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# Technical Details Underlying the Management Strategy Evaluation Process Leading to Selection of a Management Procedure for Western Component (4Xopqrs5) Pollock

# Aspects techniques du processus d'évaluation de la stratégie de gestion utilisé pour choisir une procédure de gestion de la goberge de la composante Ouest (4Xopqrs5)

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## ABSTRACT

This document provides full technical details of the computations carried out during the process of developing and selecting a Management Procedure (MP) for providing annual catch limits for Western Component (4Xopqrs5) Pollock. This process commenced at a workshop held on 9-10 December 2010, and was completed at a Regional Assessment Process held on 9-10 May 2011. First key aspects of the methodology are elaborated: the various operating models of the Pollock population dynamics used in the simulation testing of Candidate MPs for the resource; the projection methodology for simulating population behaviour into the future; the statistics agreed to measure Candidate MP performance; and finally the details of the Candidate MPs, which all specify catch limits based on the three-year geometric mean of the survey abundance index for the resource. The results of these simulations are reported, together with an explanation of how one of the Candidate MPs was selected on the basis of best satisfying three medium term objectives agreed for management of the resource. These relate to considerations of sustainability, catch and limitations on the extent of annual catch changes.

## RÉSUMÉ

Le présent document décrit tous les aspects techniques des calculs effectués dans le cadre du processus de sélection d’une procédure de gestion (PG) visant à fixer des limites de captures annuelles applicables à la goberge de la composante Ouest (4Xopqrs5). Ce processus amorcé lors d’un atelier les 9 et 10 décembre 2010 a été terminé à une réunion du Processus d’évaluation régional les 9 et 10 mai 2011. Il s’agissait d’abord de définir les principaux aspects de la méthode : les divers modèles opératoires de dynamique de la population de goberge utilisés dans la simulation des PG proposées; la méthode de projection servant à simuler le comportement de la population dans l’avenir; les statistiques retenues pour mesurer les résultats des PG proposées et enfin le contenu détaillé de ces PG, qui fixent toutes des limites de captures en fonction de la moyenne géométrique sur trois ans de l’indice d’abondance de la ressource d’après les relevés. On rend compte ici des résultats des simulations, en expliquant comment le choix s’est porté sur une des PG proposées, parce que c’était celle qui correspondait le mieux aux trois objectifs à moyen terme dont il avait été convenu pour la gestion de la ressource. Ce sont des objectifs liés à la viabilité écologique de la ressource, aux captures et à la limitation de l’ampleur des changements dans les captures annuelles.

# INTRODUCTION

Porter and Docherty (2011) reported on the proceedings of a workshop held on 9-10 December 2010 at the St Andrews Biological Station, St. Andrews, New Brunswick to gain understanding of the Management Strategy Evaluation (MSE) process and to initiate the development of a Management Procedure (MP) as a basis for risk management of the Canadian Western Component (4Xopqrs5) Pollock resource. This workshop reviewed assessments of the resource, as well as proposals for Operating Models (OMs) to be used in MSE, and some initial results of the testing of some candidate MPs (CMPs) under those OMs. Workshop participants agreed on a set of 12 OMs, set out some medium term management objectives, and developed a workplan to complete the process over a five month period.

This process was duly completed (following a series of conference calls at which progress was discussed) at a Regional Advisory Process (RAP) held on 9-10 May 2011, in St. Andrews, NB, with a final MP selected for Western Component Pollock. The details of the MSE process and MP selected are summarised in DFO (2011a), with the proceedings of the RAP reported in DFO (2011b).

The material that follows provides full technical details of the calculations carried out during this MSE process, and summarises the considerations that led to the selection of a specific MP.

It should be noted that during this process an error was detected in the computer code that had been used to provide initial results of testing some CMPs at the December 2010 meeting (recorded in DFO 2011b Appendix 4c). This error led to inappropriately optimistic projections for future resource abundance, and hence to the overly optimistic catch trends reported in Porter and Docherty (2011). Correction of this error necessitated a rediscussion and some amendments to the management objectives set at the December 2010 workshop during the RAP, as indicated below.

# METHODOLOGY

The MSE process comprises a number of components which are pursued more or less sequentially:

- Developing a set of OMs (rather than focusing on a single ‘best assessment’) to be used to represent alternative plausible underlying dynamics of the resource and associated fishery in computer simulation testing of CMPs. This set is intended to cover the major sources of uncertainty about the resource and the associated fishery.
- Detailing the methodology for projecting resource dynamics into the future for those OMs in a manner that also provides realizations of future monitoring data upon which future TACs would be based. This methodology includes making allowance for the noise in the relationships between the actual underlying resource variables and the associated observations available (such as abundance indices from research surveys).
- Specifying performance statistics related to future catch catch variability and resource abundance for use in evaluating the CMPs against broad medium term management objectives.
- Specifying details of the CMPs themselves; these are essentially formulae which translate results of those observations into management measures such as TACs.
- Conducting simulation testing of these CMPs under the OMs, with the results arising used to select amongst the CMPs on the basis of their performances compared to management objectives.

The first four of these components are each elaborated below, with the outcomes from the simulation tests detailed in the Results section.

## Operating Models

Table 1 summarises the OMs used in the final MSE computations as agreed at the 9-10 May 2011 RAP. This set of OMs was selected to span the major sources of uncertainty in the Pollock assessment and the projections arising from it. These include:

- Variability of RV Surveys and hence in the relationship between the Survey Biomass Index and the underlying population abundance,
- Changes in natural mortality (*M*) over time,
- Changes in partial recruitment (PR), also termed selectivity, on older ages,
- High variability in recruitment (note also that recruitment is poorly estimated for the last two years), and
- How recruitment will depend on spawning biomass in the future.

The OMs are all based on VPA, and are all variants of the Reference Case OM1, so that only changes from the specifications of OM1 are noted in the descriptions of each that follow.

1) OM1: This OM corresponds to RAD1 of Rademeyer and Butterworth (2011). Natural mortality is taken as 0.2 throughout the period (past and future), there is no bias correction and the 2010 survey estimate is included in the model fitting procedure. To generate recruitment in the future, a hockey-stick stock-recruitment relationship is assumed based on the last 10 years of reliable recruitment estimates (see equation 19 following).
2) OM2: This OM is described in Stone (2011). It includes bias correction, *M*=0.2 and also the 2010 survey estimate. As for OM1, the hockey-stick stock-recruitment relationship used to generate future recruitment is based on the last 10 years of reliable recruitment estimates.
3) OM3: This is another OM based on Stone (2011) VPA, but excluding the 2010 survey estimate. As for OM2, it includes bias correction, *M*=0.2 and future recruitment based on the last 10 years of reliable recruitment estimates.
4) OM4: Instead of assuming a direct proportion between observed abundance indices and their expected values, a square root relationship is assumed, *i.e.,* equation A8 of Rademeyer and Butterworth (2011) is replaced by:

$$\hat{I}_{y,a} = q_a \left( N_{y,a} \frac{1-e^{-Z_{y,a}}}{Z_{y,a}} \right)^{\beta} \qquad (1)$$

where $\beta = 0.5$. Similarly in the future, equations 25, 28 and 30 following are replaced by:

$$I_y = q \, \left(B_y\right)^{\beta} e^{\varepsilon_y} \qquad (2)$$

$$\ell n\, \hat{q} \; = 1/27 \sum_{y=1984}^{2010} \left( \ln I_y - \ln\left(\hat{B}_y\right)^{\beta} \right) \qquad (3)$$

$$\varepsilon_y = \ell \text{n}(I_y) - \ell \text{n}(q\left(\hat{B}_y\right)^{\beta}) \qquad (4)$$

5) OM5: Here the observed abundance indices are assumed to be proportional to the square of the expected values, *i.e.,* $\beta = 2$ in equations 1-4 above.
6) OM6: Past dynamics are as for OM1, but future survey abundance indices are generated by assuming two "regimes" in the future, *i.e.,*:

   for the "low" regime, *i.e.,* all years where $\hat{B}_y < 40$ thousand tons:

$$\ell n\, \hat{q}^{low} = 1/n^{low} \sum_{y \in Low} \left( \ln I_y - \ln \hat{B}_y \right) \quad (5)$$

and

$$\hat{\sigma}^{low} = \sqrt{1/n^{low} \sum_{y \in low} \left( \varepsilon_y \right)^2} \quad (6)$$

   and for the "high" regime, *i.e.,* all years where $\hat{B}_y > 40$ thousand tons (1988, 1990, 1996, 2006, 2008 and 2009):

$$\ell n\, \hat{q}^{high} = 1/n^{high} \sum_{y \in high} \left( \ln I_y - \ln \hat{B}_y \right) \quad (7)$$

and

$$\hat{\sigma}^{high} = \sqrt{1/n^{high} \sum_{y \in high} \left( \varepsilon_y \right)^2} \quad (8)$$

   Future surveys are then generated randomly from the low or high regime in the proportion 21:6.

7) OM7: As OM1, but with increased natural mortality (for the past dynamics from 1996 as well as the future) for ages 7 and above: *M*=0.2 for ages 6 or less, and *M*=0.617 for ages 7 and above.
8) OM8: As OM1, but with increased natural mortality (for the past dynamics from 1996 as well as the future) for ages 5 and above: *M*=0.2 for ages 4 or less, *M*=0.579 for ages 5 and 6 and *M*=0.617 for ages 7 and above. (Note: after 1995 there was a decline in the abundance of older ages in the CAA, hence the starting year of 1996 for higher M).
9) OM9: As OM7, but natural mortality in the future is set to 0.2 from 2016 onwards.
10) OM10: As OM8, but natural mortality in the future is set to 0.2 from 2016 onwards.
11) OM12: Survey selectivity is assumed to decline exponentially from age 8 and above, with a minimum of 0.5. The slope of the decline is computed from the decline over ages 7 to 8.
12) OM13: As OM1, but the hockey-stick stock-recruitment relationship is based on the last 5 years of reliable recruitment estimates.
13) OM14: As OM1, but the future stock-recruitment relationship is a Beverton-Holt curve capped at a maximum value, see equation 20.
14) OM15: As OM8, but the hockey-stick stock-recruitment relationship is based on the last 5 years of reliable recruitment estimates.
15) OM16: This OM is a combination of higher natural mortality at older ages (*M*=0.2 pre-1996 and from 1996 *M*=0.2 for ages 6 or less, *M*=0.76 for ages 7 and above, no changes in the future) and low future recruitment (hockey-stick stock-recruitment relationship based on the last 5 years of reliable recruitment estimates).
16) OM17: As OM1 but the hockey-stick stock-recruitment relationship is based on all years with reliable recruitment estimates (1984-2008).

17) OM18: As OM1 but the hockey-stick stock-recruitment relationship is based on years with relatively good recruitment (1984-1994).
18) Rob3: This robustness test is run for each OM in the RS. Future recruitments are as described in the OMs forming the RS, but in the first eight years of projections, recruitment is assumed to be at the level of the lowest recruitment over the 1999-2008 period.

The set of OMs agreed initially included OM11 which would have generated future CPUE values to be used as additional input to the MP for TAC computation (Porter and Docherty 2011). However time constraints precluded this option from being investigated further.

The subset of six of these OMs which comprise the Reference Set (RS) includes OMs 1, 2, 3, 8, 14 and 17 (see Table 1). This subset was chosen to cover the most important uncertainties in a balanced way. Most of the simulation testing of the CMPs was carried out using the RS. (Note: DFO 2011a,b detail the process used to amend this full set and the RS slightly from the earlier specifications agreed at the 9-10 December 2010 workshop.)

The Table lists values of $\sigma_R$ and $\sigma_{survey}$ for each OM. These indicate the extents to which future recruitment varies about its expected value and survey results vary about the underlying (survey-selectivity weighted) biomass when projecting. They are inferred from the variation evident from past trends in recruitment and surveys about expected values in the assessment corresponding to the OM concerned. Technically they reflect the standard deviations of the logs of the quantities concerned about their expected values. Roughly speaking a $\sigma$ value of 0.4 corresponds to a 95% probability interval between half to double of the expected value, and 0.8 from a quarter to four times this amount. The values of $\sigma_R$ and $\sigma_{survey}$ are generally high, especially for the survey index. This means that the quality of the information which the survey provides about resource trends is poor, which in turn makes setting appropriate catch levels without compromising resource abundance particularly difficult.

Fig. 1 illustrates the time series of past recruitments and biomasses estimated for the OMs considered. Note the high recent recruitment and biomass estimates when the 2010 survey result is omitted from the assessment (OM3), and further the higher recruitments and biomasses over the last two decades in instances where there has been an increase in the value of natural mortality *M* (OM7, OM8 and OM16). Fig. 2 shows fits of alternative stock-recruitment models to results from the assessment corresponding to OM1. These various stock-recruitment models provide the basis for generating future recruitments when projecting the resource forward, as discussed in more detail below.

## Projection Methodology

Projections into the future under a specific Candidate Management Procedure (CMP) are evaluated using the following steps, which update the numbers-at-age in the population that result from the effects of natural mortality and the catch taken that year:

### *Step 1: Begin-year Numbers-at-age*

The components of the numbers-at-age vector at the start of 2010 ($N_{2010,a}$ : $a$ = 2,…, $m$) are obtained from the Maximum Likelihood Estimates (MLEs) provided by an assessment of the resource using VPA. The 2010 recruitment ($N_{2010,2}$) is generated deterministically from the estimated stock-recruitment relationship (see below). Error is included for ages 2 to 7 because these are poorly estimated in the assessment given limited information on these year-classes, *i.e.,*:

$$N_{2010,a} \rightarrow N_{2010,a} e^{\varepsilon_a} \qquad \varepsilon_a \text{ from } N\left(0, \left(\sigma_R\right)^2\right) \tag{9}$$

where $\sigma_R$ is estimated in the process of fitting a stock-recruitment relationship to the outputs from that assessment as described below. Equation 9 is approximate in that it omits to adjust for past catches from the year-class concerned, but these are so small that the differential effect is negligible.

*Step 2: Catch*

These numbers-at-age are projected one year forward at a time given a catch for the year concerned.
For 2010: A catch of 4200t is assumed.
For 2011: A catch of 6000t is assumed.
From 2012 onwards: $C_y$ is as specified by the CMP.

This requires specification of how the catch is disaggregated by age to obtain $C_{y,a}$, and how future recruitments are specified.

*Step 3: Catch-at-age*

The selectivity each year is selected randomly from the selectivity vectors for the last 10 years (2000 to 2009) estimated in the assessment. The selectivity vectors for 2000 to 2009 are computed as follows:

$$S_{y,a} = F_{y,a} / \max\left(F_{y,a}\right) \tag{10}$$

where the maximum is taken across the ages for that year.

From this it follows that:

$$F_y = C_y / \sum_a w_{y,a}^{mid} N_{y,a} e^{-M_a/2} S_{y,a} \tag{11}$$

where $w_{y,a}^{mid}$ is each year selected randomly from the weight-at-age vectors for the last 10 years (2000 to 2009) used in the assessment (Table 2) , and hence that:

$$C_{y,a} = N_{y,a} e^{-M_a/2} S_{y,a} F_y \tag{12}$$

Thus the circumstances of the last 10 years with regard to weight-at-age and selectivity are assumed to carry forward into the future.

If $F_y > 0.95$, *i.e.,* unrealistically large, some modifications are necessary. First, the maximum catch for that year is computed assuming all ages are fully selected and a fishing proportion of 0.95:

$$C_y^{\max} = \sum_a 0.95 N_{y,a} w_{y,a}^{mid} e^{-M_a/2} \tag{13}$$

If $C_y^{\max} < C_y$, the TAC for that year cannot be caught giving: $S_{y,a}^{*} = 1$ and $F_y^{*} = 0.95$ and a catch that year of $C_y^{\max}$.

If $C_y^{\max} \geq C_y$, then:

$$S_{y,a}^{*} = (1 - g_y) S_{y,a} + g_y \tag{14}$$

Solving for $g_y$:

$$g_y = \frac{\left( \sum_a S_{y,a} w_{y,a}^{mid} 0.95 N_{y,a} e^{-M_a/1} \right) - C_y}{\left( \sum_a S_{y,a} w_{y,a}^{mid} 0.95 N_{y,a} e^{-M_a/1} \right) - \left( \sum_a w_{y,a}^{mid} 0.95 N_{y,a} e^{-M_a/1} \right)} \tag{15}$$

and hence:

$$C_{y,a} = N_{y,a}\, e^{-M_a/2} S_{y,a}^{*} 0.95 \tag{16}$$

The numbers-at-age can then be computed for the beginning of the following year (*y*+1):

$$N_{y+1,2} = R_{y+1} \tag{17}$$

$$N_{y+1,a+1} = \left( N_{y,a}\, e^{-M_a/2} - C_{y,a} \right) e^{-M_a/2} \qquad \text{for } 2 \leq a \leq m-1 \tag{18}$$

These equations reflect Pope's approximation.

The maximum age *m* is 13 (not a plus-group).

*Step 4: Recruitment*

Future recruitments (age 2) are provided by a Hockey-stick or a capped Beverton-Holt stock-recruitment relationship with autocorrelation in the stock-recruitment residuals:

$$R_y = \begin{cases} A e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } B_{y-2}^{sp} \geq B_{\min}^{sp} \\ \dfrac{A}{B_{\min}^{sp}} B_{y-2}^{sp} e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } B_{y-2}^{sp} < B_{\min}^{sp} \end{cases} \tag{19}$$

for the Hockey-stick, and

$$R_y = \begin{cases} \dfrac{\alpha B_{y-2}^{sp}}{\beta + B_{y-2}^{sp}} e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } \dfrac{\alpha B_{y-2}^{sp}}{\beta + B_{y-2}^{sp}} < R_{\max} \\ R_{\max} e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } \dfrac{\alpha B_{y-2}^{sp}}{\beta + B_{y-2}^{sp}} \geq R_{\max} \end{cases} \tag{20}$$

for the capped Beverton-Holt, where

$$\varepsilon_y^{SR} = \rho\varepsilon_{y-1}^{SR} + \sqrt{1-\rho^2}\zeta_y$$

with $\zeta_y$ from $N\left(0,\sigma_R^2\right)$,

$$A = \exp\left(\sum_{y=y1}^{y2} \ln R_y \Big/ (y2 - y1 + 1)\right) ,$$

$B_{\min}^{sp} = \min\left(B_y^{sp}\right)$ for the period (y1-2) to (y2-2) and

$$R_{\max} = \exp\left(\sum_{y=1984}^{2009} \ln(R_y) \Big/ n\right) \tag{21}$$

where the summation includes all years for which $B_{y-2}^{sp} > 20000\,\mathrm{t}$, and $\rho$ is obtained by minimising the following negative log-likelihood function:

$$-\ln L^{SR} = \sum_{1984}^{2009}\left[\ln\sigma_R + \left(\frac{\varepsilon_y^{SR} - \rho\varepsilon_{y-1}^{SR}}{\sqrt{1-\rho^2}}\right)^2 \Big/ 2\sigma_R^2\right] \tag{22}$$

with

$$\sigma_R = \sqrt{\sum_{y=y1}^{y2}\left(\varepsilon_y^{SR}\right)^2 \Big/ \left(y2 - y1 + 1\right)} \tag{23}$$

$$B_y^{sp} = \sum_{a=1}^{m} f_a w_{y,a} N_{y,a} \tag{24}$$

where $w_{y,a}$ is each year selected randomly from the weight-at-age vectors for the last 10 years (2000 to 2009) used in the assessment (Table 3), and $f_a$ is the maturity-at-age, taken to be 0 to age 3 and 1 from age 4 and above.

*<u>Step 5</u>:*

The information obtained in Step 1 is used to generate a value of the abundance index $I_{2011}$ (summer survey, in terms of biomass). Indices of abundance in future years will not be exactly proportional to true abundance, as they are subject to observation error. Log-normal observation error is therefore added to the expected value of the abundance index evaluated:

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \tag{25}$$

$\varepsilon_y^i$ from $N\left(0,\left(\sigma^i\right)^2\right)$ (26)

where

$B_y^i$ is the biomass (or numbers) available to the survey:

$$B_y^{summer} = \sum_{a=1}^{m} w_{y,a}^{mid} S_{y,a}^{surv} N_{y,a} e^{-M_a/2}\left(1 - S_{y,a}\, F_y \big/ 2\right) \quad (27)$$

The survey selectivities are taken as the catchabilities ($q_a^i$) estimated in that assessment, renormalized so that $\max(q_a^i) = 1$. The survey selectivity is assumed to be zero for age 2, and for ages 9 and above, the selectivity is assumed to remain flat at the age 8 level.

The constant of proportionality $q^i$ is as estimated for the assessment in question by:

$$\ell n\, \hat{q}^i = 1/27 \sum_{y=1984}^{2010}\left(\ln I_y^i - \ln \hat{B}_y^i\right) \quad (28)$$

$$\hat{\sigma}^i = \sqrt{1/27 \sum_{y=1984}^{2010}\left(\varepsilon_y^i\right)^2} \quad (29)$$

$$\varepsilon_y^i = \ell\mathrm{n}(I_y^i) - \ell\mathrm{n}(q^i \widehat{B}_y^i) \quad (30)$$

where the survey index of biomass $I_y^i$ is given in Table 4.

*Step 6*:

Given the new survey indices $I_{y+1}^i$ compute $TAC_{y+1}$ using the CMP.

*Step 7*:

Steps 1-6 are repeated for each future year in turn for as long a period as desired, and at the end of that period the performance of the candidate MP under review is assessed by considering statistics such as the average catch taken over the period and the final spawning biomass of the resource.

## Performance Statistics

It was decided during the process that three properties should be evaluated in a risk management context:

I) the risk of decline of the exploitable biomass (ages 4 to 8) below the 2000 level be kept low;
II) the risk of annual average catch variation of greater than 20% be kept moderately low; and
III) the magnitude of the average catch in the short, medium term and long term be maximized.

A number of mathematical expressions (Performance Statistics) were then proposed to capture these four properties:

(a) $\dfrac{B_{2021}^{4-8}}{B_{2000}^{4-8}}$, where $B_y^{4-8} = \sum_{a=4}^{8} w_{y,a}^{mid} N_{y,a}$ is the exploitable biomass in year *y*;

(b) $\dfrac{B_{2021}^{sp}}{B_{2000}^{sp}}$, where $B_y^{sp} = \sum_{a=1}^{m} f_{y,a} w_{y,a}^{mid} N_{y,a}$ is the spawning biomass in year *y*;

(c) $\dfrac{B_{2021}^{4-8}}{B_{2010}^{4-8}}$;

(d) $\dfrac{B_{2021}^{4-8}}{B_{1982-2010}^{4-8}}$, where $B_{1982-2010}^{4-8}$ is the average exploitable biomass over the 1982-2010 period;

(e) $\dfrac{B_{2021}^{4-8}}{B_{\text{target}}^{4-8}}$, where $B_{\text{target}}^{4-8}$ is pre-defined recovery target population size, for which 1984-1994 will be used;

(f) (Average) annual catch over short and medium terms:

$C_{2011}$, $C_{2012}$, $C_{2013}$, $C_{2014}$, $C_{2015}$, $C_{2016}$ and $\sum_{y=2011}^{2020} C_y \Big/ 10$;

(g) Average annual variation in catch over the medium term:

$$AAV_{2011-2020} = \frac{1}{10} \sum_{y=2011}^{2020} \left| C_y - C_{y-1} \right| / C_{y-1}$$

**<u>The Candidate Management Procedures</u>**

The seven CMPs that were considered at the 9-10 May RAP are all "target-based" MPs, for which the TAC drops linearly (see equation 31 below) as the value of the survey index drops, until a quadratic penalty term (see equation 32 below) kicks in to decrease the TAC faster once the index falls below a threshold value $J_0$. This "target-based" approach was used instead of a derivative-based approach where TAC adjustments depend on the trend in the index over time, because the former approach tends to show lesser variability in TACs from year to year.

In general terms, the formulae used by these target-based Candidate Management Procedures (CMPs) for computing the TAC each year are as follows:

$$C_{y+1} = \left[a + b\left(J_y - J_0\right)\right] - pen \qquad (31)$$

with

$$pen = \begin{cases} 0 & \text{if } J_y \geq J_0 \\ c\left(J_y - J_o\right)^2 & \text{if } J_y < J_0 \end{cases} \tag{32}$$

where

$C_y$ is the total TAC recommended for year *y*,
$a$ , $b$ and $c$ are tuning parameters,
$J_0$ is a tuning parameter, and
$J_y$ is a measure of the immediate past level in the survey abundance index relative to a target level as available to use for calculations for year *y*:

$$J_y = \frac{\exp\left(\sum_{y-2}^{y} \ln\left(I_y\right) \Big/ 3\right)}{\exp\left(\sum_{1984}^{1994} \ln\left(I_y\right) \Big/ 11\right)} \tag{33}$$

where $I_y$ is the survey abundance index in year *y*.

Note: $I_{2009}$ is set to 15 (rather than to the actual value of 47.04 – see Table 4) in all the CMPs presented here for enhanced stability of the TAC in the short term. Furthermore, $I_{2010}$ is also fixed (see Table 5) to achieve certain performance than set equal to the actual survey result of 5.39 that year for the CMP*+ options.

The maximum allowable annual increase in TAC is set to 20% or 500 t, whichever is the greatest - this is so that the TAC can recover (reasonably quickly given appropriate survey results) after going down to very low values. Furthermore, a cap (upper bound) on the TAC of 20000t has been imposed.

The maximum allowable decrease in TAC from one year to the next is:

$$MaxDecr_y = \begin{cases} 20\% & \text{if } J_y \geq Q_{\min} \\ \text{linear between } 20\% \text{ and } x\% & \text{if } Q_{\min} - 0.1 \leq J_y < Q_{\min} \\ 100\% & \text{if } J_y < Q_{\min} - 0.1 \end{cases} \tag{34}$$

where

$Q_{\min}$ is a tuning parameter.

The tuning parameters for each of these seven CMPs considered are given in Table 5, and Fig. 3 plots of the relationships between the TAC output from these CMPs (pre- the application of interannual constraints on catch allocation changes) and the three-year average survey index used as input to the CMPs (these relationships constitute the Harvest Control Rules). The three-year period for this average was found to provide the best balance between shorter periods which allow faster reaction to changes in resource abundance, and longer periods which reduce the extent of TAC variability by averaging over the errors in the survey results about the actual underlying abundance. Note that geometric rather than arithmetic averages of survey abundance indices are used as input to the formula for the TAC, as this was found to reduce the risk of unintended resource reduction (by reducing the influence of unusually high or low survey results) without compromising catches.

The seven CMPs considered comprise:

- CMPD whose control parameter values were pre-selected on the basis of indications from past data of likely sustainable catch levels at different levels of abundance and hence survey index values.
- CMPR and CMPH which are respectively less and more conservative in regard to TACs, and reflect the ends of the range of medium term recovery levels that were considered to span appropriate realistic choices by the 9-10 May RAP. Note from Table 5 that CMPH has a higher value of the control parameter $J_0$ than CMPR, so that the quadratic penalty term in the TAC formula comes into play earlier as the survey index drops than for CMPR, as is evident from Fig. 3.
- CMPint, which is intermediate between CMPR and CMPH in terms of the expected extent of recovery of the exploitable component of the biomass over the next decade.
- CMPR+, CMPint+ and CMPH+ which are variants of CMPR, CMPint and CMPH respectively that achieve roughly the same extents of resource recovery, but in situations where this requires some initial catch reduction before subsequent probable increase, reduce this reduction in the earlier years as a trade-off against possible greater later reduction. The Note above explains how CMPs are adjusted to achieve this greater stability of catches in the short term.

The fact that these rules admit the possibility of TACs dropping to zero necessitates some adjustment to the computation of the Annual Average TAC Variation (AAV) performance statistic defined above. In the event of the TAC reaching zero, the annual contribution that year to AAV, cannot be calculated because of dividing by zero. If the TAC the following year is also zero, then the Annual Variation for that year is obviously set to zero, if not the Annual Variation is set to 25%.

## RESULTS

The Tables and Figures of results of the application of the seven CMPs to the various OMs were chosen primarily to aid the comparison of performances of these CMPs, especially as they relate to the revised medium term Management Objectives that were agreed at the 9-10 May RAP (DFO 2011a,b). Note that these results have been obtained under the assumption of equality of the TAC and subsequent catch made that year, *i.e.,* that there is no 'implementation error'). Results for a C=0 option of no future catches are also shown at times to illustrate maximum resource recovery potential so as to put the performances of the other CMPs in context in this regard.

Table 6, which lists the performance statistics for application of these CMPs to the Reference Set (RS) of OMs is of particular importance, as it provides values for these statistics which can be compared directly with targets set in the Management Objectives (see Discussion section below). As would be expected from the plots in Fig. 3 relating the TAC to the average survey index, at the conservative end of this range of CMPs, CMPD and CMPH show the greatest increase in exploitable biomass, but the lowest total catches, over the next decade, with the reverse evident for CMPR at the other end of the range. Median increases in exploitable biomass compared to the low level in 2000 range from about 100% to only 25% as the range is traversed, with a concomitant increase in average annual catch from about 4000 to 5000 t.

In contrast, Table 7 shows those results separately for each of the six OMs that comprise the RS under application of one of the CMPs, CMPint+, which was the one eventually selected. This table provides an indication of how MP performance varies across what are considered to be a balanced set of the most important sources of uncertainty. Catches are highest if OM3 reflects reality, and lowest for OM1, reflecting the difference between whether or not the result from the 2010 survey is taken into account in the corresponding assessment. Resource recovery is least under OM14 with its Beverton-Holt stock-recruitment relationship, for which recruitment is lower than for the other OMs at spawning biomasses close to that at present (see Fig. 2), and greatest if the higher future recruitments of OM17 eventuate.

Fig. 4 is intended to provide a helpful initial impression of how the TAC responds to future survey abundance estimates for each of the CMPs, by considering a range of different fixed future survey results to see what TACs result for each CMP. These show the slight delay in the reaction of the TAC to changes in the survey results because the formula is based on an average of these results over three years. They also indicate that it is only in the final example of a marked reduction in survey outcomes over the next few years that there is in due course a substantial reduction in the current TAC.

Fig. 5 plots ten future realizations of TACs and exploitable biomasses for the application of CMPint+ to each of the OMs comprising the RS. It is a form of graphical equivalent to Table 7, and is included to emphasise the extent of future variability to be expected in both the TAC and the exploitable biomass ($B_{4\text{-}8}$), which is high for both. This is not immediately apparent from plots following in Figs. 6 and 7 which show projections as medians and probability interval envelopes, and which can lead to false impressions of smoothness in future TACs and resource biomass over time.

Figs. 6a-h show projections under the RS in the form of those medians and probability envelopes for C=0 and each of the seven CMPs for a variety of future catch, biomass, survey, recruitment and related quantities. Wide future variation is evident in nearly all these plots. This follows from the high variability in the survey index $J_y$, which is a consequence of both high recruitment variability and high variance in the index about the underlying abundance as indicated in Table 1. Only the inter-annual proportional changes in the TAC are generally low (through the CMP design – equation 34), but even these can display large reductions if the survey index drops to low levels. Note the occasional instances of values above +20% in these plots, which arise from the rule that increases of up to 500 t are allowed even if this exceeds 20% of the current TAC.

Fig. 7 is an extract from Fig. 6 which compares median and lower 25%iles for future catches and exploitable biomasses under the RS for these same CMPs. The reason for choosing this particular extraction is to provide a focus on the performance statistics most closely related to the Management Objectives (see Discussion section below). Note the feature of less early and more later “pain” displayed by the “+” variants of the CMPs (Fig. 7b), which show higher initial catches than their respective counterparts (without the “+”) for the first few years, but see this difference reverse after about five years.

Figs. 8 and 9 are alternative approaches to summarizing these performance statistics. Fig. 8 compares performances for C=0 and the seven CMPs under the RS, while Fig. 9 compares results for CMPint+ under each of the full set of OMs. These plots condense a considerable amount of information in a manner that makes comparisons and trade-offs amongst the different Management Objectives more readily apparent – in Fig. 8 to assist choose amongst the CMPs, and in Fig. 9 to be able to check whether a specific CMP achieves reasonably robust performance across the full range of major uncertainties about the resource and its associated fishery.

In Fig. 8, the trade-off of increased catch over the first five years against lesser recovery by 2021 is very clear as one moves from left (CMPD and CMPH) to right (through to CMPR) in these plots, though the average level of variability in the TACs from year to year hardly changes. Fig. 9 shows that resource recovery is poor if OM13 with its poor average future recruitment level applies, and that this becomes worse if that scenario is coupled to a past increase in *M* (OM15). On the positive side, the highest catches result if OM3 (developed by ignoring the 2010 survey result) applies, and catches also increase after a few years if either OM10 (an increase in *M* in the past returning to its earlier lower value) or high average recruitment (OM18) eventuate.

## DISCUSSION

The medium-term Management Objectives agreed the pollock MSE at the 9-10 May RAP (DFO 2011a,b), to be evaluated under the RS of OMs, were:

- *Sustainability:* the median of the ratio of the projected exploitable biomass ($B_{4\text{-}8}$) in 2021 to that in 2000 must be at least 1.5; the lower 25 percentile for this ratio must be at least 1;
- *Catch*: projections of median catch resulting from the HCR must be greater than 4000 t for each of the next 5 years starting in 2012 (note that the projections assume that the catch taken each year is exactly as set);
- *Restrictions on annual catch changes and maximum catch*: Maximum annual catch increase of 20% or 500 t, whichever is greater; maximum inter-annual TAC decrease of 20% provided the geometric mean of the last three survey estimates remains at least 20% of the geometric mean over the 1984-1994 period (if this value drops below the 20% level, greater decreases are permissible); maximum annual catch of 20,000 t.

The requirements of the third of these bullets are met “by construction” (*i.e.,* are “hard-wired”) in the rules that apply to all of the CMPs (see equation 34 and preceding text).

Inspection of the results shown in Table 6 (see the bolded figures in particular) shows that while meeting sustainability targets, CMPD, CMPH and CMPH+ fail to meet the targets for median catches over the next 5 years, as these drop below 4000 t on occasion. In contrast, CMPR and CMPR+ meet the catch targets, but fail the sustainability requirements with the exploitable biomass in 2021 failing to achieve a 50% increase over the 2000 level in median terms, and at the lower 25%-ile falling below this level by some 25%.

CMPint virtually meets the sustainability targets, but fails to meet the catch target for 2013 only. Adjusting CMPint to CMPint+, however, sees all targets for both catch and sustainability met.

Accordingly the RAP chose CMPint+ as the MP to apply to the Western Component of 4x5 Pollock.

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*Table 1: Summary of the different OMs and Rob3, where the notes on each OM summarise differences from OM1. (Note that #11 was eliminated from consideration.)*

| | Included in RS | Characteristics | Stock-recruitment relationship | $\sigma_R$ | $\sigma_{survey}$ |
|---|---|---|---|---|---|
| OM1 | √ | RAD1 (Rademeyer and Butterworth, 2011): no bias correction, *M* =0.2, including 2010 survey estimate | based on last 10 reliable years (1999-2008) | 0.40 | 0.78 |
| OM2 | √ | Stone (Stone, 2011): with bias correction, *M* =0.2, including 2010 survey estimate | based on last 10 reliable years (1999-2008) | 0.72 | 0.80 |
| OM3 | √ | Stone (Stone, 2011): with bias correction, *M* =0.2, excluding 2010 survey estimate; | based on last 10 reliable years (1999-2008) | 0.25 | 0.76 |
| OM4 | | Survey abundance: square root | based on last 10 reliable years (1999-2008) | 0.49 | 0.76 |
| OM5 | | Survey abundance: power (square) | based on last 10 reliable years (1999-2008) | 0.26 | 1.56 |
| OM6 | | Survey abundance: mixture distribution for future | based on last 10 reliable years (1999-2008) | 0.40 | 0.44 - 0.53 |
| OM7 | | *M* =0.2 age 6 or less, age 7-13 *M* =0.675 – no change in future | based on last 10 reliable years (1999-2008) | 0.38 | 0.71 |
| OM8 | √ | *M* =0.2 for ages 4 or less, *M* =0.579 for ages 5 and 6 and *M*= 0.617 for ages 7 and above - no change in future | based on last 10 reliable years (1999-2008) | 0.37 | 0.71 |
| OM9 | | *M* as in OM7 but all back to 0.2 after 5 years | based on last 10 reliable years (1999-2008) | 0.38 | 0.71 |
| OM10 | | *M* as in OM8 but all back to 0.2 after 5 years | based on last 10 reliable years (1999-2008) | 0.37 | 0.71 |
| OM12 | | Dome shaped survey selectivity | based on last 10 reliable years (1999-2008) | 0.40 | 0.78 |
| OM13 | | As OM1 | based on last five reliable years (2004-2008) | 0.57 | 0.78 |
| OM14 | √ | As OM1 | Beverton-Holt, fit up to a max value corresponding to the average values for $B^{sp}$ | 0.49 | 0.78 |
| OM15 | | As OM8 | based on last five reliable years (2004-2008) | 0.70 | 0.71 |
| OM16 | | M=0.2 age 6 or less, age 7-13 M=0.76 – no change in future | based on last five reliable years (2004-2008) | 0.38 | 0.72 |
| OM17 | √ | As OM1 | based on all reliable years (1984-2008) | 0.61 | 0.78 |
| OM18 | | As OM1 | based on 1984-1994 period | 0.21 | 0.78 |
| Rob3 | | for each OM in the RC | based as each OM in the RS, but recruitment in the first eight years of projections is assumed to be at the level of the lowest recruitment over the 1999-2008 period | - | - |

*Table 2: Mid-year weights-at-age (kg) matrix for Canadian Pollock in the Western Component (4Xopqrs5). Note: a missing value for age 12 in 2008 has been replaced by the average of the five previous years, while missing values for age 13 have been replaced by 11 kg.*

| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1982 | 0.943 | 1.427 | 2.529 | 3.462 | 4.211 | 4.772 | 5.681 | 6.239 | 7.687 | 8.622 | 10.621 | 10.802 |
| 1983 | 0.881 | 1.349 | 1.983 | 3.373 | 4.367 | 5.105 | 5.651 | 6.624 | 7.220 | 8.381 | 8.886 | 9.188 |
| 1984 | 0.914 | 1.635 | 2.331 | 3.005 | 4.078 | 5.401 | 6.062 | 6.208 | 6.661 | 7.230 | 9.725 | 8.091 |
| 1985 | 0.974 | 1.615 | 2.462 | 3.169 | 3.695 | 4.296 | 6.022 | 7.315 | 7.185 | 7.968 | 9.343 | 9.401 |
| 1986 | 0.738 | 1.554 | 2.306 | 3.095 | 3.929 | 4.530 | 5.791 | 6.651 | 7.161 | 7.322 | 8.698 | 6.835 |
| 1987 | 0.943 | 1.475 | 2.266 | 3.046 | 3.564 | 4.315 | 4.907 | 5.300 | 6.794 | 7.482 | 7.909 | 8.806 |
| 1988 | 1.195 | 1.549 | 2.240 | 3.096 | 3.807 | 4.191 | 4.979 | 5.886 | 7.073 | 8.169 | 8.454 | 8.467 |
| 1989 | 0.880 | 1.313 | 2.095 | 3.068 | 3.885 | 4.491 | 4.869 | 6.012 | 6.334 | 8.911 | 7.133 | 10.715 |
| 1990 | 0.571 | 1.263 | 2.055 | 2.894 | 3.657 | 4.766 | 5.818 | 6.371 | 6.966 | 7.625 | 9.770 | 9.070 |
| 1991 | 0.906 | 1.344 | 2.153 | 2.866 | 3.736 | 4.730 | 5.711 | 6.460 | 6.815 | 8.060 | 9.030 | 9.778 |
| 1992 | 1.033 | 1.271 | 1.831 | 2.615 | 3.509 | 4.614 | 5.466 | 6.141 | 6.864 | 8.164 | 9.189 | 8.947 |
| 1993 | 0.761 | 1.110 | 1.666 | 2.312 | 3.143 | 3.754 | 4.723 | 5.492 | 6.704 | 7.704 | 8.131 | 8.606 |
| 1994 | 0.805 | 1.250 | 1.586 | 2.163 | 3.058 | 3.765 | 4.219 | 4.854 | 6.268 | 6.082 | 7.846 | 8.539 |
| 1995 | 0.671 | 1.132 | 1.806 | 2.296 | 3.038 | 3.941 | 4.796 | 5.389 | 7.348 | 8.573 | 8.781 | 9.392 |
| 1996 | 0.896 | 1.336 | 1.795 | 2.353 | 3.057 | 3.665 | 5.205 | 6.296 | 8.502 | 9.561 | 11.422 | 11.474 |
| 1997 | 0.915 | 1.388 | 1.938 | 2.446 | 3.288 | 3.976 | 5.101 | 7.763 | 10.058 | 6.737 | 11.915 | 11.000 |
| 1998 | 0.867 | 1.103 | 1.720 | 2.361 | 3.144 | 4.219 | 5.159 | 5.640 | 8.615 | 8.833 | 12.063 | 11.000 |
| 1999 | 0.806 | 1.193 | 1.682 | 2.419 | 3.245 | 4.288 | 5.659 | 7.057 | 9.939 | 9.943 | 10.000 | 11.000 |
| 2000 | 0.757 | 1.247 | 1.796 | 2.478 | 3.166 | 4.168 | 5.412 | 5.745 | 9.003 | 9.821 | 10.000 | 11.000 |
| 2001 | 0.453 | 1.039 | 1.987 | 2.929 | 3.734 | 4.775 | 6.532 | 8.118 | 8.539 | 9.026 | 10.788 | 13.067 |
| 2002 | 0.280 | 0.931 | 1.592 | 2.528 | 3.714 | 4.829 | 6.328 | 6.936 | 8.663 | 10.872 | 11.081 | 16.975 |
| 2003 | 0.590 | 0.977 | 1.536 | 2.376 | 3.528 | 4.780 | 6.289 | 7.427 | 9.281 | 10.090 | 8.875 | 11.000 |
| 2004 | 0.475 | 0.873 | 1.621 | 2.210 | 3.125 | 4.290 | 6.509 | 7.369 | 8.699 | 9.077 | 12.027 | 15.595 |
| 2005 | 0.391 | 0.955 | 1.439 | 2.152 | 2.801 | 4.087 | 5.479 | 5.956 | 9.216 | 14.277 | 14.277 | 11.000 |
| 2006 | 0.654 | 0.931 | 1.722 | 2.180 | 3.101 | 3.715 | 4.680 | 5.186 | 9.121 | 9.906 | 10.851 | 11.000 |
| 2007 | 0.660 | 0.948 | 1.573 | 2.525 | 2.973 | 3.944 | 4.567 | 6.229 | 7.352 | 10.195 | 13.091 | 11.000 |
| 2008 | 0.758 | 1.202 | 1.681 | 2.299 | 3.191 | 3.819 | 4.907 | 5.552 | 5.985 | 8.832 | 11.824 | 11.000 |
| 2009 | 0.585 | 1.137 | 1.884 | 2.451 | 3.318 | 4.153 | 4.558 | 5.074 | 5.324 | 11.959 | 12.974 | 13.123 |
| 2010 | 0.683 | 1.026 | 1.754 | 2.456 | 3.091 | 3.804 | 4.358 | 4.471 | 4.969 | 6.365 | 10.252 | 11.000 |

*Table 3: Begin-year weights-at-age (kg) matrix for Canadian Pollock in the Western Component (4Xopqrs5).*

| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1982 | 0.284 | 0.811 | 1.693 | 2.988 | 3.818 | 4.483 | 5.207 | 5.954 | 6.925 | 8.141 | 9.569 | 10.809 |
| 1983 | 0.303 | 1.235 | 1.660 | 2.949 | 3.888 | 4.637 | 5.193 | 6.134 | 6.712 | 8.027 | 8.753 | 10.809 |
| 1984 | 0.360 | 0.944 | 2.615 | 2.730 | 3.709 | 4.857 | 5.563 | 5.923 | 6.643 | 7.225 | 9.028 | 9.887 |
| 1985 | 0.323 | 0.807 | 2.301 | 2.900 | 3.332 | 4.186 | 5.703 | 6.659 | 6.679 | 7.285 | 8.219 | 10.343 |
| 1986 | 0.423 | 0.900 | 1.608 | 3.136 | 3.529 | 4.091 | 4.988 | 6.329 | 7.238 | 7.253 | 8.325 | 10.138 |
| 1987 | 0.185 | 0.642 | 1.884 | 2.554 | 3.321 | 4.118 | 4.715 | 5.540 | 6.722 | 7.320 | 7.610 | 9.782 |
| 1988 | 0.572 | 0.696 | 1.364 | 2.704 | 3.405 | 3.865 | 4.635 | 5.374 | 6.123 | 7.450 | 7.953 | 9.327 |
| 1989 | 0.366 | 0.750 | 1.901 | 2.688 | 3.468 | 4.135 | 4.517 | 5.471 | 6.106 | 7.939 | 7.633 | 9.643 |
| 1990 | 0.254 | 0.656 | 1.323 | 2.784 | 3.350 | 4.303 | 5.112 | 5.570 | 6.471 | 6.950 | 9.331 | 8.858 |
| 1991 | 0.366 | 0.590 | 1.154 | 2.416 | 3.288 | 4.159 | 5.217 | 6.131 | 6.589 | 7.493 | 8.298 | 10.367 |
| 1992 | 0.331 | 0.776 | 1.374 | 1.990 | 3.171 | 4.152 | 5.085 | 5.922 | 6.659 | 7.459 | 8.606 | 9.966 |
| 1993 | 0.444 | 0.560 | 1.168 | 2.202 | 2.867 | 3.629 | 4.668 | 5.479 | 6.416 | 7.272 | 8.148 | 10.054 |
| 1994 | 0.309 | 0.693 | 1.108 | 1.617 | 2.659 | 3.440 | 3.980 | 4.788 | 5.867 | 6.385 | 7.775 | 9.457 |
| 1995 | 0.213 | 0.482 | 1.183 | 1.967 | 2.563 | 3.472 | 4.249 | 4.768 | 5.972 | 7.331 | 7.308 | 9.290 |
| 1996 | 0.200 | 0.613 | 1.042 | 1.951 | 2.649 | 3.337 | 4.529 | 5.495 | 6.769 | 8.382 | 9.896 | 9.828 |
| 1997 | 0.204 | 0.974 | 1.340 | 2.102 | 2.782 | 3.486 | 4.324 | 6.357 | 7.958 | 7.568 | 10.673 | 11.209 |
| 1998 | 0.375 | 0.604 | 0.971 | 2.016 | 2.773 | 3.725 | 4.529 | 5.364 | 8.178 | 9.426 | 9.015 | 11.448 |
| 1999 | 0.222 | 0.607 | 1.191 | 1.828 | 2.768 | 3.672 | 4.886 | 6.034 | 7.487 | 9.255 | 9.398 | 11.519 |
| 2000 | 0.264 | 0.697 | 1.209 | 1.838 | 2.767 | 3.678 | 4.817 | 5.702 | 7.971 | 9.880 | 9.972 | 10.488 |
| 2001 | 0.313 | 0.525 | 1.479 | 2.353 | 3.042 | 3.888 | 5.218 | 6.628 | 7.004 | 9.015 | 10.293 | 10.488 |
| 2002 | 0.257 | 0.605 | 1.173 | 2.115 | 3.298 | 4.246 | 5.497 | 6.731 | 8.386 | 9.635 | 10.001 | 10.894 |
| 2003 | 0.220 | 0.708 | 1.175 | 2.101 | 2.986 | 4.213 | 5.511 | 6.856 | 8.023 | 9.349 | 9.823 | 11.040 |
| 2004 | 0.205 | 0.566 | 1.430 | 1.906 | 2.725 | 3.890 | 5.578 | 6.808 | 8.038 | 9.178 | 11.016 | 9.881 |
| 2005 | 0.227 | 0.597 | 1.243 | 1.891 | 2.465 | 3.542 | 4.724 | 6.120 | 8.083 | 11.144 | 11.384 | 11.502 |
| 2006 | 0.350 | 0.702 | 1.393 | 1.926 | 2.524 | 3.196 | 4.335 | 5.194 | 7.245 | 9.372 | 12.447 | 12.532 |
| 2007 | 0.223 | 0.700 | 1.441 | 2.191 | 2.542 | 3.490 | 4.118 | 5.422 | 6.175 | 9.643 | 11.388 | 10.925 |
| 2008 | 0.370 | 0.772 | 1.342 | 1.966 | 2.835 | 3.365 | 4.390 | 5.034 | 6.132 | 8.058 | 10.979 | 12.000 |
| 2009 | 0.455 | 0.869 | 1.666 | 2.113 | 2.762 | 3.640 | 4.172 | 4.990 | 5.437 | 8.460 | 10.705 | 11.405 |
| 2010 | 0.073 | 0.750 | 1.550 | 2.180 | 2.753 | 3.553 | 4.254 | 4.514 | 5.021 | 5.821 | 11.073 | 11.946 |

*Table 4: Stratified mean catch per tow (kg) of pollock from the DFO summer research vessel survey in 4X strata corresponding to the western component.*

| Year | Stratified mean wt/tow |
|---|---|
| 1984 | 35.65 |
| 1985 | 39.23 |
| 1986 | 36.59 |
| 1987 | 37.27 |
| 1988 | 93.07 |
| 1989 | 31.70 |
| 1990 | 86.20 |
| 1991 | 30.48 |
| 1992 | 13.86 |
| 1993 | 37.15 |
| 1994 | 18.20 |
| 1995 | 14.35 |
| 1996 | 64.51 |
| 1997 | 8.84 |
| 1998 | 6.10 |
| 1999 | 5.30 |
| 2000 | 5.79 |
| 2001 | 14.84 |
| 2002 | 6.13 |
| 2003 | 18.37 |
| 2004 | 20.86 |
| 2005 | 15.16 |
| 2006 | 121.01 |
| 2007 | 23.90 |
| 2008 | 40.44 |
| 2009 | 47.04 |
| 2010 | 5.39 |

*Table 5: Tuning parameter values for each CMP. Parameters related to catches have units of t.*

| | 2011 catch assumed | a | b | c | $J_0$ | $I_{2009}$ | $I_{2010}$ | $Q_{min}$ | Interannual change constraints | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | *MaxIncr* | *MaxDecr* | Cap |
| CMPD | 6000 | 6000 | 9000 | 90000 | 0.48 | 15 | 5.39 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPH | 6000 | 6000 | 8000 | 200000 | 0.42 | 15 | 5.39 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPH+ | 6000 | 6000 | 8000 | 200000 | 0.44 | 15 | 15 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPint | 6000 | 6000 | 8000 | 200000 | 0.36 | 15 | 5.39 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPint+ | 6000 | 6000 | 8000 | 200000 | 0.39 | 15 | 11 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPR | 6000 | 6000 | 8000 | 200000 | 0.30 | 15 | 5.39 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |
| CMPR+ | 6000 | 6000 | 8000 | 200000 | 0.30 | 15 | 15 | 0.2 | +20%/500t | -20%/-40%/-100% | 20000t |

*Table 6: Projection results (first line: median and 50% PI in parenthesis, second line: percentage difference between median and corresponding median for CMPint+) for a series of performance statistics for different CMPs under the RS. Figures in* ***bold*** *relate to satisfying the Management Objectives. Catches are in t (per year).*

| | C=0 | | CMPD | | CMPH | | CMPH+ | | CMPint | | CMPint+ | | CMPR | | CMPR+ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $B^{4\text{-}8}_{2021}/B^{4\text{-}8}_{2000}$ | 3.52 | (2.45; 4.53) | **2.00** | (**1.35**; 2.89) | **1.90** | (**1.25**; 2.75) | **1.84** | (**1.16**; 2.65) | **1.65** | (**0.99**; 2.56) | **1.67** | (**1.01**; 2.54) | **1.35** | (**0.76**; 2.18) | **1.27** | (**0.69**; 1.97) |
| | 111% | | 20% | | 14% | | 10% | | -1% | | 0% | | -19% | | -24% | |
| $B^{sp}_{2021}/B^{sp}_{2000}$ | 8.70 | (5.93; 10.65) | **2.90** | (1.70; 4.75) | **2.60** | (1.58; 4.61) | **2.51** | (1.49; 4.28) | **2.11** | (1.23; 3.86) | **2.16** | (1.26; 3.93) | **1.67** | (0.92; 3.17) | **1.55** | (0.85; 2.72) |
| | 303% | | 35% | | 21% | | 16% | | -2% | | 0% | | -22% | | -28% | |
| $B^{4\text{-}8}_{2021}/B^{4\text{-}8}_{2010}$ | 2.12 | (1.64; 3.10) | 1.39 | (0.82; 2.14) | 1.31 | (0.72; 2.08) | 1.23 | (0.71; 1.97) | 1.07 | (0.61; 1.83) | 1.10 | (0.61; 1.84) | 0.90 | (0.46; 1.59) | 0.84 | (0.44; 1.47) |
| | 92% | | 26% | | 19% | | 11% | | -3% | | 0% | | -18% | | -24% | |
| $B^{4\text{-}8}_{2021}/\mathrm{av}(B^{4\text{-}8}_{1982\text{-}2010})$ | 1.26 | (0.97; 1.58) | 0.76 | (0.52; 1.05) | 0.70 | (0.46; 1.03) | 0.70 | (0.45; 1.00) | 0.62 | (0.38; 0.94) | 0.63 | (0.38; 0.94) | 0.52 | (0.28; 0.83) | 0.47 | (0.25; 0.73) |
| | 100% | | 21% | | 12% | | 11% | | -1% | | 0% | | -18% | | -25% | |
| $C_{2011}$ | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) |
| | 0% | | 0% | | 0% | | 0% | | 0% | | 0% | | 0% | | 0% | |
| $C_{2012}$ | 0 | (0; 0) | **4800** | (4800; 4800) | **4800** | (4800; 4800) | **5064** | (4800; 6260) | **4800** | (4800; 5691) | **5373** | (4800; 6289) | **5699** | (4800; 6287) | **6710** | (6132; 7200) |
| | -100% | | -11% | | -11% | | -6% | | -11% | | 0% | | 6% | | 25% | |
| $C_{2013}$ | 0 | (0; 0) | **3840** | (3561; 3840) | **3840** | (3561; 4825) | **4648** | (3840; 6210) | **3840** | (3582; 5760) | **4786** | (3840; 6280) | **5092** | (3715; 6293) | **6313** | (5246; 7451) |
| | -100% | | -20% | | -20% | | -3% | | -20% | | 0% | | 6% | | 32% | |
| $C_{2014}$ | 0 | (0; 0) | **3072** | (2750; 4608) | **3961** | (2756; 5517) | **4296** | (3046; 6555) | **4608** | (2774; 6667) | **4608** | (3046; 6912) | **5638** | (3190; 7215) | **5970** | (3973; 7698) |
| | -100% | | -33% | | -14% | | -7% | | 0% | | 0% | | 22% | | 30% | |
| $C_{2015}$ | 0 | (0; 0) | **3637** | (2098; 5530) | **3686** | (2129; 5588) | **3686** | (2274; 6707) | **5117** | (2352; 6834) | **4441** | (2351; 7086) | **5680** | (2791; 7618) | **5655** | (2931; 7790) |
| | -100% | | -18% | | -17% | | -17% | | 15% | | 0% | | 28% | | 27% | |
| $C_{2016}$ | 0 | (0; 0) | **3853** | (1885; 6636) | **4256** | (1926; 6636) | **3877** | (1877; 6648) | **4919** | (2230; 6923) | **4381** | (2037; 7249) | **5697** | (2628; 7973) | **5072** | (1672; 8026) |
| | -100% | | -12% | | -3% | | -12% | | 12% | | 0% | | 30% | | 16% | |
| $C_{2011\text{-}2020}$ | 600 | (600; 600) | 4219 | (3053; 6150) | 4552 | (3103; 6454) | 4429 | (3012; 6330) | 4900 | (3262; 6733) | 4677 | (3249; 6609) | 5085 | (3527; 6912) | 4969 | (3273; 6934) |
| | -87% | | -10% | | -3% | | -5% | | 5% | | 0% | | 9% | | 6% | |
| $AAV_{2011\text{-}2020}$ | 0 | (0; 0) | 20 | (17; 22) | 22 | (21; 25) | 22 | (20; 25) | 22 | (20; 26) | 22 | (19; 25) | 22 | (19; 26) | 22 | (19; 26) |
| | -100% | | -12% | | 0% | | 0% | | 0% | | 0% | | 0% | | -1% | |

*Table 7: Projection results (median and 50% PI in parenthesis), for a series of performance statistics for **CMPint+** for each OM in the RS. Figures in **bold** relate to satisfying the Management Objectives. Catches are in t (per year).*

| | OM1 | | OM2 | | OM3 | | OM8 | | OM14 | | OM17 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $B^{4-8}_{2021}/B^{4-8}_{2000}$ | **1.79** | (**1.05;** 2.49) | **1.88** | (**0.91;** 3.24) | **1.49** | (**1.01;** 2.02) | **1.42** | (**1.06;** 1.78) | **1.27** | (**0.53;** 2.27) | **2.50** | (**1.59;** 3.48) |
| $B^{sp}_{2021}/B^{sp}_{2000}$ | **2.49** | (1.50; 4.24) | **3.38** | (1.44; 5.73) | **1.76** | (1.11; 2.60) | **1.67** | (1.25; 2.09) | **1.68** | (0.87; 3.65) | **3.94** | (2.09; 6.73) |
| $B^{4-8}_{2021}/B^{4-8}_{2010}$ | 1.27 | (0.77; 1.84) | 1.58 | (0.73; 2.95) | 0.61 | (0.41; 0.89) | 1.29 | (0.90; 1.67) | 0.86 | (0.40; 1.62) | 1.65 | (0.95; 2.72) |
| $B^{4-8}_{2021}/av(B^{4-8}_{1982-2010})$ | 0.63 | (0.37; 0.88) | 0.67 | (0.33; 1.16) | 0.51 | (0.34; 0.69) | 0.68 | (0.51; 0.85) | 0.45 | (0.19; 0.80) | 0.89 | (0.56; 1.22) |
| $C_{2011}$ | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) | 6000 | (6000; 6000) |
| $C_{2012}$ | **5306** | (4800; 6042) | **4800** | (4800; 5871) | **6599** | (5800; 7113) | **4800** | (4800; 5658) | **5342** | (4800; 6098) | **5482** | (4800; 6262) |
| $C_{2013}$ | **4569** | (3840; 5766) | **3840** | (3485; 5446) | **7205** | (6190; 8124) | **3950** | (3840; 5144) | **4488** | (3840; 5832) | **5095** | (3840; 6310) |
| $C_{2014}$ | **4437** | (3070; 6195) | **3066** | (1969; 5201) | **8366** | (7023; 9419) | **3465** | (2766; 4942) | **4242** | (2954; 6012) | **5585** | (3243; 6937) |
| $C_{2015}$ | **3868** | (2458; 5689) | **2377** | (0; 5168) | **8495** | (7288; 10323) | **3212** | (2157; 4653) | **3122** | (1850; 5530) | **5383** | (3269; 7537) |
| $C_{2016}$ | **3748** | (2190; 5942) | **1976** | (0; 4634) | **8721** | (7205; 10007) | **2881** | (1937; 5120) | **2399** | (0; 4832) | **5695** | (3414; 8083) |
| $C_{2011-2020}$ | 4318 | (3469; 5307) | 3334 | (1954; 5069) | 7241 | (6761; 7868) | 3990 | (3217; 5000) | 3304 | (2690; 4773) | 5934 | (4409; 7247) |
| $AAV_{2011-2020}$ | 23 | (20; 25) | 24 | (21; 28) | 20 | (18; 22) | 23 | (21; 25) | 23 | (21; 26) | 21 | (19; 22) |


*Fig. 1: Time-trajectories of recruitment (N2), exploitable biomass (B4-8) and spawning biomass (B4+) for the OMs. Trajectories for OM6, OM12, OM13, OM14, OM17 and OM18 are the same as OM1 in the past, only the future dynamics are different. Similarly, OM9 trajectories are the same as that of OM7 and OM10 and OM15 trajectories are the same as OM8.*

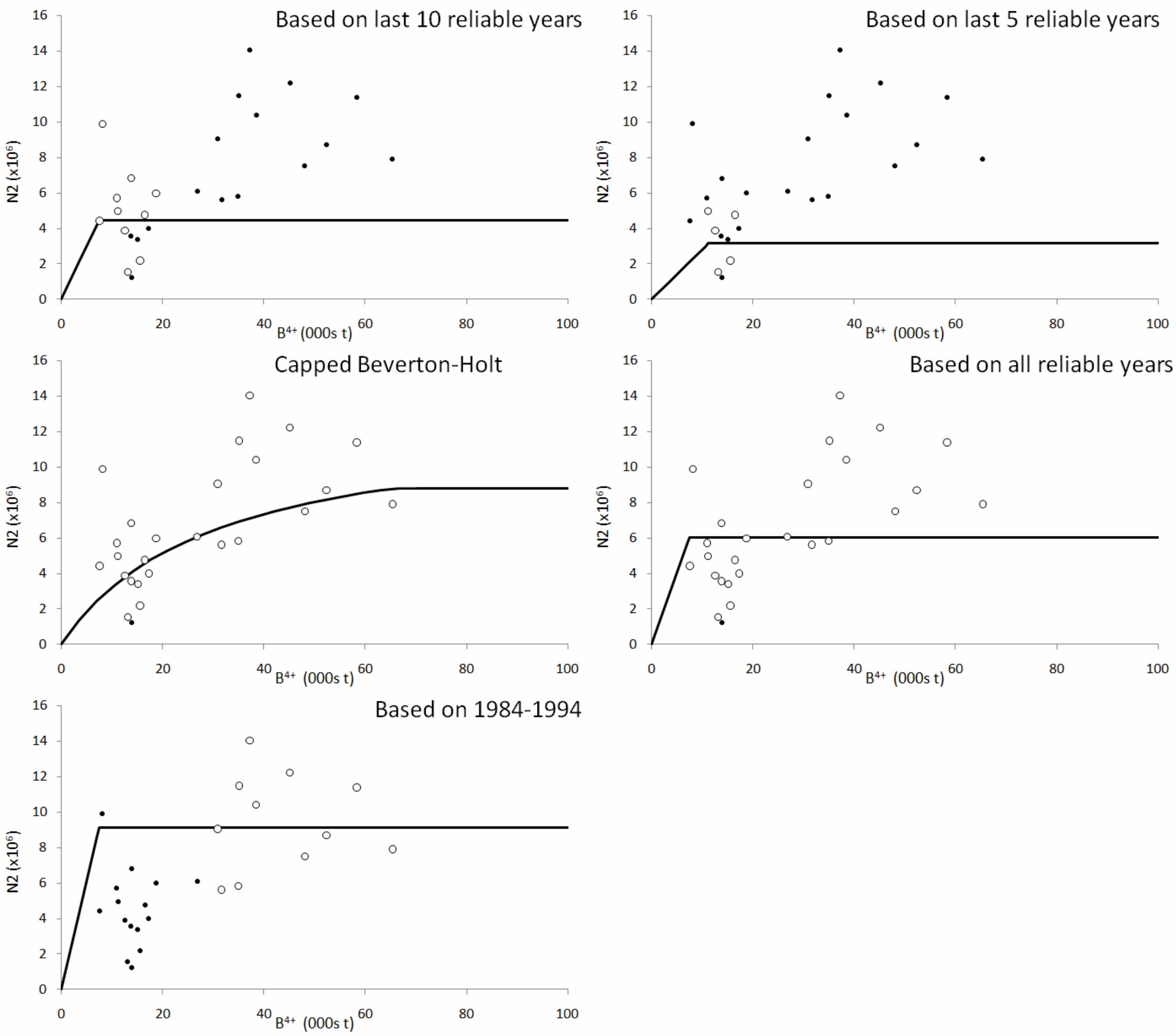


*Fig. 2: Different stock-recruitment relationships used in the OM for future recruitments. The past "data" shown are those for OM1 (open circles show the data on which the relationships are based).*

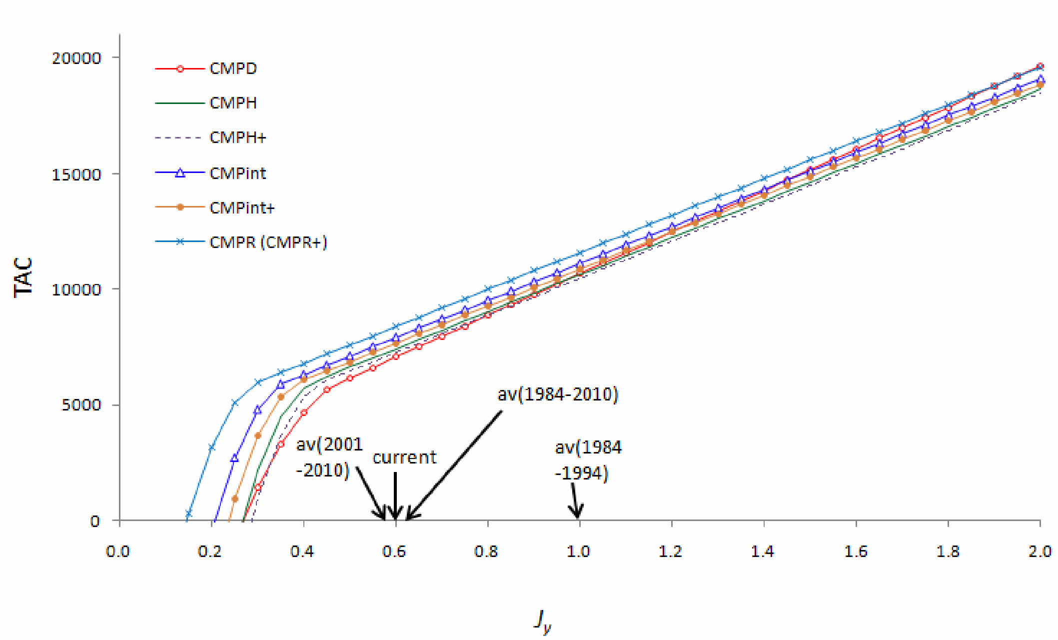


*Fig. 3: TAC (in t) as a function of $J_y$ for each of the seven CMPs presented.*

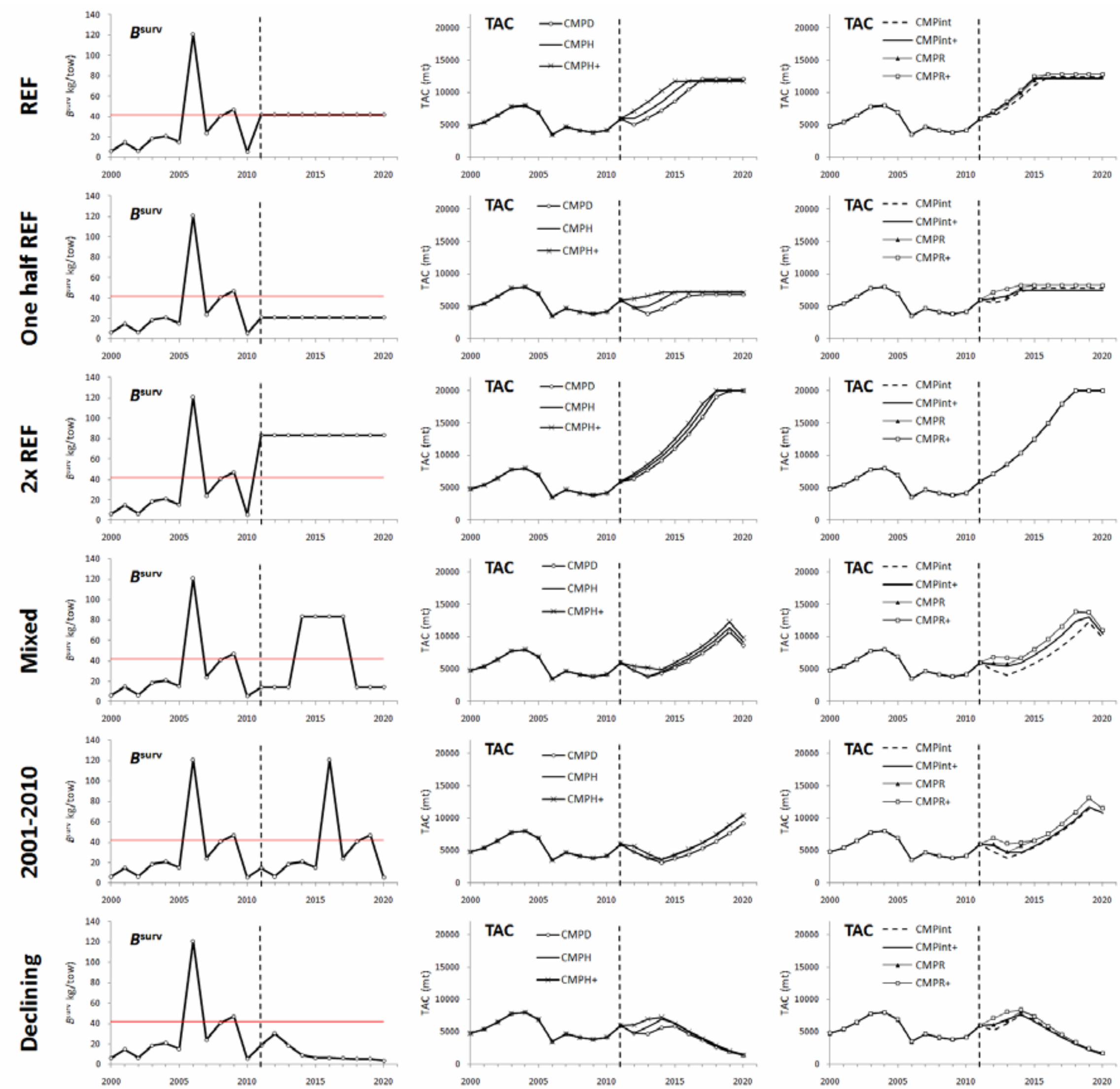


*Fig. 4: Catch and survey biomass trajectories under each CMP for a series of future survey scenarios provided by H. Stone.*

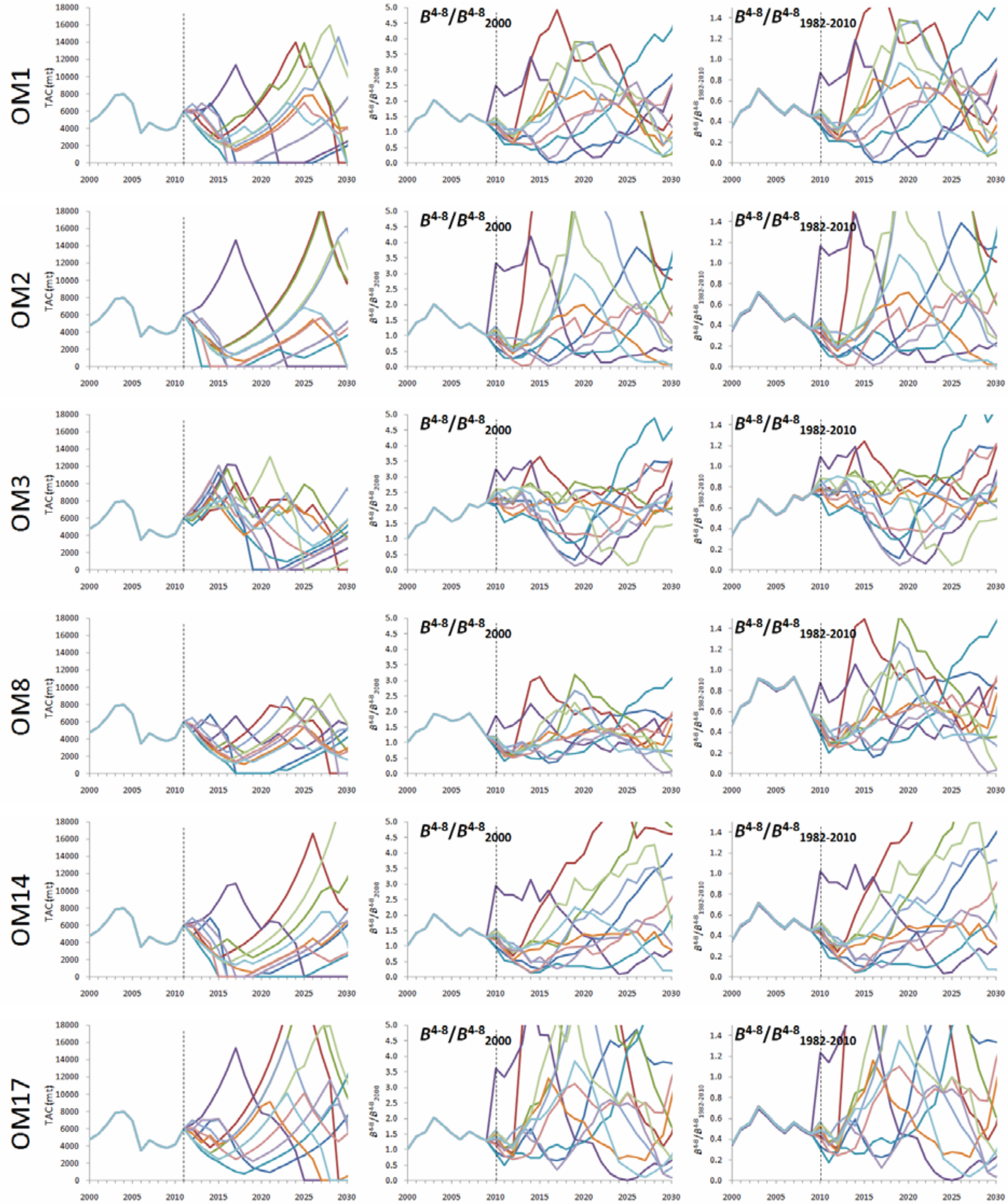


*Fig.5: "Worm" plots for a series of performance statistics for* ***CMPint+*** *applied to each OM in the RS.*

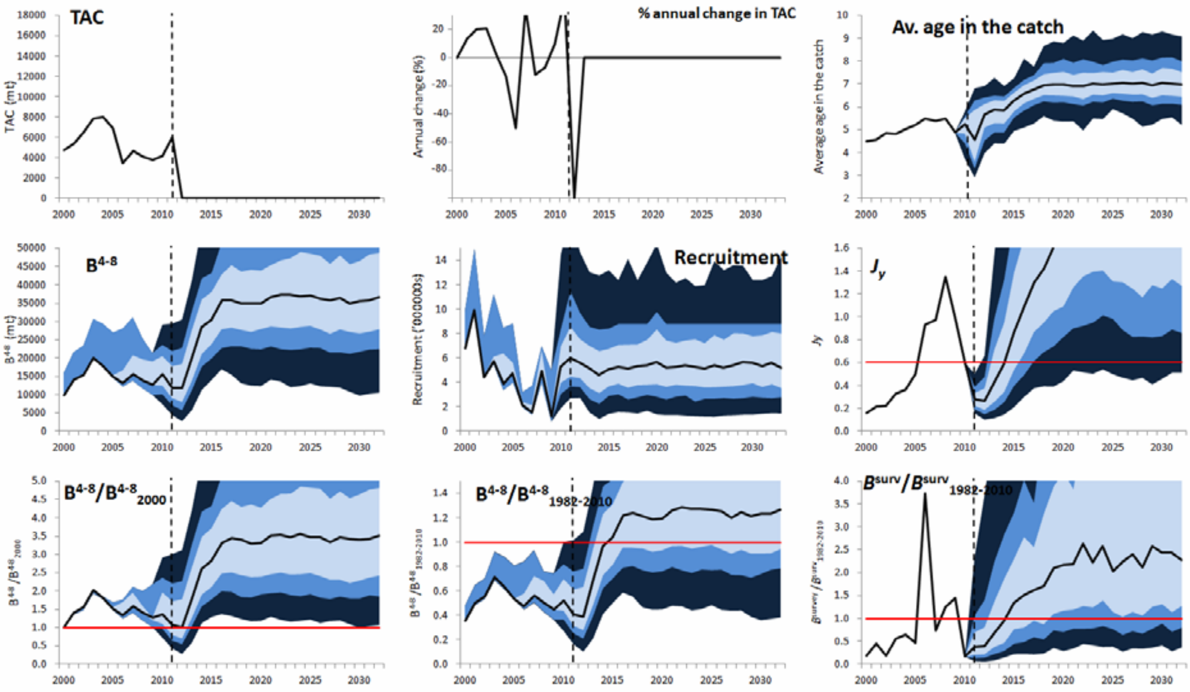


*Fig. 6a: 95, 75, 50% PI and median for a series of performance statistics for **C=0** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

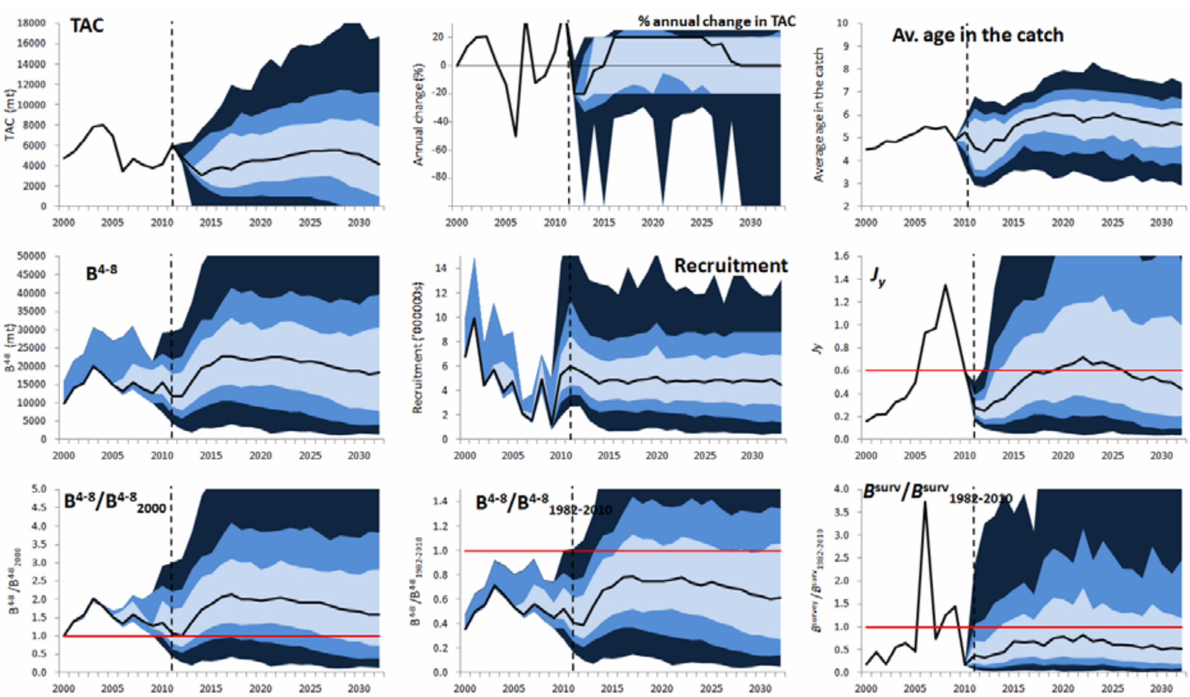


*Fig. 6b: 95, 75, 50% PI and median for a series of performance statistics for **CMPD** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

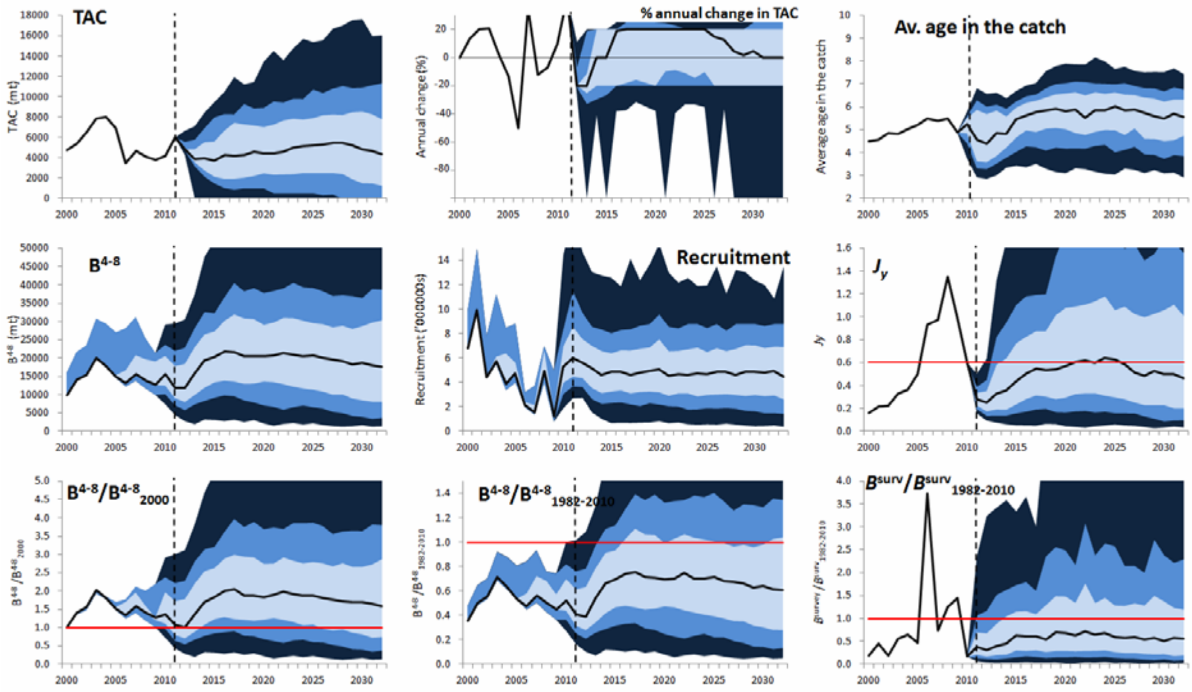


*Fig. 6c: 95, 75, 50% PI and median for a series of performance statistics for **CMPH** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

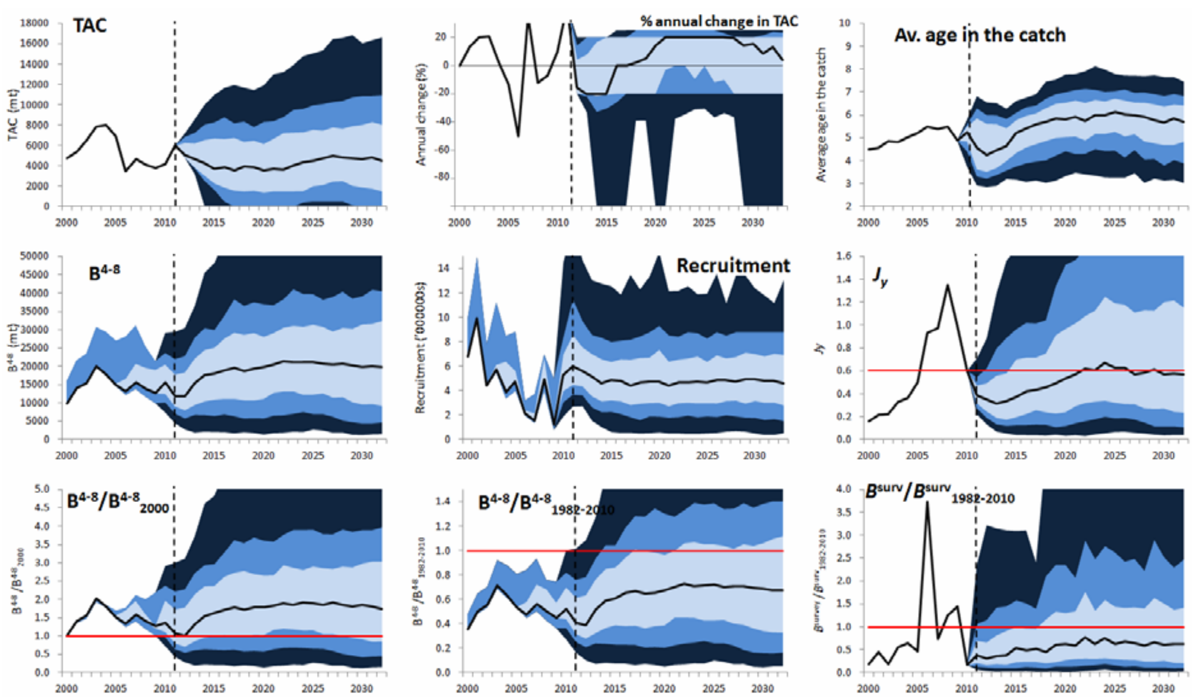


*Fig. 6d: 95, 75, 50% PI and median for a series of performance statistics for **CMPH+** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

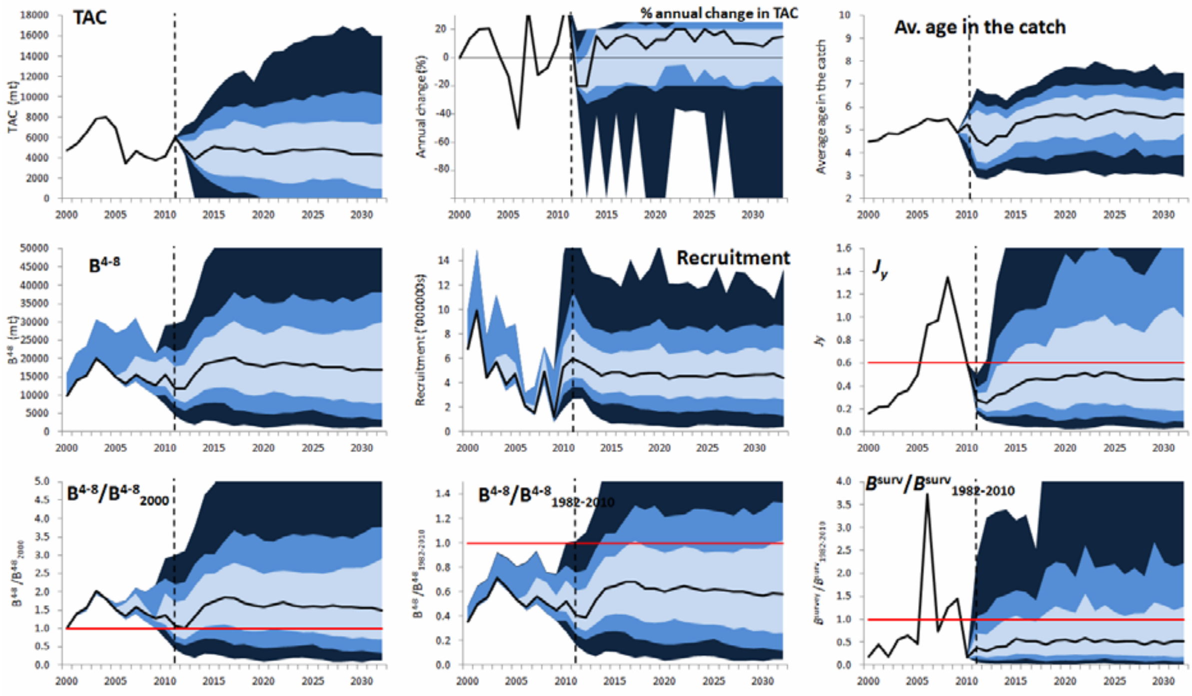


*Fig. 6e: 95, 75, 50% PI and median for a series of performance statistics for **CMPint** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

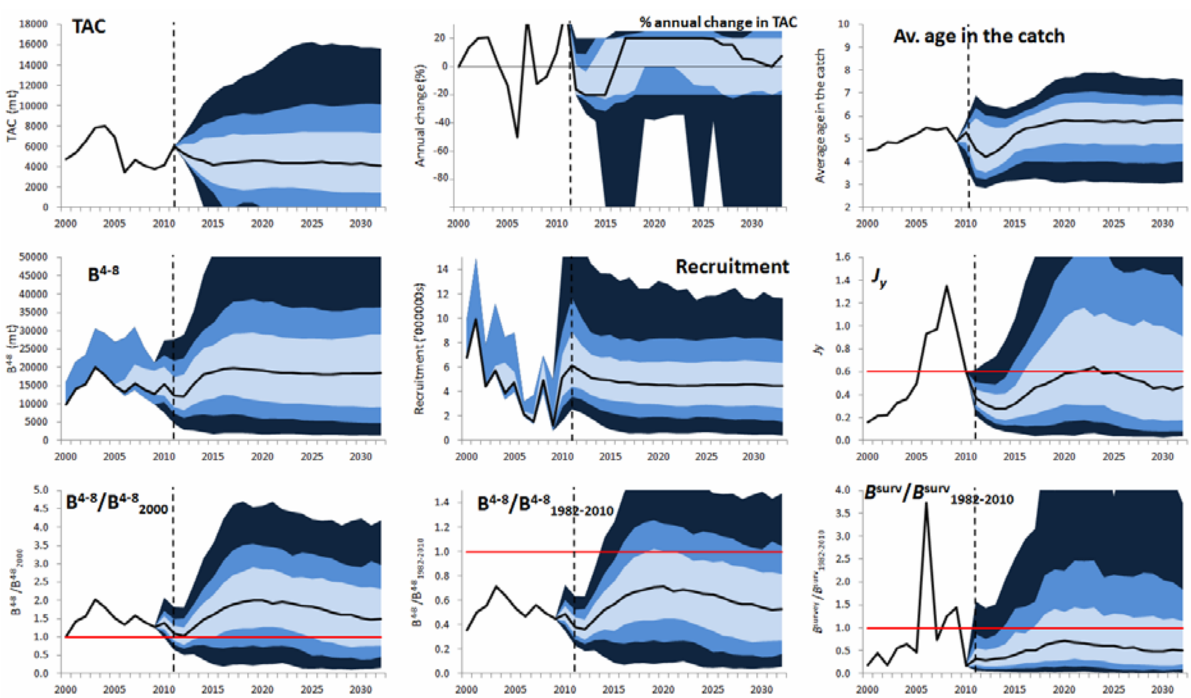


*Fig. 6f: 95, 75, 50% PI and median for a series of performance statistics for **CMPint+** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

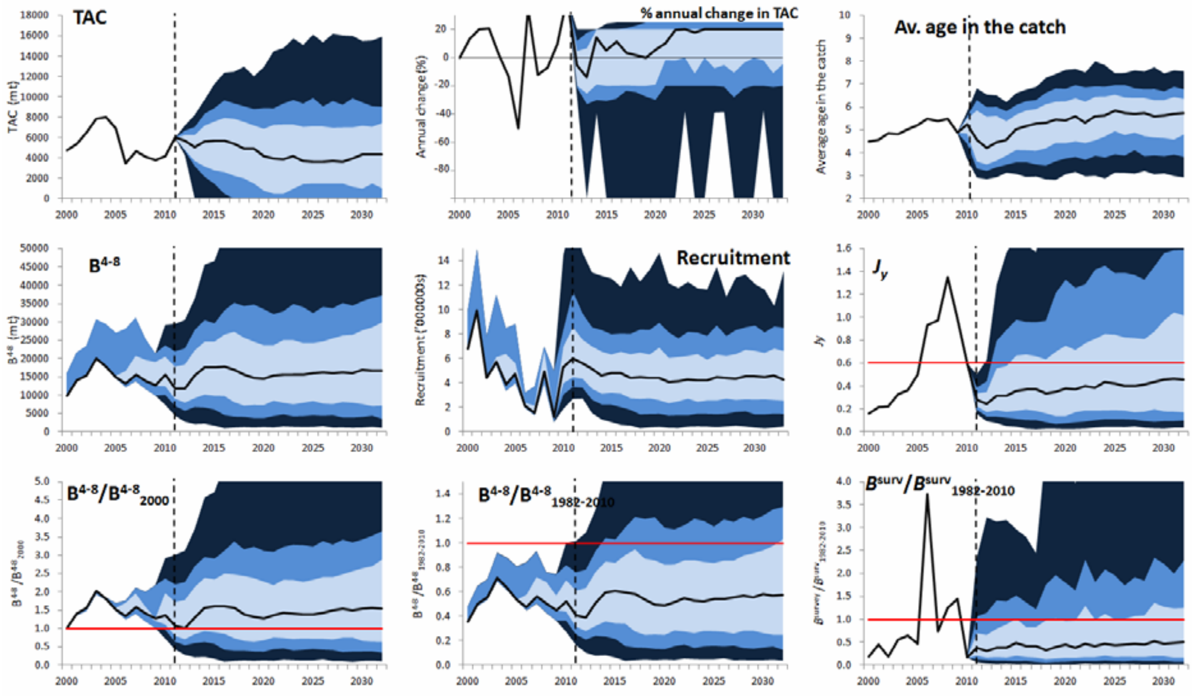


*Fig. 6g: 95, 75, 50% PI and median for a series of performance statistics for **CMPR** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

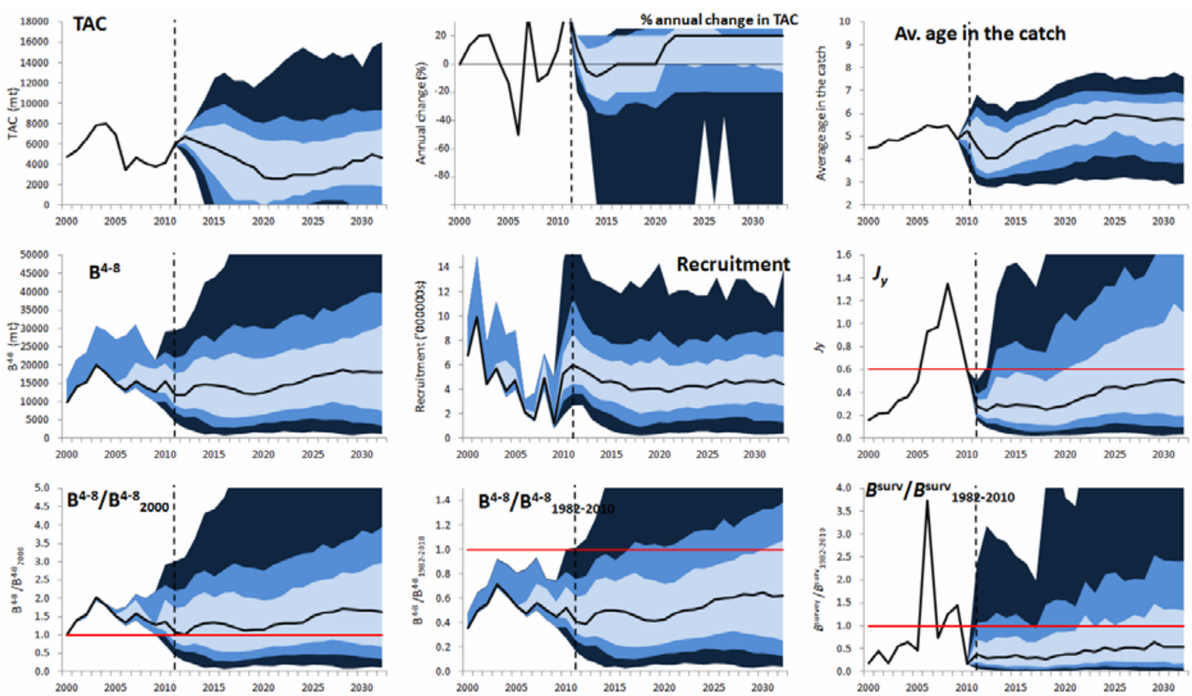


*Fig. 6h: 95, 75, 50% PI and median for a series of performance statistics for **CMPR+** under the **RS**. See equation (33) for the definition the normalised average survey index $J_y$ used in the formula for the TAC. The horizontal line in the plot of $J_y$ represents the geometric mean over the past decade (0.60).*

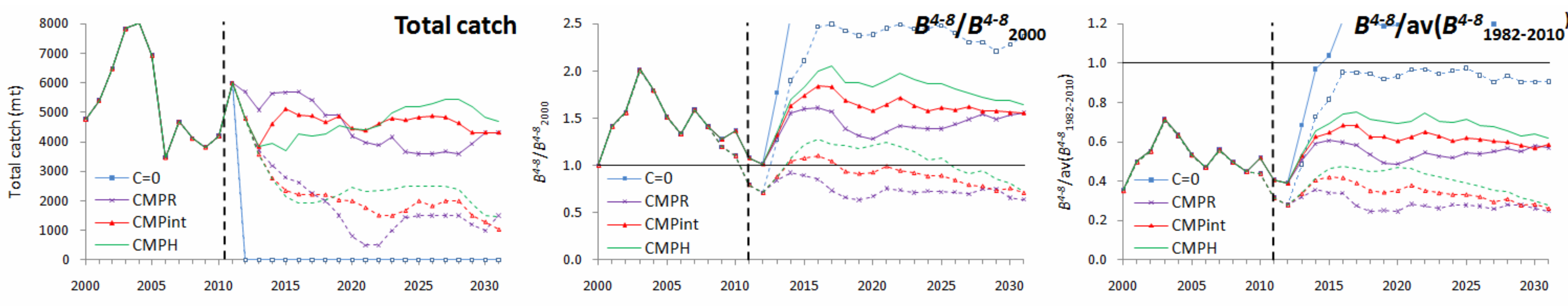


*Fig. 7a: Median (full lines) and lower 25%iles (bottom row) (dashed lines) TAC and exploitable (ages 4 to 8) biomass (relative to 2000 level and the average 1982-2010 level) for **C=0**, **CMPR, CMPint** and **CMPH*** applied to the **RS.**

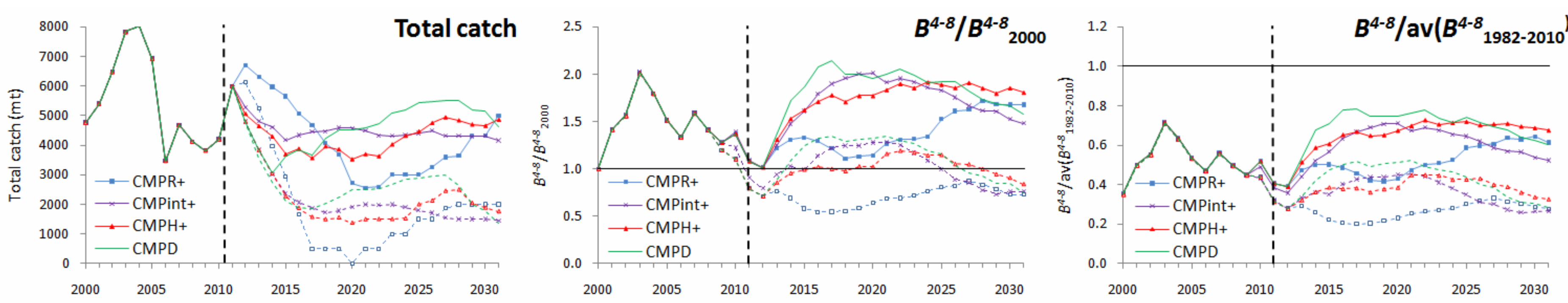


*Fig. 7b: Median (full lines) and lower 25%iles (bottom row) (dashed lines) TAC and exploitable (ages 4 to 8) biomass (relative to 2000 level and the average 1982-2010 level) for **CMPR+**, **CMPint+, CMPH+** and **CMPD*** applied to the **RS.**

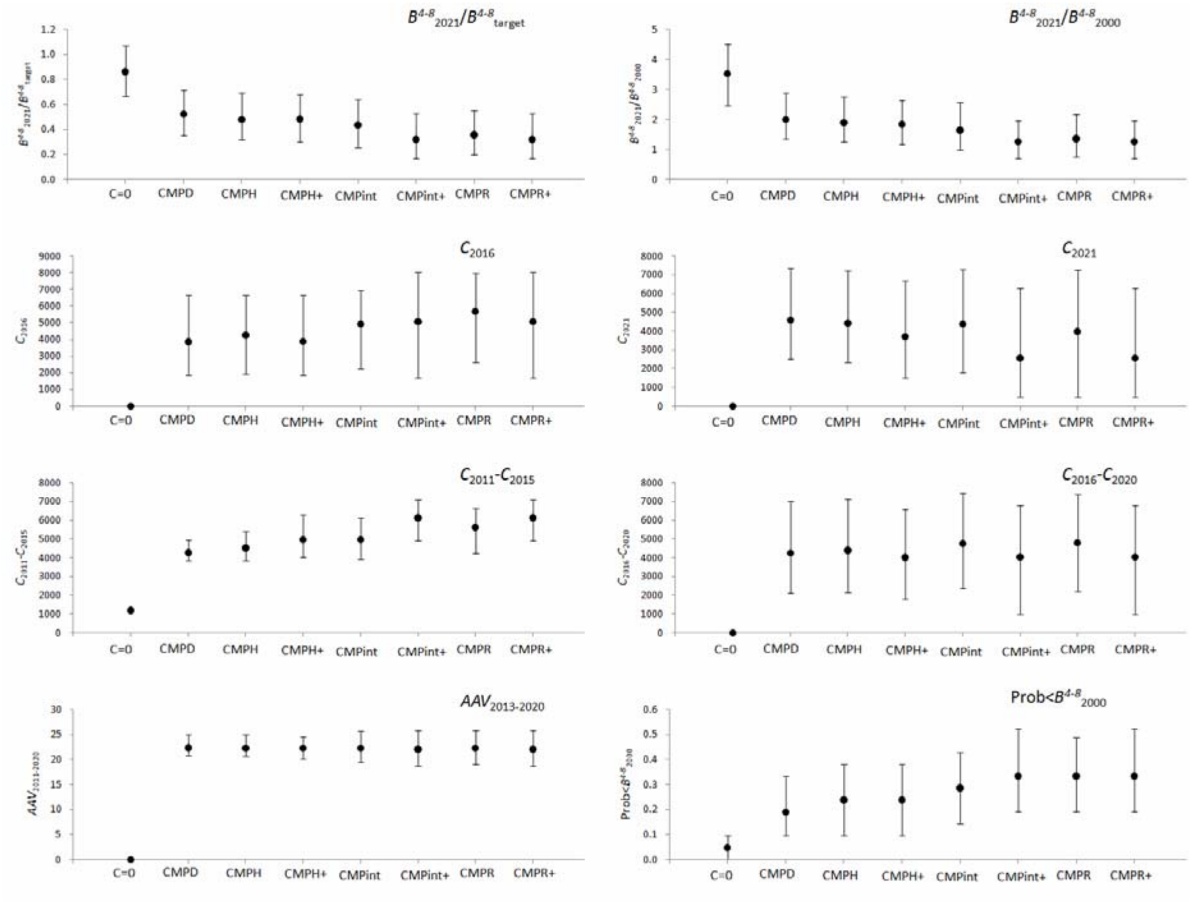


*Fig. 8: Medians (dots) and 50% PIs (bars) for a series of performance statistic for different CMPs applied to the* ***RS****.*

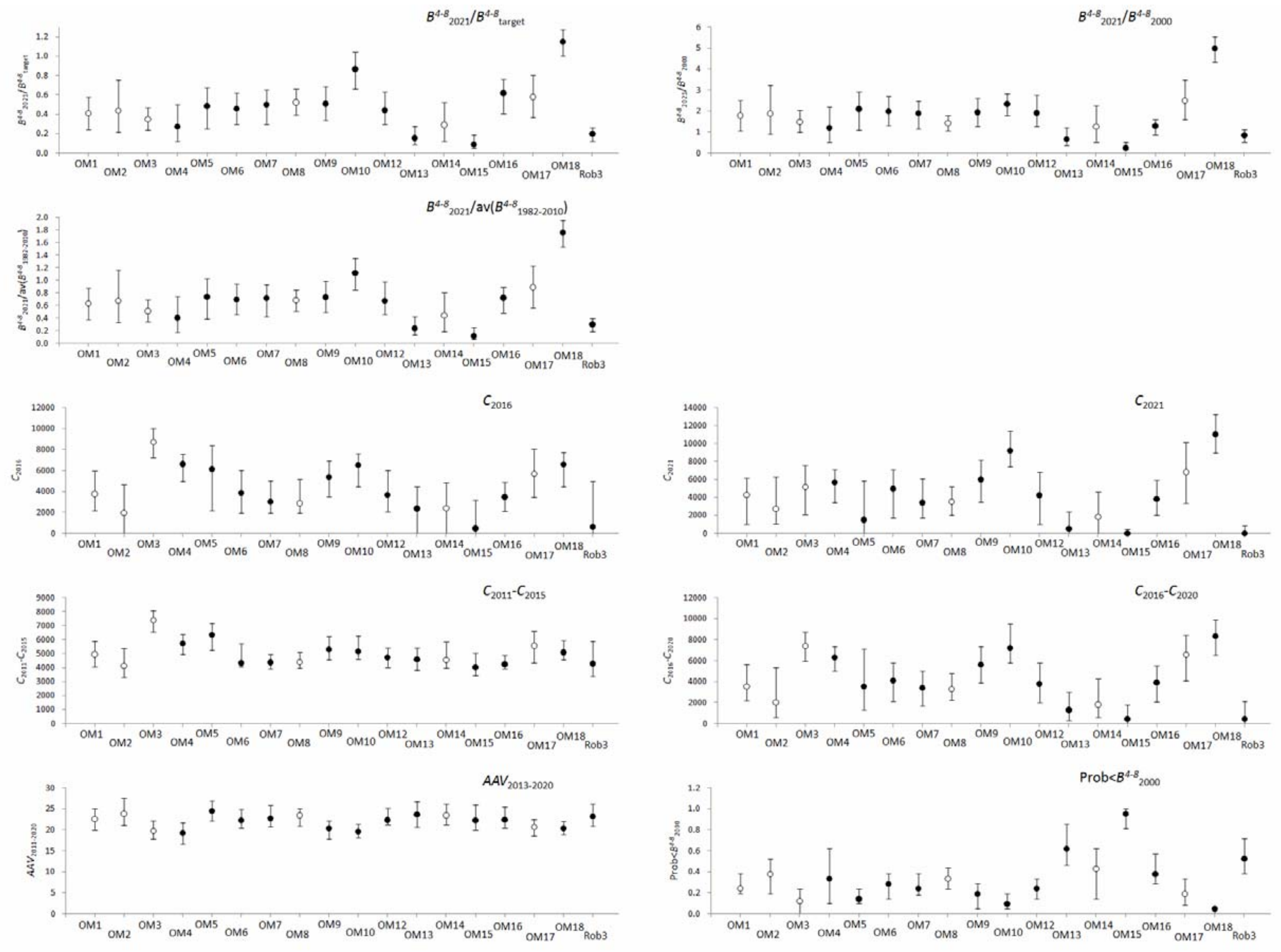


*Fig. 9: Medians (dots) and 50% PIs (bars) for a series of performance statistic for* ***CMPint+*** *applied to each OM in the RS and the robustness tests. The white dots show the OMs that are in the RS.*