i is their autocorrelation, averaged over the OMs, as used for generating future pseudo-data. Table 1 lists these values for σ^i.

2017 is used for the "average of historical I_y^i".

The actual index used in the CMPs, $J_{av,y}^{E/W}$, is the average over the last three years for which data would be available at the time the MP would be applied, hence:

$$J_{av,y}^{E/W} = \frac{1}{3}\left(J_y^{E/W} + J_{y-1}^{E/W} + J_{y-2}^{E/W}\right)$$

(A3)

[1] These years are for the Eastern indices: 2014-2017 for FR_AER_SUV2, 2012-2016 for MED_LAR_SUV, 2015-2018 for GBYP_AER_SUV_BAR, 2012-2018 for MOR_POR_TRAP and 2012-2019 for JPN_LL_NEAtl2; and for the Western indices: 2006-2017 for GOM_LAR_SURV, 2006-2018 for all US_RR and MEXUS_GOM_PLL indices, 2010-2019 for JPN_LL_West2 and 2006-2017 for CAN_SWNS.

[2] For the aerial surveys, there is no value for 2013, (French) and 2018 (Mediterranean). These years were omitted from this averaging where relevant. Note also that the GBYP aerial survey has not been included at this stage.

where the $J_{av,y}^{E/W}$ applies either to the East or to the West area.
CMP specifications

The BR Fixed Proportion CMPs tested set the TAC every second year simply as a multiple of the J_{av} value for the area at the time (see Figure 1), but subject to the change in the TAC for each area being restricted to a maximum of 20% (up or down). The formulae are given below.

For the East area:

$$TAC_{E,y} = \begin{cases} \left(\frac{TAC_{E,2020}}{J_{E,2017}}\right) \cdot \alpha \cdot J_{av,y-2}^{E} & \text{for } J_{av,y}^{E} \geq T^{E} \\ \left(\frac{TAC_{E,2020}}{J_{E,2017}}\right) \cdot \alpha \cdot \frac{\left(J_{av,y-2}^{E}\right)^2}{T^{E}} & \text{for } J_{av,y}^{E} < T^{E} \end{cases}$$
(A4a)

For the West area:

$$TAC_{W,y} = \begin{cases} \left(\frac{TAC_{W,2020}}{J_{W,2017}}\right) \cdot \beta \cdot J_{av,y-2}^{W} & \text{for } J_{av,y}^{W} \geq T^{W} \\ \left(\frac{TAC_{W,2020}}{J_{W,2017}}\right) \cdot \beta \cdot \frac{\left(J_{av,y-2}^{W}\right)^2}{T^{W}} & \text{for } J_{av,y}^{W} < T^{W} \end{cases}$$
(A4b)

Note that in equation (A4a), setting $\alpha = 1$ will amount to keeping the TAC the same as for 2020 until the abundance indices change. If α or $\beta > 1$ harvesting will be more intensive than at present, and for α or $\beta < 1$ it will be less intensive.

Below T, the law is parabolic rather than linear at low abundance (i.e. below some threshold, so as to reduce the proportion taken by the fishery as abundance drops); this is to better enable resource recovery in the event of unintended depletion of the stock. For the results presented here, the choices $T^E = 1$ and $T^W = 1$ have been made.

<u>Constraints on the extent of TAC increase and decrease</u>

Maximum increase (note that this section has been changed from earlier versions):

For the West area, the maximum increase is fixed at 20%:
If $TAC_{i,y} \geq 1.2 * TAC_{i,y-1}$ then

$$TAC_{W,y} = 1.2 * TAC_{W,y-1} \qquad \text{(A5a)}$$

For the East area, unless otherwise specified, the maximum increase allowed from one TAC to the next is a function of the immediate past trend in the indices, s_y^E:

$$maxincr = \begin{cases} 0 & s_y^E \leq 0 \\ \text{linear btw 0 and 0.2} & 0 < s_y^E < 0.1 \\ 0.2 & 0.1 \leq s_y^E \end{cases} \qquad \text{(A5b)}$$

where
s_y^E is a measure of the immediate past trend in the average index J_y^E (equation A1), computed by linearly regressing lnJ_y^E *vs* year *y'* for y'=y-6 to y'=y-2 to yield the regression slope s_y^E.

If $TAC_{E,y} \geq (1 + maxincr) * TAC_{i,y-1}$

then $TAC_{i,y} = (1 + maxincr) * TAC_{i,y-1}$ (A5c)

Maximum decrease:

If $TAC_{i,y} \leq 0.8 * TAC_{i,y-1}$

then $TAC_{i,y} = (1 - maxdecr) * TAC_{i,y-1}$ (A6)

where

$$maxdecr = \begin{cases} 0.2 & J^i_{av,y-2} \geq J_{i,2017} \\ \text{linear btw 0.2 and } D & 0.5J_{i,2017} < J^i_{av,y-2} < J_{i,2017} \\ D & J^i_{av,y-2} \leq 0.5J_{i,2017} \end{cases} \quad \text{(A7)}$$

where D= 0.3 in implementations.

<u>Maximum TAC</u>

A cap on the maximum allowable TAC is set. This can potentially improve performance, particularly in the event of a shift to a lower productivity regime. By ensuring that TACs have not risen so high that they cannot be reduced sufficiently rapidly following such an event to adjust for the lower resource productivity. In investigations to date, this has been found to be useful to implement for the East area, where TACs can otherwise rise to in excess of 70 kt. The cap for the East area is set at 55 000t.

Table A1: σ^i (averaged over the OMs) values used in weighting when averaging over the indices to provide composite indices for the East and the West areas (see following equation A2).

EAST Index name	σ^i	w_i $(=\frac{1}{(\sigma^i)^2})$	WEST Index name	σ^i	w_i $(=\frac{1}{\sqrt{\sigma^i}})$
FR_AER_SUV2	0.49	1.43	GOM_LAR_SUV	1.48	0.46
MED_LAR_SUV	0.57	1.33	US_RR_66_144	0.57	3.12
GBYP_AER_SUV_BAR	0.99	1.01	MEXUS_GOM_PLL2	0.88	1.28
MOR_POR_TRAP	1.37	0.85	JPN_LL_West2	1.09	0.84
JPN_LL_NEAtl2	3.49	0.54	CAN_SWNS	0.36	7.57

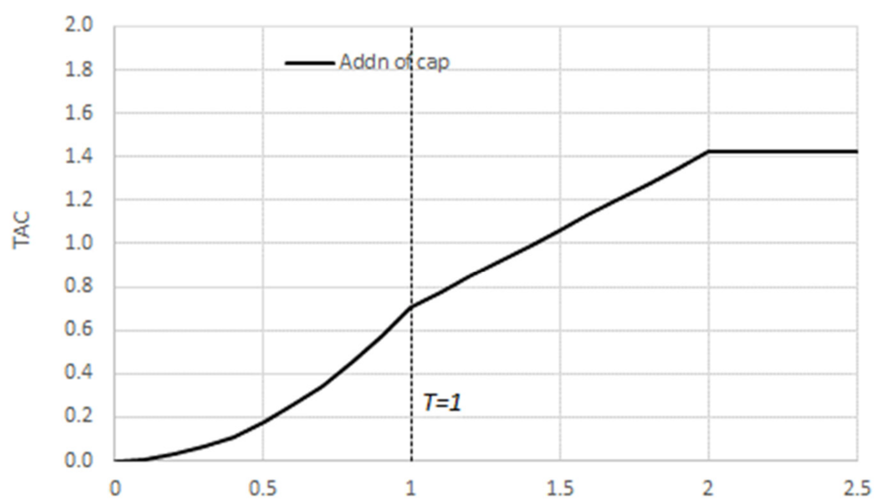

Figure A1. Illustrative relationship (the "catch control law") of TAC against $J_{av,y}$ for the BR CMPs, which includes the parabolic decrease below T and the capping of the TAC so as not to exceed some maximum value.

EA_x CMPs (EU)

Authors: Andonegi, Rueda, Rouyer, Gordoa, Arrizabalaga, and Rodriguez-Marín
Documents: SCRS/2021/032

EA_x CMPs are empirical, based on inputs related to abundance indices which are first standardized for magnitude, then aggregated by way of a weighted average of all indices available for the East and the West areas. TACs are then set based on the concept of taking a fixed proportion of the abundance present, as indicated by these aggregated abundance indices.

Data sets

Four indices have been selected for each stock, aiming at best reflecting the dynamics of each of the stocks. For the East:

- French Aerial Survey (1. FR_AER_SUV2)
- Mediterranean Larval (2. MED_LAR_SUV)
- Moroccan-Portuguese Trap (5. MOR_POR_TRAP)
- North East Atlantic Japanese Longline (6. JPN_LL_NEAtl2)

And for the West:

- Gulf of Mexico Larval (3.GOM_LAR_SUV)
- West Japanese Longline (10.JPN_LL_West2)
- US Rod & Reel 66-144 (13.US_RR_66_144)
- USA-MEX Long Line standardized spatial (14.MEXUS_GOM_PLL)

Status Estimator: the aggregated abundance index

An aggregated abundance index *Irat*, computed as the weighted mean of all indices *n (n*=4 for both areas), is developed for each of the East and the West areas. It is calculated as follows:

$$Irat_y = \sum_i^n w_i * I_{i,y}^* / Targ$$

where w_i are the weights used for each index *i*. The weight of each of the indices is inversely proportional to the variance of the residuals being calculated as:

$$w_i = 1/\sigma_i^2$$

and $\sigma_i = SD_i/(1 - AC_i)$
where SD is the standard deviation and AC the lag 1 autocorrelation of residuals.
Targ is the value of the target Br30 for each specific tuning level.
The standardised index for each index series *i* is:

$$I_{i,y}^* = {I_{i,y}} \Big/ {Average\ of\ historical\ I_{i,t-4}}$$

where *t* is the last year of the historical data (2019).
The actual index used for both the East and the West area, is the average over the last three years for which data would be available at the time the MP would be applied:

$$Irat_{av,y} = {}^{1}\!/_{3}\ (Irat_y + Irat_{y-1} + Irat_{y-2})$$

The Harvest Control Rule (HRC)

The EAx cMPs tested set the TAC every second year subject to a varying percentage of maximum up and down TAC change (Delta up and Delta down) for each area as follows:

$$TAC_y = \begin{cases} TAC_{y-2} * (1\text{– Deltadown}) & if\ Irat < (1 - Deltadown) \\ TAC_{y-2} * (1 + \text{Deltaup}) & if\ Irat > (1 + Deltaup) \\ TAC_{y-2} * \text{Irat} & if\ Irat \geq (1 - \text{Deltadown})\text{and}\ Irat \leq (1 + \text{Deltaup}) \end{cases}$$

Table 1. Indices used to estimate the aggregated index for each ABF area, together with the σ and w values.

	Sigma (σ)	Weight (w)
EAST		
FR_AER_SUV2	0.5	4.0
MED_LAR_SUR	1.03	0.95
MOR_POR_TRAP	0.53	3.59
JPN_LL_NEAtl2	0.62	2.62
WEST		
GOM_LAR_SUR	0.54	3.43
US_RR_66-144	1.16	0.744
MEXUS_GOM_PLL	0.52	3.68
JPN_LL_West2	0.57	3.045

TN_x CMPs (JPN)

Authors: Tsukahara and Nakatsuka
Documents: SCRS/2021/041

Used index:
(West TAC) JPN_LL_West2
(East TAC) JPN_LL_NEAtl2

Tuning parameters (Those must be positive values.)
k_1_E: adjustment value for increase of TAC in eastern Atlantic
k_2_E: adjustment value for decrease of TAC in eastern Atlantic
k_1_W: adjustment value for increase of TAC in western Atlantic
k_2_W: adjustment value for decrease of TAC in western Atlantic

For the sake of simplicity, the formulation is described without suffix of area in the index and the tuning parameter. The respective index rate for JPN_LL_West2 and JPN_LL_NEAtl2 are calculated by bellow:

$$Index\ rate = \frac{mean(Index[y-2:y-4])}{mean(Index[y-5:y-7])} \tag{1}$$

, then New TAC is calculated by the trend of index. When index shows increase trend, which mean index rate are 1 and over, new TAC is calculated by below:

$$New\ TAC = Current\ TAC * \min(\{1 + max\ change\ rate\ of\ TAC\}, \{1 + (Index\ ratio - 1) * k_1\}\ ))$$

On the other hand, when index shows decrease trend, which mean index rate is less than 1, new TAC is calculated by below:

$$New\ TAC = Current\ TAC * \max\left(\{1 - max\ change\ rate\ of\ TAC\}, \left\{1 - \frac{(1 - Index\ ratio)}{k_2}\right\}\right))$$

When k_1 is set to higher than 1, the increase of TAC become bigger than multiplication by original index rate, and vice versa. When k_2 is set to higher than 1, the decrease of TAC become smaller than original multiplication by original index rate. Therefore, higher values of parameters on both, k_1 and k_2, lead to more aggressive CMPs, while lower values of parameters make CMP precautionary. There is a possibility to have negative TAC value when adjustment with small k_2 value, although maximum change rate of TAC prevents TAC from getting the negative values.

LW & PW CMPs (NOAA)

Authors: Peterson, Lauretta, and Walter
Documents: SCRS/2021/155

LW and PW are based on constant harvest rate (ConstU) strategies for both the east and west stocks. In the MSE, the indices of abundance are assumed to be proportional to vulnerable biomass, i.e. the base parameterization assumes time-invariant catchability. Therefore, a relative harvest rate for each stock can be calculated as follows:

$$harvest\ rate = catch/abundance$$

$$relative\ abundance = catchability * abundance$$

$$relative\ harvest\ rate = \frac{catch}{relative\ abundance}$$

Under this approach, management procedures for east and west stocks were designed to apply a constant harvest rate strategy tracking catches and indices of relative abundance.

$$U_{target_i} = \frac{\overline{C_{t52:t50}}}{\overline{I_{i,t52:t50}}} \cdot x$$

where
U=relative harvest rate
C=catch in mt
I=averaged relative abundance index for index i
t=model year, and
x=constant multiplier

$$U_{current_i} = \frac{\overline{C_{t-2:t-0}}}{\overline{I_{i,t-2:t-0}}}$$

$$\Delta_{ratio} = FUN_i\left(\frac{U_{target_i}}{U_{current_i}}\right)$$

where FUN is a function to summarize across ratios for each index (e.g., mean or minimum)

$$TAC_{t+1:t+3} = \Delta_{ratio} \cdot TAC_{t-2:t-0}$$

where
TAC=total allowable catch limit

Subsequent restrictions (e.g., TAC caps, allowable annual % TAC change) were implemented, as necessary.

LW Particulars

For the West stock, the GOM_LAR_SUV and MexUS_GOM_PLL indices are used, and for the East stock, the MED_LAR_SUV and JPN_LL_NEAtl2 indices are used. FUN used to summarize across *Δratio*s for each index was mean.

The notable distinction of the LW cMP is that it accounts for eastern biomass in the West. This replaces calculation of $I_{current}$ and I_{target} with

$$I_{target_{west}} = \frac{I_{west\ i,t50:t52}}{I_{west_{i,t1:t52}}} + \frac{I_{east_{i,t50:t52}}}{I_{east_{i,t1:t52}}}$$

$$I_{current_{west}} = \frac{I_{west_{i,t-2:t-0}}}{I_{west_{i,t0:t}}} + \frac{I_{east\ i,t50:t52}}{I_{east_{i,t0:t}}}$$

PW Particulars

For the West stock, the GOM_LAR_SUV and MexUS_GOM_PLL indices are used, and for the East stock, the MED_LAR_SUV and JPN_LL_NEAtl2 indices are used. FUN used to summarize across $\Delta ratio$s for each index was minimum. PW also penalized TACs if $I_{current}$ was below I_{target} by setting

$$TAC_{t+1:t+3} = \begin{cases} \Delta_{ratio} \cdot TAC_{t-2:t-0} & if\ I_{current} \geq I_{target} \\ p * \Delta_{ratio} \cdot TAC_{t-2:t-0} & if\ I_{current} < I_{target} \end{cases}$$

where the penalty parameter (p) was set equal to 0.75.

FZ, FP, FV, FX, FU, FY, NC CMPs (DFO)

Authors: Hanke and Duprey
Documents: SCRS/2021/156

An $F_{0.1}$ based cMP

This cMP sets the TAC using an estimate of $F_{0.1}$ and the current abundance of the stock. The $F_{0.1}$ calculation depends on choosing 3 indicators from each management area that index the relative abundance of young, middle aged and older stock components. Prior to use, these indicators are subjected to a range normalization and the average value for the most recent 3 years is determined:

$$I'_{sm} = (I_{sm} - \min(I_{sm}))/(\max(I_{sm}) - \min(I_{sm}))$$

$$I'_{md} = (I_{md} - \min(I_{md}))/(\max(I_{md}) - \min(I_{md}))$$

$$I'_{lg} = \left(I_{lg} - \min\left(I_{lg}\right)\right)/(\max\left(I_{lg}\right) - \min\left(I_{lg}\right))$$

$$\overline{I'_{sm}} = \frac{1}{3}\sum\nolimits_{N-2}^{N} I'_{sm}$$

$$\overline{I'_{md}} = \frac{1}{3}\sum\nolimits_{N-2}^{N} I'_{md}$$

$$\overline{I'_{lg}} = \frac{1}{3}\sum\nolimits_{N-2}^{N} I'_{lg}$$

$$I_{tot} = \overline{I'_{sm}} + \overline{I'_{md}} + \overline{I'_{lg}}$$

$F_{0.1}$ is a calculation based on a yield-per-recruit analysis from *fishmethods* (Nelson, 2019) that follows the modified Thompson-Bell algorithm :

$$Z_a = M_i + PR_a * F_a$$

$$N_{a+1} = N_a * e^{-Z_a}$$

$$\overline{N}_a = (1 - e^{-Z_a}) * \frac{N_a}{Z_a}$$

$$\overline{N}_{a+} = \frac{N_{a+}}{Z_{a+}}$$

$$C_a = (N_a - N_{a+1}) * \frac{PR_a * F_a}{Z_a}$$

$$Y_a = \overline{W}_a C_a = PR_a * \overline{F}_a B_a$$

where the ages *a* for each management area are as defined in the 2015 VPA,

Y_a , C_a , N_a , B_a = Yield, Catch, Numbers and Biomass at age respectively,

W_a = Weight at age is from the 2015 VPA for the west and 2017 VPA for the east,

F_a = Fishing mortality at age,

M_a = Natural mortality at age scaled to the Lorenzen function (Walter et. al. 2018),

Z_a= Total mortality at age (F_a+M_a),

$PRe_{1:10}$ = the partial recruitment vector applied to fishing mortality (F) to obtain partial F-at-age is calculated from the east MP indicators,

$PRw_{1:16}$ = the partial recruitment vector applied to fishing mortality (F) to obtain partial F-at-age is calculated from the east MP indicators,

q = an index and stock specific tuning parameter.

East values

$$a = \{1,2,3,4,5,6,7,8,9,10)\}$$

$$W_{1:10} = \{3.0, 10.0, 19.0, 35.0, 50.0, 69.0, 90.0, 113.0, 138.0, 205.0)\}$$

$$M_{1:10} = \{0.40, 0.33, 0.27, 0.23, 0.20, 0.18, 0.16, 0.14, 0.13, 0.12\}$$

$$PRe_{1:10} = \left\{ \frac{\overline{I'_{sm}}}{I_{tot}}_{1:4} \frac{\overline{I'_{md}}}{I_{tot}}_{5:6} \frac{\overline{I'_{lg}}}{I_{tot}}_{7:10} \right\}$$

$$I_{sm,md,lg} = \{ FR\_AER\_SUV2, JPN\_LL\_NEAtl2, MED\_LAR\_SUV \}$$

$$I_{bm} = \{ MED\_LAR\_SUV \}$$

$$q = 1.875\mathrm{E}-7$$

West values

$$a = \{1,2,3,4,5,6,7,8,9,1011,12,13,14,15,16)\}$$

$$W_{1:16} = \{3.1,9.8,15.1,19.9,43.3,60.5,89.9,111.6,144.8,174,201.1,225.5,247.7,264,283.5,340\}$$

$$M_{1:16} = \{0.40, 0.33, 0.27, 0.23, 0.20, 0.18, 0.16, 0.14, 0.13, 0.12, 0.12, 0.11, 0.11, 0.11, 0.11, 0.11\}$$

$$PRw_{1:16} = \left\{ \frac{\overline{I'_{sm}}}{I_{tot}}_{1:4} \frac{\overline{I'_{md}}}{I_{tot}}_{5:6} \frac{\overline{I'_{lg}}}{I_{tot}}_{7:16} \right\}$$

$$I_{sm,md,lg} = \{ US\_RR\_66\_144, CAN\ SWNS, MEXUS\_GOM\_PLL \}$$

$$I_{bm} = \{ MEXUS\_GOM\_PLL \}$$

$$q = 2.136444\mathrm{e}-07$$

The $F_{0.1}$ estimate is based on yield-per-recruit calculation for F ranging from 0 to 10 in increments of 0.01. The last age in the a vector is a plus group and the oldest age in the plus group is 35.

Eastern and Western area TAC

$$TAC_{N+1} = \begin{cases} F_{0.1} * \dfrac{I_{bm,N}}{q},\ I_{tot} > 0 \\ 0.2 * \dfrac{I_{bm,N}}{q}, I_{tot} = 0 \end{cases}$$

Constraint on TAC increase (upper=1.26, lower=0.6)

$$TAC_{N+1} = TAC_N * \left(0.6 + \frac{1}{1.5 + e^{-8*\left(\frac{TAC_{N+1} - TAC_N}{TAC_N}\right)}} \right)$$

A simple indicator based cMP

This cMP tracks the relative abundance of an indicator and sets a TAC based on the ratio of the most recent 3 years of index values relative to the 3 years prior to that.

Eastern management procedure index

$$I_{bm} = \{\, MOR\_POR\_TRAP \,\}$$

Western management procedure index

$$I_{bm} = \{\, MEXUS\_GOM\_PLL \,\}$$

The basis for the TAC calculation is the I_{ratio} estimate and depends on the most recent 6 years of index values:

$$I_{ratio} = \left(\frac{1}{3}\sum\nolimits_{N-2}^{N} I_{bm}\right) \Big/ \left(\frac{1}{3}\sum\nolimits_{N-5}^{N-3} I_{bm}\right)$$

Index-Catch difference

In order to avoid situations where the population is changing faster than the trend in catch, the difference between the scaled index and catch is used to make an adjustment that attempts to make the two more similar. See figure 1 for example.

$$Scale(x) = \frac{(x - \overline{x})}{sd(x)}$$

$$Diff = abs(Scale(I_{bm}) - Scale(C_{obs})\,)$$

where C_{obs} is a vector of observed catches.

$$\Delta Diff = \frac{Diff_N}{Diff_{N-1}}$$

Western area TAC

$$TAC_{N+1} = \begin{cases} TAC_N, & I_{ratio} \geq 1 \ \wedge \ (\Delta Diff \leq 1 \ \vee \ \Delta Diff \geq 2) \\ 1.05 * TAC_N, & I_{ratio} \geq 1 \ \wedge \ (1 < \Delta Diff < 2) \\ I_{ratio} * 1.05 * TAC_N, & I_{ratio} < 1 \ \wedge \ (\Delta Diff \leq 1 \ \vee \ \Delta Diff \geq 2) \\ I_{ratio} * 0.9648 * TAC_N, & I_{ratio} < 1 \ \wedge \ (1 < \Delta Diff < 2) \end{cases}$$

Eastern area TAC

$$TAC_{N+1} = \begin{cases} TAC_N, & I_{ratio} \geq 1 \ \wedge \ (\Delta Diff \leq 1 \ \vee \ \Delta Diff \geq 2) \\ 1.05 * TAC_N, & I_{ratio} \geq 1 \ \wedge \ (1 < \Delta Diff < 2) \\ I_{ratio} * 1.072 * TAC_N, & I_{ratio} < 1 \ \wedge \ (\Delta Diff \leq 1 \ \vee \ \Delta Diff \geq 2) \\ I_{ratio} * 0.9648 * TAC_N, & I_{ratio} < 1 \ \wedge \ (1 < \Delta Diff < 2) \end{cases}$$

TC & AI (BM)

Authors: Carruthers
Documents: SCRS/2021/165 (TC)

<u>TC</u>

Fixed harvest rate, index-based CMP accounting for stock mixing

Data smoothing

In order to reduce noise in both indices and catches, the MP uses a polynomial ('loess') smoothing function *S()*. Smoothed catches $\tilde{C}$ and smoothed are (A) and stock (S) indices $\tilde{I}$ are calculated from the raw observed catches C and indices I by area a and index type i, using the same smoothing parameter ω:

$$\tilde{I}^A_{a,i} = S(I^A_{a,i}, \omega) \quad (1)$$
$$\tilde{I}^S_{a,i} = S\left(I^S_{a,i}, \omega\right) \quad (2)$$
$$\tilde{C}_a = S(C_a, \omega) \quad (3)$$

The function is parameterized such that the approximate number of smoothing parameters is a linear function of the length of the time series. The effect of the ratio of smoothing parameters to length of the time series ω, is illustrated in Figure 1.

Vulnerable biomass and fishing rate estimation

A multi-stock, multi-area management procedure 'MPx', was designed to provide TAC advice in a given time period t using Stock biomass indices (I^S) by stock s and Catch Rate Indices (I^A) by area a, calibrated to current stock assessments of vulnerable biomass B (estimates of catchability q for stock and area indices) (Figure 2). In order to, for example, interpret West area biomass in terms of Eastern stock biomass, an estimate of stock mixing is required $\theta^{mix}_{s=East\_stock,a=West}$ that is the fraction of Eastern stock biomass that can be expected to be vulnerable to fishing in the West area. Where there are more than one spawning stock index ($n_{s,i} > 1$) or more than one area index ($n_{a,i} > 1$) overall biomass estimates were the mean of those from the multiple indices:

$$B^S_{a,t} = \frac{\sum_s \sum_i \tilde{I}^S_{s,i,t} q^S_{s,i} \theta^{mix}_{s,a}}{n_{s,i}} \quad (4)$$

$$B^A_{a,t} = \frac{\sum_s \sum_i \tilde{I}^A_{a,i,t} q^A_{a,i}}{\mathrm{n}_{a,\mathrm{i}}} \quad (5)$$

The q parameters are calibrated to 2016 estimates spawning biomass (by stock) θ^S_s, and vulnerable biomass (by area) θ^A_a:

$$q^S_s = \frac{\theta^S_{s,2016}}{\tilde{I}^S_{s,2016}} \quad (6)$$

$$q^A_a = \frac{\theta^A_{a,2016}}{\tilde{I}^A_{a,2016}} \quad (7)$$

The estimates of vulnerable biomass B arising from the calibrated indices can be used to estimate the fishing mortality rate using observations of catches C

$$F_{a,t}^{A} = -\ln\left(1 - \frac{C_{a,t}}{B_{a,t}^{A}}\right) \quad (8)$$

$$F_{a,t}^{S} = -\ln\left(1 - \frac{C_{a,t}}{B_{a,t}^{S}}\right) \quad (9)$$

Combining inference from SSB and CPUE indices

Assessment estimates of vulnerable biomass at *MSY* (θ^{BMSY}) can be used to calculate current vulnerable biomass relative to *BMSY,* here inference from catch rate and spawning indices is equally weighted as the geometric mean:

$$\Delta_{a,t}^{B} = exp\left(\frac{1}{2}\left[ln\left(\frac{B_{a,t}^{S}}{\theta_a^{BMSY}}\right) + ln\left(\frac{B_{a,t}^{A}}{\theta_a^{BMSY}}\right)\right]\right) \quad (10)$$

The same approach was used to combined estimates of *F* relative to *FMSY*:

$$\Delta_{a,t}^{F} = \exp\left(\frac{1}{2}\left[ln\left(\frac{F_{a,t}^{S}}{\tilde{\theta}_a^{FMSY}}\right) + ln\left(\frac{F_{a,t}^{A}}{\tilde{\theta}_a^{FMSY}}\right)\right]\right) \quad (11)$$

A harvest control rule for TAC adjustment based on estimates of B/BMSY and F/FMSY

TACs in the following year are based on TAC in the previous time step multiplied by a factor $\varphi_{a,t}$:

$$TAC_{a,t+1} = TAC_{a,t}\ \varphi_{a,t} \quad (12)$$

where the factor $\varphi_{a,t}$ is determined by adjustments for fishing rate $\delta_{a,t}^{F}$ and stock status $\delta_{a,t}^{B}$:

$$\tilde{\varphi}_{a,t} = \delta_{a,t}^{F}\ \delta_{a,t}^{B} \quad (13)$$

The adjustment to *F* is the inverse of *F*/*FMSY* ($\Delta_{a,t}^{F}$) where the magnitude of the adjustment is determined by β^F. The parameter α^F controls the target *F* level where *F*/*FMSY* = 1 and *B*/*BMSY* = 1. For example, at a value of 0.8, the MP deliberately aims to underfish at 80% of *FMSY* when the stock is at *BMSY* and current *F* is *FMSY*. Note that when α^F=1 and β^F = 1 the *F* adjustment $\delta_{a,t}^{F}$ is the inverse of $\Delta_{a,t}^{F}$ and hence recommends *FMSY* fishing rate (and depends on the assumption that biomass will be comparable at t+1).

$$\delta_{a,t}^{F} = \alpha^F\ exp\left(\ \beta^F\ ln\left(1/\Delta_{a,t}^{F}\right)\right) \quad (14)$$

The adjustment according to biomass is exponentially related to the disparity between current biomass and BMSY. The term $|\Delta_{a,t}^{B} - 1|$ is the positive absolute difference (modulus). The magnitude of the adjustment for biomass is controlled by the parameter α^B while the (extent of the TAC change for biomass levels far from BMSY) is controlled by the exponent β^B. This is analogous to a traditional harvest control rule (e.g. '40-10') and throttles fishing rates at low stock sizes to speed recovery while also increasing fishing rates at high stock sizes to exploit additional biomass (Figure 3). When α^B = 0 there is no biomass adjustment and $\delta_{a,t}^{B}$ is invariant to β^B.

$$\delta_{a,t}^{B} = \begin{cases} exp\left[\left(\alpha^B|\Delta_{a,t}^{B} - 1|\right)^{\beta^B}\right] & 1 < \Delta_{a,t}^{B} \\ exp\left[-\left(\alpha^B|\Delta_{a,t}^{B} - 1|\right)^{\beta^B}\right] & \Delta_{a,t}^{B} \le 1 \end{cases} \quad (15)$$

This generalized TAC harvest control rule can accommodate a wide range of control schemes of varying sensitivity to estimates of current exploitation rate and stock status.

TAC adjustment limits

The maximum rate of TAC adjustment is determined by θ^{down} and θ^{up} and the minimum amount is controlled by θ^{min}:

$$\hat{\varphi}_{a,t} = \begin{cases} \theta^{down} & \tilde{\varphi}_{a,t} < \theta^{down} \\ \tilde{\varphi}_{a,t} & \theta^{down} < \tilde{\varphi}_{a,t} < (1-\theta^{min}) \\ 1 & (1-\theta^{min}) < \tilde{\varphi}_{a,t} < (1+\theta^{min}) \\ \tilde{\varphi}_{a,t} & (1+\theta^{min}) < \tilde{\varphi}_{a,t} < \theta^{up} \\ \theta^{up} & \theta^{up} < \tilde{\varphi}_{a,t} \end{cases} \tag{16}$$

Table 1. The input data, parameters of the current default MPx managment procedure.

Description		Value
Biomass calculation		
$\mathrm{I}^{S}_{East\_stock}$	Spawning stock biomass index for eastern stock	MED_LAR_SUV (#2), GBYP_AER_SUV_BAR (#5)
$\mathrm{I}^{S}_{West\_stock}$	Spawning stock biomass index for western stock	GOM_LAR_SUV (#4)
I^{A}_{East}	Vulnerable biomass catch rate index for eastern area	MOR_POR_TRAP (#6), JPN_LL_NEATL2 (#7)
I^{A}_{West}	Vulnerable biomass catch rate index for western area	US_RR_177 (#10), JPN_LL_West2 (#12)
θ^{BMSY}_{East}	Eastern area biomass at maximum sustainable yiel d	800 kt
θ^{BMSY}_{West}	Western area biomass at maximum sustainable yield	20 kt
θ^{FMSY}_{East}	Eastern area harvest rate at MSY	0.06
θ^{FMSY}_{West}	Western area fishing mortality rate at MSY	*tuned* (0.004 – 0.04)
$\theta^{S}_{East\_stock,recent}$	Mean Vuln. biomass of eastern stock in 2013-2017	800 kt
$\theta^{S}_{West\_stock,recent}$	Mean Vuln. biomass of western stock in 2013-2017	20 kt
$\theta^{A}_{East,recent}$	Mean Vuln. biomass in eastern area in 2013-2017	730 kt
$\theta^{A}_{West,recent}$	Mean Vuln. biomass in western area in 2013-2017	120 kt
$\theta^{mix}_{West,East}$	Fraction of western stock in eastern area	0.1
$\theta^{mix}_{East,West}$	Fraction of eastern stock in western area	0.05
Harvest control rule		
α^{B}	The magnitude of the adjustment for biomass relative to BMSY	0 (no biomass adjustment)
β^{B}	Exponent parameter controlling extent of the adjustment for biomass relative to BMSY	NA (given α^{B} = 0)
α^{F}	Target fishing mortality rate (fraction of FMSY) at F/FMSY = 1 and B/BMSY =1	1
β^{F}	The magnitude of the adjustment for fishing rate relative to FMSY	0.33
Data smoothers		

ω	The ratio of the No. polynomial smoothing parameters to the number of years of time series data. I.e. loess(dat, enp.target = $\omega \cdot n_t$)	0.15

Table 1. Continued.

Description		Value
TAC adjustment limits		
θ^{up}	The maximum fraction that TAC can increase	0.25
θ^{down}	The maximum fraction that TAC can decrease	0.25
θ^{min}	The minimum fractional change in TAC	0.025
θ_{East}^{TACmin}	Minimum TAC for the East area	10 kt
θ_{West}^{TACmin}	Minimum TAC for the West area	0.5 kt
θ_{East}^{TACmax}	Maximum TAC for the East area	80 kt
θ_{West}^{TACmax}	Maximum TAC for the West area	4.5 kt
$\theta_{West}^{TACmax\_near}$	Near-term maximum TAC for the West area	2 kt
$\theta_{West}^{n\_near}$	Western near-term period	25 years
Index recalibration rule		
γ^{n}	The length of the time series for detecting slope of indices	6
γ^{East}	The magnitude of F reduction in the East area in relation to the slope in Eastern stock biomass index	1
γ^{West}	The magnitude of F reduction in the West area in relation to the slope in Western stock biomass index	2

AI CMP

Fixed harvest rate CMP using estimates of area-based vulnerable biomass from an artificial neural network. Details of the neural network configuration are available in Table 2.

Simulated datasets were generated by projecting nine constant fishing mortality rate CMPs for all 96 stochastic reference set operating models. These nine CMPs comprised high, medium and low harvest rates in the West area crossed with high, medium and low harvest rates in the East area. These simulations created a range of simulated outcomes for both stocks. The stochastic operating models include 48 simulations each. Over 9 CMPs this leads to 41,472 simulated projections (96 x 48 x 9). In each of these projections a single projection year was sampled, and for this year eight types of data were recorded:

(1) current index level of all 13 indices subject after Loess smoothing (13 data points);
(2) the mean level of the index in the projection to date (13 data points);
(3) the slope in the index in the first 4 projection years (13 data points);
(4) the slope in the index in the first 6 projection years (13 data points);
(5) mean catches over the last three years in both ocean areas (2 data points);
(6) mean catches in both ocean areas to date (2 data points);
(7) the projection year;
(8) the total simulated biomass in each ocean area of fish age 3 or older (2 data points).

This results in 57 independent variables (input layer features) and 1 dependent variable (the output layer - area biomass of fish age 3+) for training two neural networks, one for predicting total biomass of 3+ fish in the East area and another for predicting total biomass of age 3+ fish in the West area. Only one projection year was sampled per simulation to ensure all data points originate from independent time series. Random seeds were generated to ensure that the projected simulated data and dynamics were not the same as those used in MSE testing.

The wider dataset of 41,472 'observations' was split into three component datasets, a training set, a validation set and a testing set. The training set was used to fit the neural network using the backpropagation algorithm. The validation set was used to monitor training and where possible adjust meta parameters of the fitting and network design to improve accuracy. The testing set remained completely independent of the process of fitting or the selection of training hyperparameters that controlled the network fitting process. The split of these data was approximately 75% training, 20% validation, 5% testing.

Prior to fitting, data were all normalized to have mean 0 and standard deviation 1. The parameters of this data normalization was saved in the neural network design to ensure it was preserved when predictions are made from the new datasets provided to a CMP. To focus estimation on smaller stock sizes where CMP performance is most critical, the highest 10% of simulated biomasses were removed from the fitting (include many optimistically high outliers) and fit was conducted by minimizing mean squared error on log area biomass.

It has been shown that two hidden layers are sufficient to characterize the structure of any non-linear problem, and that at least two are required to capture complex hierarchical interactions. It follows that a three-layer (two hidden layers) neural network was investigated allowing for deep learning. As is typically the case in the design of neural networks, the width (number of nodes) and depth (number of hidden layers) was decided by ad-hoc experimentation as it is specific to each problem. In both East and West neural networks, relatively high accuracy was achieved with two hidden layers comprising 24 in the first layer and 24 in the second (Figures 1 and 2). This leads to 2,017 parameters per neural network which are the weights among the layers (the coloured lines of Figure 1), in addition to the biases in the hidden and output layers (one for each of the nodes in the lower three layers of nodes in Figure 1) (2,017 = 57 x 24 + 24 x 24 + 24 x 1 + 24 + 24 + 1). In general, the validation loss rate (the mean squared error in log total biomass of age 3+ fish) stopped improving after 350 epochs (iterations of fitting) (see Figure 2 for mean absolute error plots).

The neural networks were used in fixed harvest rate CMPs. The TACs in each area were set by the 3+ biomass estimate from the corresponding neural network multiplied by a tuning parameter that is the fixed harvest rate in each area. CMPs AI1, AI2 and AI3 were tuned to an eastern stock Br30 (spawning stock biomass, SSB relative to dynamic SSB MSY after 30 projected years) of approximately 1.55 and western stock Br30 of 1.00, 1.25 and 1.50, respectively. Similarly to other CMPs, the TAC advice arising from the A.I. CMPs were constrained by minimum (10kt East, 0.5kt West) and maximum (50kt East, 4kt West) levels in addition to maximum percentage increases (25%) and decreases (35%). If the new TAC is less than a 5% different from the previous TAC no change is implemented.

Table 2. Neural network configuration

Configuration	Used in this analysis	Alternatives
1. Software	KERAS R package (Falbel et al. 2021) + Tensorflow (2021) + NVIDIA CUDA (NVIDIA 2021)	neuralnet R package (Fritsch *et al.* 2016) nnet R package (Ripley 2016) (and many others)
2. Network type	Simple recurrent	Fully recurrent, Recursive, Multilayer perceptron, Convoluted, Bi-directional, Hierarchical, Stochastic, Long short-term memory, Sequence to sequence, Shallow, Echo state
3. Training algorithm (optimizer)	'rmsprop'	'adam', 'sgd', 'adamax', 'adadelta', 'adagrad'
4. Cost function	Mean squared error	Mean absolute error, mean squared, logarithmic error, mean absolute percentage error
5. Intensiveness of training	500 epochs (sufficient for stabilization of cost function, Figure 2)	-
6. Input data types	• Current index level (13 indices, each loess smoothed) • Index slope: first 4 yr. of projection • Index slope first 6 yrs of projection • Index • Mean index level in projection • Projection year number • Mean catch levels in projection (both East and West area)	
7. Output data	East / West Area specific biomass (age 3+)	Stock biomass, stock biomass x exploitation rate
8. Size of training / validation / testing data sets	31,519 / 7,880 / 2,074 (approx. 75% / 20% / 5%)	-
9. Network design (number of neurons in consecutive layers demarked by ':') and Activation functions	**Input layer**: 57 (data types) **Hidden layers**: 24:24 (2,401 parameters) **Output layer**: 1 **Activation functions:** rectified linear unit	Linear, sigmoid, hyperbolic, tangent
10. Neural net performance evaluation	**Validation**: cross-validation **Estimation performance**: mean squared error / mean absolute error **Management performance**: MSE testing with ABT-MSE package	

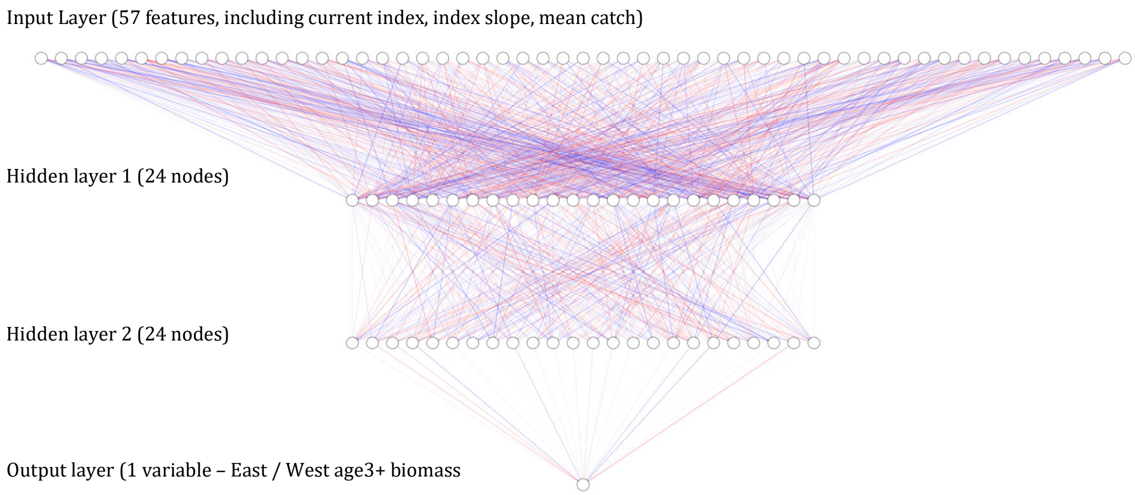

Figure 1. Neural network design. Lines represent estimated weights, circles represent nodes for which a bias is estimated per node for each hidden layer and the output layer.