Further results for three simple initial Candidate Management Procedures for the Toothfish (*Dissostichus eleginoides*) Resource in the Prince Edward Islands vicinity

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ABSTRACT

Brandão and Butterworth (2019a) proposed a simple Candidate Management Procedure (CMP) control rule based upon recent trends in CPUE by to provide future TAC recommendations for the Prince Edward Islands toothfish resource. Several suggestions made by a Task Team that evaluated the performance of this CMP are addressed in this paper. In particular, the CMP considered is tuned to target median final depletion levels of 30%, 40% and 50% under OM10 (which is the Operating Model (OM) with a better fit to the last two low trotline CPUE indices). These three CMPs are referred to as CMP30, CMP40 and CMP50 respectively. These CMPs are able to secure an increase in the TAC without adversely affecting the status of the resource under most OMs, especially for the more conservative CMP50. However, the performance under OM17, which addresses the concern with the poor fit to the trotline CPUE data in the last two years by assuming an increased tag loss rate, is not satisfactory. In order to tune these CMPs to react satisfactorily under the scenario assumed by OM17 would heavily penalise TACs under the scenarios reflected by the other OMs. A CMP which incorporates other information, to hopefully be able in some sense to better distinguish what the status of the resource is, might perform better under all OMs. Deterministic projections of mean length and the cumulative number of tags recaptured are examined for this purpose, and are suggestive that incorporation of these data could improve CMP performance.

INTRODUCTION

An initial simple empirical Candidate Management Procedure (CMP) was proposed by Brandão and Butterworth (2019a) for computing future TACs for toothfish in the Prince Edward Islands region. This simple empirical CMP is based on recent trends in the trotline CPUE to set TACs. Some suggestions made by a Task Team after evaluating the performance of this CMP are addressed in this paper; a further two suggestions with lower priority will be addressed at a later time. Some of the suggestions that have been incorporated in this paper relate to the presentation of results. Those that relate to the methodology and that have been implemented in this paper are:

- projections use values of OM-specific assumptions of cetacean depredation,

- the updated GLMM-standardised trotline CPUE estimate for 2018[1] (0.906 see Brandão and Butterworth, 2019b) is used as the starting point input in projections,
- a robustness test has been run in which no bias in the projections of trotline CPUE index is assumed (OM18),
- the uncertainty regarding the currently unallocated 11.4% of the TAC and the TACs that have already been set for the 2018 and 2019 seasons have been taken into account (as described below),
- the CMP considered is tuned to target median final depletion levels of 30%, 40% and 50% under OM10 (referred to as CMP30, CMP40 and CMP50 respectively), and
- deterministic projections of the mean length of the catch and the cumulative numbers of tag-recapture data are investigated for possibly being incorporated as a means of providing a more rapid response to resource depletion.

OPERATING MODELS AND PROJECTIONS

Assessment component

Brandão and Butterworth (2019c) presented the conditioning of a Reference Set (RS) of Operating Models (OMs) to be used to generate future data to test Candidate Management Procedures (CMPs). Table 1 lists the final Reference Set of OMs and gives details of the differences between the Base case OM (OM01) and each alternative OM. OM18 has been added to this list; however, this is a robustness test that affects only projections of CPUE and presently has been run on the Base case OM only. The OMs developed are Age-Structure Production Models (ASPMs) and the methodology applied to fit ("condition") these models to updated data together with the associated results are given in Appendix 1.

Projections component

The three CMPs investigated here assume that commercial trotline CPUE data will continue to be available annually. The current level of cetacean predation assumed for trotlines by each OM is then assumed to continue in the future. It is assumed that no IUU catches take place in the future.

The evaluation of the CMPs require the simulation of such future data from projections for the population. These projections are effected using the following procedure:

1. Numbers-at-age ($N_{y',a}$) for the start of the year in which projections commence (i.e. $y' = 2018$) are estimated by applying equations (A1.1)–(A1.3). To allow for variation in biomass projections initially (as the stochastic effects enter later only through variability in future recruitment which takes a period to propagate through to the exploitable component of the biomass), the numbers-at-age for the first seven years are allowed to vary, where these variations are simulated by generating $\varphi_{y'}$ factors distributed as $N\left(0,\sigma_R^2\right)$, where $\sigma_R = 0.5$. The reason for this is that the catch-at-length data to which the OMs are fitted provides no information on recruitment residuals $\zeta_{y'}$ for these year classes which have yet to enter the fishery, so that these $\zeta_{y'}$ are estimated to be zero in the assessments. Thus, for ages 1–7, the numbers-at-age are given by $N_{y',a}e^{\left(\varphi_{y'}-\sigma_R^2/2\right)}$. The future catches-at-age ($C_{y',a}$) are obtained from equation (A1.4) and (A1.5). Such future catch-at-age values are generated under the assumption that the commercial selectivity function remains the same as that for the last year of the assessment. Future recruitments are obtained from the stock-recruitment relationship given by equation (A1.35), which allows for fluctuations about this

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[1] A year y in this paper refers to a "fishing"-year or season, which is defined to be from 1 December of year y-1 to 30 November of year y.

relationship. These fluctuations are computed for each future year simulated by generating $\zeta_{y'}$ factors distributed as $\mathrm{N}\left(0,\sigma_R^2\right)$, where $\sigma_R = 0.5$.

2. Future spawning and exploitable biomasses are calculated using equations (A1.14) and (A1.23). Given the exploitable biomass for trotlines, the expected (trotline) CPUE abundance index $I_{y'}^{CPUE}$ is first generated using equation (A1.24); then a log-normal observation error is added to this expected value. The fits to the trotline CPUE indices by the RS OMs do not estimate the last two of these indices well, and as a result future projected CPUE indices are much higher than those observed recently. To take this into account, the projected CPUE indices were multiplied by the ratio of the average of the observed last two CPUE indices to the fitted average for each OM $\left(\vartheta\right)$. Thus projections of the trotline CPUE (accounting for bias and cetacean depredation) are given by:

$$I_{y'}^{CPUE} = \frac{\vartheta}{\phi} q B_{y'}^{\exp} e^{\varepsilon_{y'}} ,$$

   where $\varepsilon_{y'}$ is normally distributed with a mean zero and a standard deviation σ which is the estimate obtained by the operating model (equation (A1.26)) as is *q* (from equation (A1.25)), for the trotline fishery.

3. For the purpose of applying equation (1) below, which describes the CMP considered to calculate future TACs, the following strategy has been adopted to take into account the actual TACs already set for 2018 and 2019:

$$TAC_{y'} = \begin{cases} 575 & y' = 2018 \\ 543 & y' = 2019 \\ TAC_y & y' \geq 2020 \end{cases},$$

   For future years (i.e. 2020, 2021, etc. for year *y′*), the generated trotline CPUE abundance indices are used to compute future TACs ($TAC_{y'+1}$) from the TACs for the current year ($TAC_{y'}$) as described in the next section which specifies the CMPs.

4. The true catch ($C_{y'}$) is given by the sum of $TAC_{y'}$ (the legal component) and any assumed illegal component (taken to be zero at present), together with the assumed level of cetacean depredation which is taken to remain at its current level of the OM. To account for the now known catch in 2018 and the currently unallocated percentage of the TAC that is set until the 2021 season, the true catch is calculated as:

$$C_{y'} = \begin{cases} \phi\left(342 + IUU_{y'}\right), & y' = 2018 \\ \phi\left(\tau 543 + + IUU_{y'}\right), & y' = 2019 \\ \phi\left(\tau TAC_y + IUU_{y'}\right), & y' = 2020 \\ \phi\left(TAC_y + IUU_{y'}\right), & y' \geq 2021 \end{cases},$$

   where ϕ denotes the factor by which the catch is changed due to the cetacean depredation assumed and τ is the percentage of the TAC that is being allocated (0.886). The numbers-at-age for year *y′* are projected forward under this true catch; the operating model is used to obtain $C_{y',a}$ and

$N_{y'+1,a}$. The same assumptions about the commercial selectivity function and recruitment fluctuations as made in step (1) above are made.

5. Steps (2)–(4) are repeated for each future year considered.
6. This projection procedure is replicated 100 times, to provide the probability distributions for projection results arising from uncertainties in future recruitment and observation errors in CPUE.

Deterministic projections of the mean length of the catch and the cumulative numbers of tag-recapture data are computed as follows:

- Given the catch-at-age $C_{y',a}$ for trotlines, the deterministic mean length ($\overline{\ell}_{y'}$) of toothfish for year y' caught by trotlines is given by:

  $$\overline{\ell}_{y'} = \frac{\sum_{\ell} \ell C_{y',\ell}}{\sum_{\ell} C_{y',\ell}} = \frac{\sum_{\ell} \ell \left(\sum_{a} C_{y',a} A_{a,\ell} \right)}{\sum_{\ell} C_{y',\ell}},$$

  where:

  $A_{a,\ell}$ is the proportion of fish of age a that fall in length group ℓ (equations (A1.29)–(A1.30)) for trotlines,

  $C_{y',\ell}$ is the catch-at-length ℓ for trotlines in year y', and

  ℓ is the length class (where the minus group is to 54 cm and the plus group is from 138 cm, in steps of 2 cm, and these values are used for the minus and plus group lengths in the averaging process of the equation above).

- equation (A1.38) is used to compute future estimated numbers of recaptured tags for trotlines, where the number of tags released each year assumed to be constant and set equal to the average over the last five years of observed data. The cumulative recapture numbers are then calculated from the age aggregated estimated numbers of recaptured tags.

THE CMP CONSIDERED

A simple initial CMP is considered in this paper, where the TAC is modified in synchrony with the trend in a resource abundance index (such as CPUE), e.g.:

$$TAC_{y+1} = TAC_{y} \left[1 + \lambda \left(\frac{\mu_{CPUE} - t}{t} \right) \right] \tag{1}$$

where μ_{CPUE} is the mean trotline CPUE for the last 3 years and λ and t are control parameters. This CMP also constrains TACs to a maximum inter-annual change of 15%.

RESULTS AND DISCUSSION

The performances of different CMPs have been considered in terms of future projections over a 20 year period, and in particular the following four categories of statistics which are intended to capture key features of the trade-off choices to be made:

Catches achieved

Average annual catch: $\overline{C^s} = \frac{1}{20}\sum_{y=2019}^{2038} C_y^s$, where s represents simulation s as well as other averages of annual catch for different periods of projections.

Risk to resource

Final resource depletion: $B_{2038}^{sp(s)} \big/ K^{sp(s)}$

Final resource depletion relative to current (2017): $B_{2038}^{sp(s)} \big/ B_{2017}^{sp(s)}$

Final resource depletion relative to the MSY level: $B_{2038}^{sp(s)} \big/ B_{MSY}^{sp(s)}$

Industrial stability

Average annual catch variation (over 20 years): $AAV^s = \frac{1}{20}\sum_{y=2019}^{2038} \frac{\left|C_y^s - C_{y-1}^s\right|}{C_{y-1}^s}$

Economic viability

Final CPUE relative to recent level: $\frac{CPUE_{2038}^s}{\frac{1}{3}\sum_{y=2015}^{2017} CPUE_y^s}$.

Over the simulations *s* there is a distribution for each of these statistics, and performance is reported in terms of statistics of those distributions (typically the median and 90% probability interval).

Experimentation with different values of the two control parameters led to the following selections for the CMP of equation (1) under the different targets (30, 40 and 50%) of the median final depletion under OM10:

- CMP30: $\lambda = 1$ and $t = 0.719$
- CMP40: $\lambda = 1$ and $t = 0.768$
- CMP50: $\lambda = 1$ and $t = 0.835$.

Testing these CMPs for the Reference Set scenarios yields the results shown in Tables 2a to 2c. Results for the performance statistics are shown calculated for each individual OM. Figures 1 to 3 show the performance of these CMPs under the Reference Set OMs. Figure 4 shows the results for the performance statistics by combining the outputs from all OMs together. Figure 5 compares these performance statistics for the three CMPs, each under OM01, OM10, OM17 and OM18.

Tables 3a to 3c report various catch statistics while Tables 4a to 4c give results based on CPUE statistics. Median projections for some performance statistics are shown in Figures 6a and 6b for CMP30, in Figures 7a and 7b for CMP40 and in Figures 8a and 8b for CMP50. These Figures show the results for each individual OM, while Figure 9 shows results when combining all the output from the 15 OMs together and calculating the performance statistics on the 15x100 simulations. Figure 9 also shows one randomly selected worm plot from each of the OMs.

Results for the performance statistics as given in Tables 2 to 4 are given in Tables 5a to 5c by combining the outputs from all 15 OMs together and calculating the performance statistics on the 15x100 simulations.

Under most OMs, the performance of the simple empirical CPMs seem to be satisfactory in that catches increase while catch rates keep increasing and the resource status remains above B_{MSY}. However, as B_{MSY} is estimated on average over all 15 RS OMs to be about 25%, this might be an unrealistic low target for which to evaluate the performance of the CMP. CMP30, CMP40 and CMP50 give results which have been tuned to achieve median final depletion values of 30, 40 and 50% respectively under OM10 which is the OM with a better fit to the last two low trotline CPUE indices. For all CMPs, under all RS OMs except for OM17, the median final depletion remains above the specified target value. Under the most conservative CMP50 in terms of biomass, the median final spawning biomass is above the current (2017) level but for CMP40 this is not true under OM10 and OM12, while for CMP30 this problem also occurs under OM09. The exception is the performance of all CMPs under OM17 in which a better fit to the observed lower trotline CPUE indices in the last two years is achieved by increasing the tag loss rate. In this case the CMP does not react in dropping TACs in order to maintain the resource status at minimum at the current levels for CMP30 and CMP40. The more conservative CMP50 does achieve a median final spawning biomass above the current level but falls well below the target value of median final depletion.

If no bias is incorporated in the projections of CPUE (OM18), the CMP fails for all tuned target values of median final depletion. The CMP is unable to react by dropping TACs sufficiently rapidly to maintain either the CPUE or the resource status at their current levels (at least).

The concern with the poor fit to the trotline CPUE data in the last two years might indicate that a simple CMP based on only CPUE is not sufficient to react to scenarios in which the trotline CPUE continues to be low. In order to tune this CMP to react satisfactorily under the scenario assumed by OM17 would necessarily also mean that TACs would have to be decreased under other scenarios in which the status of the resource does not necessitate such lower catches. A CMP which incorporates other information to hopefully be able to distinguish what the status of the resource is might perform better under all scenarios. Figures 10a and 10b show deterministic projections for all OMs (for CMP40 considered here) of possible information that could be incorporated in a CMP, such as mean length and the numbers of recaptured tags, to aid further discussion. Decreasing mean length and more rapidly increasing cumulative numbers of tag returns for the OMs which source problematic resource trends – OM17 and OM18 – are positive indications that these indices do provide a basis to discriminate amongst the various scenarios and hence provide improved performance if incorporated into the CMPs.

REFERENCES

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Table 1. A list of the Reference Set OMs with details of the differences between the Base case OM (OM01) and each alternative OM.

Operating Model	Description	Base case values
OM01	Base case	
OM02	Natural mortality = 0.10	0.13
OM03	Natural mortality = 0.16	0.13
OM04	Steepness parameter h = 0.6	0.75
OM05	Steepness parameter h = 0.9	0.75
OM06	Cetacean predation (longlines) = +30%	+10%
OM07	Cetacean predation (trotlines) = 0%	+5%
OM08	Cetacean predation (trotlines) = +10%	+5%
OM09	Weight applied to all CPUE = 5	1
OM10	Weight applied to all CPUE = 10	1
OM12	$\ell_\infty = 174.5$ $\kappa = 0.0425$ $t_o = -1.4575$	$\ell_\infty = 152.0$ $\kappa = 0.067$ $t_o = -1.49$
OM13†	$c = 4.09\text{x}10^{-9}$ $d = 3.196$	$c = 2.54\text{x}10^{-8}$ $d = 2.8$
OM14†	$c = 4.17\text{x}10^{-9}$ $d = 3.206$	$c = 2.54\text{x}10^{-8}$ $d = 2.8$
OM15	Tag reporting rate = 0.8	1
OM17	Annual tag loss/mortality rate = 0.5	0
OM18*	Basecase (no bias in projections of CPUE, i.e. $\vartheta = 1$)	(bias in projections of CPUE)

† The weight at length conversion is given in terms of cm to tonnes.
* OM18 is a robustness test and is not part of the Reference Set OMs.

Table 2a. Medians of several performance statistics under the simple CMP considered for the Reference Set OMs together with their 90% probability intervals. Results shown are for **CMP30 which is tuned to achieve a final depletion of 30% for OM10**.

RS	B^{sp}_{2038}/K^{sp}	$B^{sp}_{2038}/B^{sp}_{2017}$	B^{sp}_{2038}/B_{MSY}	B^{sp}_{2022}/B_{MSY}	TAC (Av 20 yrs) (tonnes)	TAC (Av 4 yrs) (tonnes)	AAV (20 yrs)	AAV (4 yrs)
OM01 (Basecase)	0.49 (0.32; 0.65)	1.15 (0.75; 1.54)	1.99 (1.29; 2.65)	1.44 (1.42; 1.45)	656 (324; 1172)	519 (457; 643)	0.12 (0.09; 0.15)	0.16 (0.13; 0.23)
OM02 (M = 0.1)	0.61 (0.50; 0.73)	1.16 (0.96; 1.40)	2.40 (1.97; 2.88)	1.85 (1.83; 1.86)	415 (246; 779)	508 (449; 644)	0.12 (0.09; 0.15)	0.17 (0.13; 0.23)
OM03 (M=0.16)	0.40 (0.18; 0.61)	1.07 (0.49; 1.63)	1.68 (0.77; 2.55)	1.21 (1.19; 1.23)	898 (427; 1513)	528 (464; 645)	0.13 (0.10; 0.15)	0.16 (0.13; 0.23)
OM04 (h = 0.6)	0.47 (0.31; 0.60)	1.16 (0.77; 1.50)	1.52 (1.01; 1.96)	1.09 (1.08; 1.11)	546 (268; 994)	516 (455; 641)	0.12 (0.09; 0.15)	0.16 (0.13; 0.23)
OM05 (h = 0.9)	0.51 (0.30; 0.69)	1.17 (0.69; 1.58)	3.05 (1.82; 4.14)	2.17 (2.14; 2.20)	741 (343; 1305)	521 (458; 643)	0.13 (0.10; 0.15)	0.16 (0.13; 0.23)
OM06 ($P_{longline}$ = +30%)	0.49 (0.32; 0.65)	1.16 (0.75; 1.54)	2.00 (1.30; 2.66)	1.44 (1.42; 1.46)	667 (328; 1195)	520 (457; 643)	0.12 (0.09; 0.15)	0.16 (0.13; 0.23)
OM07 ($P_{trotline}$ = +0%)	0.48 (0.31; 0.65)	1.15 (0.73; 1.55)	1.97 (1.25; 2.64)	1.43 (1.40; 1.44)	682 (335; 1217)	521 (457; 643)	0.12 (0.09; 0.15)	0.16 (0.13; 0.23)
OM08 ($P_{trotline}$ = +10%)	0.49 (0.32; 0.65)	1.15 (0.76; 1.52)	2.00 (1.32; 2.66)	1.45 (1.43; 1.47)	632 (314; 1137)	518 (457; 642)	0.12 (0.09; 0.15)	0.16 (0.13; 0.23)
OM09 (w_{CPUE} = 5)	0.40 (0.19; 0.57)	0.94 (0.46; 1.35)	1.62 (0.79; 2.34)	1.32 (1.30; 1.33)	811 (393; 1371)	520 (462; 641)	0.13 (0.10; 0.15)	0.16 (0.13; 0.23)
OM10 (w_{CPUE} = 10)	0.30 (0.12; 0.52)	0.66 (0.26; 1.14)	1.25 (0.50; 2.14)	1.32 (1.30; 1.34)	876 (461; 1444)	516 (463; 605)	0.13 (0.10; 0.15)	0.16 (0.13; 0.21)
OM12 (alt growth)	0.58 (0.45; 0.72)	0.91 (0.71; 1.14)	2.33 (1.82; 2.91)	1.84 (1.83; 1.85)	396 (242; 699)	458 (436; 494)	0.14 (0.11; 0.15)	0.17 (0.16; 0.18)
OM13 (wt at lt Area 48.4)	0.50 (0.34; 0.66)	1.19 (0.80; 1.56)	2.00 (1.34; 2.62)	1.39 (1.37; 1.41)	585 (299; 1066)	509 (453; 634)	0.12 (0.09; 0.15)	0.16 (0.13; 0.22)
OM14 (wt at lt Area 58.5.2)	0.51 (0.34; 0.66)	1.19 (0.80; 1.56)	2.00 (1.34; 2.62)	1.39 (1.37; 1.41)	582 (298; 1062)	509 (453; 634)	0.12 (0.09; 0.15)	0.16 (0.13; 0.22)
OM15 (tag report rate = 0.8)	0.42 (0.23; 0.58)	1.08 (0.58; 1.51)	1.71 (0.92; 2.38)	1.27 (1.25; 1.29)	704 (344; 1223)	522 (459; 641)	0.12 (0.10; 0.15)	0.16 (0.13; 0.23)
OM17 (tag loss = 0.5)	0.14 (0.01; 0.30)	0.59 (0.02; 1.28)	0.56 (0.02; 1.22)	0.59 (0.56; 0.62)	593 (348; 799)	521 (472; 617)	0.13 (0.10; 0.15)	0.16 (0.13; 0.21)
OMP18 (no CPUE bias)	0.07 (0.01; 0.21)	0.16 (0.02; 0.51)	0.28 (0.04; 0.88)	1.42 (1.40; 1.44)	1706 (1091; 2224)	645 (571; 678)	0.15 (0.12; 0.17)	0.23 (0.18; 0.25)

Table 2b. Results as in Table 2a for **CMP40 which is tuned to achieve a final depletion of 40% under OM10**.

RS	B^{sp}_{2038}/K^{sp}	$B^{sp}_{2038}/B^{sp}_{2017}$	B^{sp}_{2038}/B_{MSY}	B^{sp}_{2022}/B_{MSY}	**TAC (Av 20 yrs) (tonnes)**	**TAC (Av 4 yrs) (tonnes)**	**AAV (20 yrs)**	**AAV (4 yrs)**
OM01 (Basecase)	0.56 (0.41; 0.73)	1.32 (0.97; 1.72)	2.28 (1.68; 2.96)	1.44 (1.42; 1.46)	486 (253; 907)	475 (433; 591)	0.12 (0.09; 0.15)	0.17 (0.13; 0.19)
OM02 (M = 0.1)	0.65 (0.53; 0.77)	1.25 (1.02; 1.48)	2.58 (2.11; 3.04)	1.85 (1.83; 1.86)	303 (201; 566)	470 (433; 598)	0.12 (0.09; 0.14)	0.17 (0.13; 0.19)
OM03 (M=0.16)	0.49 (0.30; 0.68)	1.31 (0.80; 1.82)	2.06 (1.25; 2.86)	1.22 (1.20; 1.24)	651 (312; 1204)	481 (436; 603)	0.13 (0.10; 0.15)	0.16 (0.12; 0.19)
OM04 (h = 0.6)	0.53 (0.40; 0.65)	1.30 (1.00; 1.62)	1.71 (1.32; 2.13)	1.10 (1.08; 1.11)	411 (223; 746)	473 (433; 590)	0.12 (0.08; 0.14)	0.17 (0.13; 0.19)
OM05 (h = 0.9)	0.59 (0.41; 0.76)	1.34 (0.94; 1.74)	3.50 (2.45; 4.56)	2.18 (2.15; 2.20)	535 (273; 1011)	476 (433; 592)	0.12 (0.10; 0.15)	0.17 (0.13; 0.20)
OM06 ($P_{longline}$ = +30%)	0.56 (0.41; 0.73)	1.33 (0.97; 1.72)	2.30 (1.68; 2.97)	1.45 (1.43; 1.46)	491 (255; 924)	475 (433; 593)	0.12 (0.09; 0.15)	0.17 (0.13; 0.20)
OM07 ($P_{trotline}$ = +0%)	0.55 (0.40; 0.72)	1.32 (0.96; 1.72)	2.26 (1.64; 2.94)	1.43 (1.41; 1.45)	500 (260; 953)	475 (433; 593)	0.12 (0.09; 0.15)	0.17 (0.13; 0.20)
OM08 ($P_{trotline}$ = +10%)	0.57 (0.42; 0.73)	1.32 (0.98; 1.71)	2.30 (1.70; 2.98)	1.46 (1.44; 1.47)	472 (248; 869)	474 (433; 591)	0.12 (0.09; 0.14)	0.17 (0.13; 0.19)
OM09 (w_{CPUE} = 5)	0.48 (0.30; 0.63)	1.13 (0.72; 1.50)	1.95 (1.25; 2.59)	1.32 (1.30; 1.34)	617 (299; 1096)	475 (434; 593)	0.13 (0.09; 0.15)	0.16 (0.12; 0.19)
OM10 (w_{CPUE} = 10)	0.40 (0.22; 0.58)	0.88 (0.49; 1.28)	1.66 (0.93; 2.41)	1.32 (1.31; 1.34)	670 (339; 1176)	471 (436; 566)	0.13 (0.09; 0.15)	0.16 (0.13; 0.19)
OM12 (alt growth)	0.62 (0.52; 0.75)	0.97 (0.81; 1.19)	2.48 (2.08; 3.04)	1.84 (1.84; 1.85)	316 (210; 524)	433 (433; 456)	0.14 (0.11; 0.15)	0.19 (0.16; 0.19)
OM13 (wt at lt Area 48.4)	0.58 (0.44; 0.72)	1.36 (1.03; 1.70)	2.28 (1.73; 2.86)	1.40 (1.38; 1.41)	436 (236; 794)	469 (433; 580)	0.12 (0.09; 0.14)	0.17 (0.13; 0.19)
OM14 (wt at lt Area 58.5.2)	0.58 (0.44; 0.72)	1.36 (1.03; 1.70)	2.28 (1.73; 2.85)	1.40 (1.38; 1.41)	434 (235; 791)	469 (433; 580)	0.12 (0.09; 0.14)	0.17 (0.13; 0.19)
OM15 (tag report rate = 0.8)	0.49 (0.32; 0.64)	1.28 (0.84; 1.67)	2.01 (1.32; 2.63)	1.28 (1.26; 1.30)	524 (273; 969)	476 (433; 589)	0.12 (0.09; 0.15)	0.17 (0.12; 0.19)
OM17 (tag loss = 0.5)	0.18 (0.03; 0.34)	0.77 (0.12; 1.44)	0.73 (0.12; 1.38)	0.60 (0.57; 0.63)	530 (307; 786)	475 (439; 568)	0.13 (0.08; 0.15)	0.16 (0.12; 0.19)
OMP18 (no CPUE bias)	0.13 (0.02; 0.31)	0.30 (0.05; 0.73)	0.51 (0.08; 1.25)	1.43 (1.41; 1.45)	1539 (990; 2023)	610 (520; 678)	0.14 (0.11; 0.16)	0.21 (0.14; 0.25)

Table 2c. Results as in Table 2a for **CMP50 which is tuned to achieve a final depletion of 50% under OM10**.

RS	B^{sp}_{2038}/K^{sp}	$B^{sp}_{2038}/B^{sp}_{2017}$	B^{sp}_{2038}/B_{MSY}	B^{sp}_{2022}/B_{MSY}	TAC (Av 20 yrs) (tonnes)	TAC (Av 4 yrs) (tonnes)	AAV (20 yrs)	AAV (4 yrs)
OM01 (Basecase)	0.62 (0.51; 0.77)	1.47 (1.20; 1.83)	2.53 (2.07; 3.16)	1.45 (1.44; 1.46)	323 (200; 593)	439 (433; 534)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM02 (M = 0.1)	0.69 (0.58; 0.80)	1.32 (1.11; 1.54)	2.72 (2.29; 3.17)	1.86 (1.84; 1.87)	223 (181; 404)	436 (433; 530)	0.13 (0.10; 0.15)	0.18 (0.14; 0.19)
OM03 (M=0.16)	0.57 (0.42; 0.75)	1.52 (1.13; 1.99)	2.39 (1.78; 3.13)	1.23 (1.21; 1.25)	450 (232; 836)	441 (433; 530)	0.13 (0.10; 0.15)	0.18 (0.13; 0.19)
OM04 (h = 0.6)	0.57 (0.47; 0.69)	1.42 (1.17; 1.72)	1.87 (1.54; 2.26)	1.10 (1.09; 1.11)	281 (191; 499)	438 (433; 530)	0.12 (0.09; 0.15)	0.18 (0.14; 0.19)
OM05 (h = 0.9)	0.66 (0.53; 0.82)	1.50 (1.20; 1.88)	3.92 (3.14; 4.91)	2.19 (2.17; 2.21)	371 (210; 656)	440 (433; 536)	0.12 (0.09; 0.15)	0.18 (0.14; 0.19)
OM06 ($P_{longline}$ = +30%)	0.62 (0.51; 0.78)	1.47 (1.20; 1.83)	2.54 (2.07; 3.17)	1.45 (1.44; 1.47)	327 (201; 603)	439 (433; 535)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM07 ($P_{trotline}$ = +0%)	0.62 (0.50; 0.77)	1.47 (1.20; 1.83)	2.52 (2.05; 3.13)	1.44 (1.42; 1.45)	338 (202; 617)	439 (433; 536)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM08 ($P_{trotline}$ = +10%)	0.62 (0.51; 0.78)	1.46 (1.20; 1.81)	2.54 (2.09; 3.16)	1.46 (1.45; 1.48)	314 (199; 576)	439 (433; 532)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM09 (w_{CPUE} = 5)	0.55 (0.42; 0.70)	1.31 (1.00; 1.66)	2.26 (1.72; 2.87)	1.33 (1.31; 1.34)	413 (222; 749)	438 (433; 522)	0.13 (0.09; 0.15)	0.18 (0.13; 0.19)
OM10 (w_{CPUE} = 10)	0.50 (0.36; 0.64)	1.10 (0.78; 1.41)	2.07 (1.47; 2.65)	1.33 (1.31; 1.35)	460 (241; 863)	436 (433; 498)	0.13 (0.10; 0.15)	0.18 (0.13; 0.19)
OM12 (alt growth)	0.66 (0.55; 0.78)	1.03 (0.87; 1.23)	2.64 (2.22; 3.14)	1.85 (1.84; 1.85)	257 (188; 390)	433 (433; 433)	0.14 (0.10; 0.15)	0.19 (0.19; 0.19)
OM13 (wt at lt Area 48.4)	0.63 (0.52; 0.77)	1.48 (1.22; 1.82)	2.49 (2.05; 3.06)	1.41 (1.39; 1.42)	296 (192; 524)	436 (433; 519)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM14 (wt at lt Area 58.5.2)	0.63 (0.52; 0.77)	1.48 (1.22; 1.82)	2.49 (2.05; 3.05)	1.40 (1.39; 1.42)	296 (192; 521)	435 (433; 518)	0.12 (0.09; 0.14)	0.18 (0.14; 0.19)
OM15 (tag report rate = 0.8)	0.57 (0.45; 0.71)	1.48 (1.17; 1.84)	2.32 (1.84; 2.89)	1.28 (1.27; 1.30)	371 (211; 640)	440 (433; 532)	0.12 (0.09; 0.15)	0.18 (0.14; 0.19)
OM17 (tag loss = 0.5)	0.25 (0.08; 0.41)	1.07 (0.32; 1.75)	1.02 (0.31; 1.67)	0.61 (0.58; 0.64)	444 (246; 723)	439 (433; 500)	0.13 (0.09; 0.15)	0.18 (0.12; 0.19)
OMP18 (no CPUE bias)	0.22 (0.07; 0.45)	0.53 (0.17; 1.06)	0.91 (0.29; 1.84)	1.44 (1.41; 1.45)	1243 (725; 1858)	546 (462; 653)	0.13 (0.10; 0.15)	0.16 (0.12; 0.24)

Table 3a. Projected median average annual legal (trotline) catches of toothfish (in tonnes) over various periods and median catch values after several years of projections under the simple CMP considered for the Reference Set OMs together with their 90% probability intervals. Results shown are for **CMP30 which is tuned to achieve a final depletion of 30% under OM10**.

RS	$\bar{C}_{2019-2038}$ **(20 yrs)**	$\bar{C}_{2019-2033}$ **(15 yrs)**	$\bar{C}_{2019-2028}$ **(10 yrs)**	$\bar{C}_{2019-2022}$ **(4 yrs)**	C_{2038} **(20 yrs)**	C_{2033} **(15 yrs)**	C_{2028} **(10 yrs)**	C_{2022} **(4 yrs)**
OM01 (Basecase)	685 (337; 1228)	583 (318; 1011)	512 (355; 818)	529 (463; 658)	1153 (346; 2752)	754 (240; 1681)	521 (204; 1150)	497 (388; 811)
OM02 (M = 0.1)	433 (255; 815)	439 (277; 702)	452 (339; 730)	517 (455; 660)	421 (115; 1379)	385 (117; 814)	371 (165; 809)	474 (376; 804)
OM03 (M=0.16)	940 (445; 1585)	732 (381; 1194)	581 (377; 898)	538 (471; 661)	1746 (519; 3743)	1188 (417; 2320)	729 (276; 1443)	522 (398; 815)
OM04 (h = 0.6)	570 (278; 1041)	534 (310; 888)	491 (351; 778)	525 (462; 657)	767 (218; 2144)	600 (172; 1279)	456 (184; 1027)	492 (386; 808)
OM05 (h = 0.9)	775 (357; 1367)	612 (324; 1064)	526 (357; 838)	531 (464; 659)	1423 (459; 3161)	882 (307; 1916)	567 (221; 1227)	501 (389; 812)
OM06 ($P_{longline}$ = +30%)	697 (341; 1252)	589 (319; 1022)	514 (356; 822)	530 (464; 659)	1191 (358; 2819)	764 (249; 1731)	532 (207; 1168)	498 (388; 811)
OM07 ($P_{trotline}$ = +0%)	679 (332; 1214)	570 (304; 986)	492 (340; 787)	505 (442; 628)	1158 (366; 2754)	757 (250; 1703)	514 (201; 1131)	476 (370; 773)
OM08 ($P_{trotline}$ = +10%)	692 (343; 1247)	599 (332; 1037)	534 (371; 848)	553 (485; 689)	1154 (331; 2768)	761 (235; 1663)	530 (209; 1175)	519 (406; 848)
OM09 (w_{CPUE} = 5)	849 (410; 1437)	673 (358; 1121)	548 (364; 862)	530 (468; 657)	1474 (462; 3349)	1051 (361; 2118)	629 (245; 1374)	502 (393; 802)
OM10 (w_{CPUE} = 10)	916 (481; 1513)	706 (386; 1202)	563 (374; 903)	526 (470; 619)	1617 (557; 3410)	1164 (455; 2313)	703 (276; 1473)	498 (396; 751)
OM12 (alt growth)	412 (251; 731)	341 (265; 503)	346 (316; 404)	465 (442; 502)	832 (287; 1797)	430 (161; 912)	251 (157; 471)	388 (354; 449)
OM13 (wt at lt Area 48.4)	611 (311; 1116)	532 (313; 900)	479 (347; 749)	518 (460; 649)	1033 (285; 2376)	657 (209; 1470)	455 (190; 1000)	477 (382; 790)
OM14 (wt at lt Area 58.5.2)	608 (310; 1112)	530 (313; 896)	479 (347; 747)	518 (459; 649)	1028 (283; 2364)	654 (208; 1463)	453 (190; 995)	477 (382; 788)
OM15 (tag report rate = 0.8)	736 (357; 1280)	613 (328; 1027)	527 (360; 828)	531 (466; 657)	1200 (368; 2683)	830 (289; 1727)	557 (221; 1242)	505 (392; 802)
OM17 (tag loss = 0.5)	619 (362; 836)	567 (345; 879)	535 (371; 852)	531 (479; 631)	594 (204; 1519)	617 (211; 1285)	557 (227; 1126)	517 (406; 755)
OMP18 (no CPUE bias)	1788 (1142; 2332)	1530 (1113; 1793)	1057 (840; 1151)	661 (584; 695)	1876 (806; 4246)	2863 (1484; 4009)	1803 (1203; 2006)	815 (649; 867)

Table 3b. Results as in Table 3a for **CMP40 which is tuned to achieve a final depletion of 40% under OM10**.

RS	$\bar{C}_{2019-2038}$ **(20 yrs)**	$\bar{C}_{2019-2033}$ **(15 yrs)**	$\bar{C}_{2019-2028}$ **(10 yrs)**	$\bar{C}_{2019-2022}$ **(4 yrs)**	C_{2038} **(20 yrs)**	C_{2033} **(15 yrs)**	C_{2028} **(10 yrs)**	C_{2022} **(4 yrs)**
OM01 (Basecase)	507 (262; 950)	440 (274; 775)	414 (316; 646)	482 (438; 605)	808 (198; 2011)	512 (145; 1180)	361 (170; 831)	423 (350; 718)
OM02 (M = 0.1)	315 (208; 591)	342 (245; 542)	377 (306; 626)	477 (438; 611)	254 (73; 892)	242 (88; 573)	254 (147; 544)	407 (350; 717)
OM03 (M=0.16)	680 (324; 1261)	538 (313; 976)	459 (324; 726)	488 (441; 617)	1331 (434; 3139)	806 (275; 1751)	481 (197; 1114)	438 (356; 715)
OM04 (h = 0.6)	428 (231; 781)	397 (263; 701)	398 (313; 626)	481 (438; 603)	536 (124; 1407)	406 (109; 921)	313 (157; 722)	420 (350; 715)
OM05 (h = 0.9)	559 (283; 1059)	473 (283; 825)	425 (319; 667)	483 (438; 606)	993 (275; 2377)	602 (184; 1373)	392 (173; 904)	426 (350; 720)
OM06 ($P_{longline}$ = +30%)	512 (265; 967)	445 (275; 785)	418 (316; 652)	483 (438; 606)	824 (203; 2054)	523 (148; 1202)	366 (171; 845)	424 (350; 720)
OM07 ($P_{trotline}$ = +0%)	497 (256; 950)	432 (263; 758)	401 (302; 627)	460 (417; 577)	810 (203; 2025)	520 (147; 1183)	358 (164; 823)	405 (333; 686)
OM08 ($P_{trotline}$ = +10%)	516 (269; 952)	452 (286; 795)	430 (330; 671)	505 (459; 633)	807 (196; 2025)	518 (145; 1183)	366 (176; 844)	442 (367; 751)
OM09 (w_{CPUE} = 5)	644 (310; 1147)	495 (290; 904)	437 (321; 704)	483 (440; 607)	1193 (383; 2794)	711 (236; 1579)	439 (185; 1003)	427 (353; 690)
OM10 (w_{CPUE} = 10)	700 (353; 1231)	523 (307; 969)	447 (328; 760)	478 (441; 578)	1344 (467; 3300)	861 (282; 1811)	479 (204; 1078)	420 (356; 673)
OM12 (alt growth)	328 (218; 547)	290 (237; 415)	313 (299; 354)	438 (438; 462)	580 (211; 1228)	303 (112; 641)	182 (134; 374)	350 (350; 390)
OM13 (wt at lt Area 48.4)	454 (244; 831)	399 (266; 687)	389 (311; 613)	476 (438; 593)	688 (170; 1693)	456 (126; 975)	306 (163; 698)	411 (350; 694)
OM14 (wt at lt Area 58.5.2)	453 (244; 828)	398 (266; 685)	389 (311; 612)	476 (438; 593)	684 (169; 1684)	454 (126; 971)	304 (162; 694)	410 (350; 693)
OM15 (tag report rate = 0.8)	547 (283; 1014)	473 (281; 803)	427 (319; 667)	484 (439; 602)	910 (271; 2314)	586 (183; 1322)	390 (172; 881)	427 (351; 718)
OM17 (tag loss = 0.5)	554 (319; 822)	471 (300; 774)	438 (327; 728)	483 (445; 580)	725 (230; 1592)	569 (179; 1233)	423 (183; 988)	429 (359; 673)
OMP18 (no CPUE bias)	1613 (1037; 2121)	1338 (873; 1670)	955 (706; 1118)	624 (530; 695)	2012 (801; 4390)	2388 (1296; 3664)	1568 (853; 1945)	751 (534; 867)

Table 3c. Results as in Table 3a for **CMP50 which is tuned to achieve a final depletion of 50% under OM10**.

RS	$\bar{C}_{2019-2038}$ **(20 yrs)**	$\bar{C}_{2019-2033}$ **(15 yrs)**	$\bar{C}_{2019-2028}$ **(10 yrs)**	$\bar{C}_{2019-2022}$ **(4 yrs)**	C_{2038} **(20 yrs)**	C_{2033} **(15 yrs)**	C_{2028} **(10 yrs)**	C_{2022} **(4 yrs)**
OM01 (Basecase)	336 (207; 620)	316 (241; 579)	343 (300; 538)	445 (438; 544)	446 (101; 1184)	309 (86; 726)	223 (139; 509)	362 (350; 578)
OM02 (M = 0.1)	231 (186; 421)	265 (229; 423)	321 (299; 481)	442 (438; 540)	130 (38; 500)	139 (64; 313)	171 (132; 373)	356 (350; 591)
OM03 (M=0.16)	469 (240; 875)	384 (255; 693)	367 (303; 607)	447 (438; 540)	834 (221; 1989)	501 (150; 1148)	300 (144; 700)	367 (350; 572)
OM04 (h = 0.6)	292 (197; 521)	294 (235; 490)	332 (299; 516)	443 (438; 540)	271 (72; 945)	231 (71; 506)	200 (134; 474)	361 (350; 566)
OM05 (h = 0.9)	386 (218; 686)	335 (247; 618)	349 (301; 546)	445 (438; 546)	569 (132; 1481)	372 (104; 827)	243 (146; 557)	363 (350; 588)
OM06 ($P_{longline}$ = +30%)	340 (208; 630)	319 (242; 583)	344 (300; 542)	445 (438; 546)	454 (103; 1211)	314 (87; 740)	226 (140; 512)	363 (350; 580)
OM07 ($P_{trotline}$ = +0%)	335 (199; 614)	308 (232; 570)	329 (286; 518)	424 (417; 520)	463 (107; 1229)	312 (85; 736)	220 (134; 493)	346 (333; 556)
OM08 ($P_{trotline}$ = +10%)	341 (216; 630)	326 (252; 591)	357 (314; 560)	465 (459; 569)	430 (99; 1188)	310 (87; 726)	230 (145; 526)	379 (367; 602)
OM09 (w_{CPUE} = 5)	431 (230; 783)	356 (247; 624)	356 (301; 571)	443 (438; 532)	730 (197; 1797)	437 (135; 1016)	279 (141; 630)	360 (350; 539)
OM10 (w_{CPUE} = 10)	479 (250; 903)	383 (260; 698)	361 (301; 540)	441 (438; 507)	984 (322; 2213)	530 (160; 1181)	311 (148; 726)	357 (350; 525)
OM12 (alt growth)	267 (194; 407)	257 (229; 348)	301 (299; 329)	438 (438; 438)	356 (109; 858)	201 (77; 432)	151 (132; 278)	350 (350; 350)
OM13 (wt at lt Area 48.4)	308 (199; 547)	296 (236; 499)	328 (299; 494)	441 (438; 528)	369 (89; 1003)	264 (79; 582)	198 (136; 469)	356 (350; 542)
OM14 (wt at lt Area 58.5.2)	307 (199; 544)	295 (236; 497)	328 (299; 493)	441 (438; 528)	366 (89; 1000)	263 (79; 578)	197 (136; 466)	355 (350; 541)
OM15 (tag report rate = 0.8)	387 (218; 669)	341 (245; 599)	351 (300; 532)	446 (438; 543)	562 (136; 1367)	379 (104; 796)	252 (144; 561)	364 (350; 599)
OM17 (tag loss = 0.5)	463 (255; 756)	372 (252; 655)	362 (301; 555)	445 (438; 509)	741 (214; 1587)	473 (152; 1087)	306 (141; 745)	363 (350; 526)
OMP18 (no CPUE bias)	1302 (758; 1948)	1057 (576; 1449)	787 (521; 992)	557 (469; 669)	2069 (755; 4275)	1834 (871; 3044)	1184 (550; 1716)	637 (433; 827)

Table 4a. Projected median CPUE indices relative to the 2017 CPUE index after several years of projections, and the median CPUE index in 2038 as a proportion of the average of the 2015 to 2017 CPUE indices. The probability of the CPUE index in 2038 being less than this average under the simple CMP considered for the Reference Set OMs together with their 90% probability intervals. Results shown are for **CMP30 which is tuned to achieve a final depletion of 30% under OM10**.

RS	$CPUE_{2038}/CPUE_{2017}$ **(after 20 yrs)**	$CPUE_{2033}/CPUE_{2017}$ **(after 15 yrs)**	$CPUE_{2028}/CPUE_{2017}$ **(after 10 yrs)**	$CPUE_{2022}/CPUE_{2017}$ **(after 4 yrs)**	$CPUE_{2038}/\overline{CPUE_{15-17}}$	**Probability** $CPUE_{2038}/\overline{CPUE_{15-17}} < 1$
OM01 (Basecase)	1.56 (0.94; 2.52)	1.61 (1.01; 2.70)	1.53 (1.03; 2.19)	1.36 (0.87; 1.90)	1.30 (0.79; 2.11)	0.19
OM02 (M = 0.1)	1.48 (0.90; 2.39)	1.45 (0.91; 2.39)	1.35 (0.89; 2.03)	1.28 (0.79; 1.81)	1.24 (0.75; 2.00)	0.25
OM03 (M=0.16)	1.56 (0.79; 2.65)	1.68 (1.08; 2.73)	1.67 (1.13; 2.42)	1.44 (0.96; 1.97)	1.30 (0.66; 2.22)	0.24
OM04 (h = 0.6)	1.53 (0.91; 2.46)	1.52 (0.95; 2.54)	1.45 (0.97; 2.09)	1.33 (0.85; 1.87)	1.28 (0.76; 2.06)	0.20
OM05 (h = 0.9)	1.59 (0.96; 2.60)	1.68 (1.06; 2.80)	1.60 (1.06; 2.29)	1.38 (0.88; 1.92)	1.33 (0.80; 2.18)	0.18
OM06 ($P_{longline}$ = +30%)	1.56 (0.94; 2.54)	1.62 (1.01; 2.71)	1.54 (1.03; 2.20)	1.37 (0.87; 1.91)	1.31 (0.79; 2.12)	0.19
OM07 ($P_{trotline}$ = +0%)	1.56 (0.94; 2.52)	1.62 (1.02; 2.73)	1.55 (1.04; 2.22)	1.37 (0.87; 1.92)	1.30 (0.79; 2.11)	0.19
OM08 ($P_{trotline}$ = +10%)	1.56 (0.94; 2.52)	1.60 (1.01; 2.68)	1.52 (1.02; 2.17)	1.35 (0.86; 1.89)	1.30 (0.79; 2.11)	0.19
OM09 (w_{CPUE} = 5)	1.53 (0.80; 2.64)	1.68 (1.06; 2.71)	1.64 (1.13; 2.39)	1.42 (0.95; 1.93)	1.28 (0.67; 2.21)	0.25
OM10 (w_{CPUE} = 10)	1.36 (0.57; 2.44)	1.75 (0.98; 2.85)	1.73 (1.20; 2.40)	1.43 (1.02; 1.92)	1.14 (0.47; 2.04)	0.37
OM12 (alt growth)	1.95 (1.35; 2.66)	1.91 (1.37; 2.69)	1.62 (1.20; 2.16)	1.13 (0.87; 1.43)	1.63 (1.13; 2.23)	0.01
OM13 (wt at lt Area 48.4)	1.60 (0.97; 2.54)	1.63 (1.01; 2.66)	1.51 (1.02; 2.17)	1.33 (0.85; 1.84)	1.34 (0.81; 2.12)	0.15
OM14 (wt at lt Area 58.5.2)	1.60 (0.97; 2.54)	1.63 (1.01; 2.66)	1.51 (1.02; 2.17)	1.32 (0.85; 1.84)	1.34 (0.81; 2.12)	0.15
OM15 (tag report rate = 0.8)	1.52 (0.92; 2.57)	1.60 (1.00; 2.68)	1.56 (1.05; 2.27)	1.38 (0.89; 1.91)	1.27 (0.77; 2.15)	0.25
OM17 (tag loss = 0.5)	1.28 (0.31; 2.31)	1.41 (0.33; 2.53)	1.48 (0.91; 2.21)	1.38 (1.00; 1.84)	1.07 (0.26; 1.93)	0.44
OMP18 (no CPUE bias)	0.65 (0.18; 1.60)	1.24 (0.73; 2.32)	1.79 (1.16; 2.77)	1.92 (1.22; 2.68)	0.54 (0.15; 1.34)	0.87

Table 4b. Results as in Table 4a for **CMP40 which is tuned to achieve a final depletion of 40% under OM10**.

RS	$CPUE_{2038}/CPUE_{2017}$ **(after 20 yrs)**	$CPUE_{2033}/CPUE_{2017}$ **(after 15 yrs)**	$CPUE_{2028}/CPUE_{2017}$ **(after 10 yrs)**	$CPUE_{2022}/CPUE_{2017}$ **(after 4 yrs)**	$CPUE_{2038}/\overline{CPUE_{15-17}}$	**Probability** $CPUE_{2038}/\overline{CPUE_{15-17}} < 1$
OM01 (Basecase)	1.73 (1.08; 2.84)	1.76 (1.12; 2.82)	1.59 (1.04; 2.29)	1.37 (0.87; 1.91)	1.45 (0.90; 2.37)	0.08
OM02 (M = 0.1)	1.58 (1.00; 2.48)	1.52 (0.96; 2.46)	1.38 (0.90; 2.09)	1.29 (0.79; 1.82)	1.32 (0.84; 2.08)	0.14
OM03 (M=0.16)	1.82 (1.13; 2.95)	1.87 (1.22; 2.91)	1.73 (1.18; 2.48)	1.45 (0.96; 1.98)	1.52 (0.94; 2.47)	0.07
OM04 (h = 0.6)	1.69 (1.05; 2.71)	1.66 (1.05; 2.63)	1.50 (0.99; 2.18)	1.34 (0.85; 1.88)	1.41 (0.87; 2.27)	0.10
OM05 (h = 0.9)	1.80 (1.09; 2.83)	1.83 (1.16; 2.94)	1.65 (1.08; 2.36)	1.38 (0.88; 1.93)	1.50 (0.91; 2.36)	0.08
OM06 ($P_{longline}$ = +30%)	1.73 (1.08; 2.85)	1.76 (1.13; 2.83)	1.60 (1.04; 2.29)	1.37 (0.87; 1.92)	1.45 (0.90; 2.38)	0.08
OM07 ($P_{trotline}$ = +0%)	1.75 (1.08; 2.83)	1.77 (1.13; 2.85)	1.61 (1.05; 2.31)	1.37 (0.88; 1.93)	1.46 (0.90; 2.37)	0.08
OM08 ($P_{trotline}$ = +10%)	1.73 (1.08; 2.83)	1.75 (1.10; 2.80)	1.58 (1.03; 2.27)	1.36 (0.87; 1.90)	1.44 (0.90; 2.37)	0.08
OM09 (w_{CPUE} = 5)	1.80 (1.12; 2.89)	1.86 (1.22; 2.89)	1.72 (1.18; 2.43)	1.43 (0.95; 1.94)	1.50 (0.94; 2.41)	0.07
OM10 (w_{CPUE} = 10)	1.69 (0.93; 2.93)	1.94 (1.22; 2.96)	1.83 (1.26; 2.49)	1.44 (1.03; 1.94)	1.42 (0.78; 2.45)	0.15
OM12 (alt growth)	2.04 (1.48; 2.76)	1.96 (1.43; 2.76)	1.65 (1.20; 2.19)	1.14 (0.87; 1.44)	1.71 (1.23; 2.31)	0.00
OM13 (wt at lt Area 48.4)	1.77 (1.12; 2.80)	1.77 (1.14; 2.76)	1.56 (1.03; 2.25)	1.33 (0.85; 1.85)	1.48 (0.94; 2.34)	0.08
OM14 (wt at lt Area 58.5.2)	1.77 (1.12; 2.80)	1.77 (1.14; 2.76)	1.56 (1.03; 2.25)	1.33 (0.85; 1.85)	1.48 (0.94; 2.34)	0.08
OM15 (tag report rate = 0.8)	1.76 (1.08; 2.78)	1.78 (1.11; 2.88)	1.63 (1.08; 2.32)	1.39 (0.90; 1.91)	1.48 (0.90; 2.33)	0.08
OM17 (tag loss = 0.5)	1.51 (0.61; 2.53)	1.66 (0.70; 2.80)	1.72 (1.12; 2.48)	1.41 (1.03; 1.88)	1.26 (0.51; 2.12)	0.32
OMP18 (no CPUE bias)	0.92 (0.28; 1.83)	1.43 (0.88; 2.70)	1.90 (1.25; 2.86)	1.93 (1.23; 2.69)	0.77 (0.23; 1.53)	0.69

Table 4c. Results as in Table 4a for **CMP50 which is tuned to achieve a final depletion of 50% under OM10**.

RS	$CPUE_{2038}/CPUE_{2017}$ **(after 20 yrs)**	$CPUE_{2033}/CPUE_{2017}$ **(after 15 yrs)**	$CPUE_{2028}/CPUE_{2017}$ **(after 10 yrs)**	$CPUE_{2022}/CPUE_{2017}$ **(after 4 yrs)**	$CPUE_{2038}/\overline{CPUE_{15-17}}$	**Probability** $CPUE_{2038}/\overline{CPUE_{15-17}} < 1$
OM01 (Basecase)	1.93 (1.28; 2.96)	1.84 (1.21; 2.92)	1.62 (1.06; 2.34)	1.37 (0.88; 1.91)	1.61 (1.07; 2.47)	0.04
OM02 (M = 0.1)	1.65 (1.04; 2.57)	1.57 (0.99; 2.51)	1.40 (0.90; 2.12)	1.29 (0.80; 1.83)	1.38 (0.87; 2.15)	0.13
OM03 (M=0.16)	2.05 (1.34; 3.18)	2.02 (1.35; 3.09)	1.78 (1.22; 2.50)	1.46 (0.97; 1.98)	1.72 (1.12; 2.66)	0.02
OM04 (h = 0.6)	1.85 (1.20; 2.79)	1.72 (1.14; 2.72)	1.53 (1.01; 2.23)	1.34 (0.86; 1.88)	1.54 (1.00; 2.34)	0.05
OM05 (h = 0.9)	1.99 (1.25; 3.06)	1.94 (1.25; 3.04)	1.68 (1.10; 2.42)	1.39 (0.89; 1.94)	1.67 (1.05; 2.56)	0.02
OM06 ($P_{longline}$ = +30%)	1.93 (1.27; 2.96)	1.85 (1.21; 2.92)	1.62 (1.06; 2.35)	1.37 (0.88; 1.92)	1.61 (1.07; 2.48)	0.04
OM07 ($P_{trotline}$ = +0%)	1.94 (1.28; 2.99)	1.86 (1.21; 2.95)	1.63 (1.07; 2.37)	1.38 (0.88; 1.93)	1.62 (1.07; 2.50)	0.04
OM08 ($P_{trotline}$ = +10%)	1.92 (1.26; 2.94)	1.83 (1.20; 2.89)	1.60 (1.05; 2.33)	1.36 (0.87; 1.90)	1.60 (1.06; 2.46)	0.04
OM09 (w_{CPUE} = 5)	2.02 (1.34; 3.09)	2.01 (1.36; 3.05)	1.77 (1.21; 2.48)	1.43 (0.96; 1.95)	1.69 (1.12; 2.59)	0.03
OM10 (w_{CPUE} = 10)	2.07 (1.32; 3.09)	2.11 (1.43; 3.08)	1.89 (1.33; 2.63)	1.45 (1.03; 1.96)	1.73 (1.10; 2.59)	0.01
OM12 (alt growth)	2.14 (1.62; 2.87)	1.98 (1.47; 2.79)	1.66 (1.20; 2.21)	1.14 (0.87; 1.44)	1.79 (1.36; 2.40)	0.00
OM13 (wt at lt Area 48.4)	1.93 (1.27; 2.90)	1.83 (1.22; 2.83)	1.58 (1.05; 2.30)	1.33 (0.86; 1.85)	1.62 (1.06; 2.42)	0.04
OM14 (wt at lt Area 58.5.2)	1.93 (1.27; 2.89)	1.83 (1.22; 2.83)	1.58 (1.05; 2.29)	1.33 (0.86; 1.85)	1.62 (1.06; 2.42)	0.04
OM15 (tag report rate = 0.8)	1.97 (1.27; 3.09)	1.93 (1.26; 3.01)	1.68 (1.12; 2.39)	1.39 (0.90; 1.92)	1.64 (1.06; 2.59)	0.03
OM17 (tag loss = 0.5)	1.86 (0.94; 3.11)	2.02 (1.15; 3.03)	1.90 (1.29; 2.63)	1.43 (1.05; 1.92)	1.56 (0.79; 2.60)	0.13
OMP18 (no CPUE bias)	1.29 (0.55; 2.54)	1.72 (1.10; 3.09)	2.00 (1.37; 3.01)	1.94 (1.24; 2.72)	1.08 (0.46; 2.12)	0.39

Table 5a. Performance statistics as in Table 2a but reported as medians across all simulations for all 15 RS OMs (OM01 – OM17) giving equal weight to each OM, for the three CMPs.

CMP	B^{sp}_{2038}/K^{sp}	$B^{sp}_{2038}/B^{sp}_{2017}$	B^{sp}_{2038}/B_{MSY}	B^{sp}_{2022}/B_{MSY}	**TAC (Av 20 yrs) (tonnes)**	**TAC (Av 4 yrs) (tonnes)**	**AAV (20 yrs)**	**AAV (4 yrs)**
CMP30	0.48 (0.15; 0.67)	1.09 (0.41; 1.51)	1.93 (0.61; 2.98)	1.40 (0.60; 2.16)	636 (299; 1230)	512 (450; 641)	0.13 (0.09; 0.15)	0.16 (0.13; 0.23)
CMP40	0.55 (0.22; 0.72)	1.26 (0.66; 1.65)	2.21 (0.93; 3.25)	1.41 (0.61; 2.17)	471 (236; 991)	471 (433; 591)	0.12 (0.09; 0.15)	0.17 (0.13; 0.19)
CMP50	0.61 (0.31; 0.76)	1.41 (0.90; 1.81)	2.45 (1.28; 3.63)	1.41 (0.62; 2.18)	332 (196; 696)	437 (433; 528)	0.12 (0.09; 0.15)	0.18 (0.14; 0.19)

Table 5b. Performance statistics as in Table 3a but reported as medians across all simulations for all 15 RS OMs (OM01 – OM17) giving equal weight to each OM, for the three CMPs.

CMP	$\bar{C}_{2019-2038}$ **(20 yrs)**	$\bar{C}_{2019-2033}$ **(15 yrs)**	$\bar{C}_{2019-2028}$ **(10 yrs)**	$\bar{C}_{2019-2022}$ **(4 yrs)**	C_{2038} **(20 yrs)**	C_{2033} **(15 yrs)**	C_{2028} **(10 yrs)**	C_{2022} **(4 yrs)**
CMP30	666 (311; 1281)	552 (307; 1041)	504 (339; 838)	522 (456; 657)	1074 (245; 2763)	724 (203; 1846)	502 (193; 1224)	491 (375; 803)
CMP40	490 (245; 1037)	418 (263; 805)	407 (308; 684)	478 (438; 607)	801 (165; 2251)	512 (131; 1406)	348 (157; 916)	415 (350; 715)
CMP50	344 (202; 728)	316 (236; 593)	337 (299; 532)	443 (438; 540)	474 (89; 1540)	307 (82; 908)	226 (132; 600)	360 (350; 575)

Table 5c. Performance statistics as in Table 4a but reported as medians across all simulations for all 15 RS OMs (OM01 – OM17) giving equal weight to each OM, for the three CMPs.

CMP	$CPUE_{2038}/CPUE_{2017}$ **(after 20 yrs)**	$CPUE_{2033}/CPUE_{2017}$ **(after 15 yrs)**	$CPUE_{2028}/CPUE_{2017}$ **(after 10 yrs)**	$CPUE_{2022}/CPUE_{2017}$ **(after 4 yrs)**	$CPUE_{2038}/\overline{CPUE}_{15-17}$	**Probability** $CPUE_{2038}/\overline{CPUE}_{15-17} < 1$
CMP30	1.56 (0.83; 2.56)	1.63 (0.97; 2.69)	1.55 (1.02; 2.27)	1.35 (0.88; 1.90)	1.31 (0.69; 2.14)	0.22
CMP40	1.74 (1.03; 2.83)	1.78 (1.10; 2.82)	1.62 (1.05; 2.37)	1.36 (0.88; 1.91)	1.46 (0.86; 2.37)	0.10
CMP50	1.94 (1.24; 3.05)	1.89 (1.20; 2.96)	1.67 (1.07; 2.43)	1.37 (0.88; 1.92)	1.62 (1.03; 2.55)	0.04

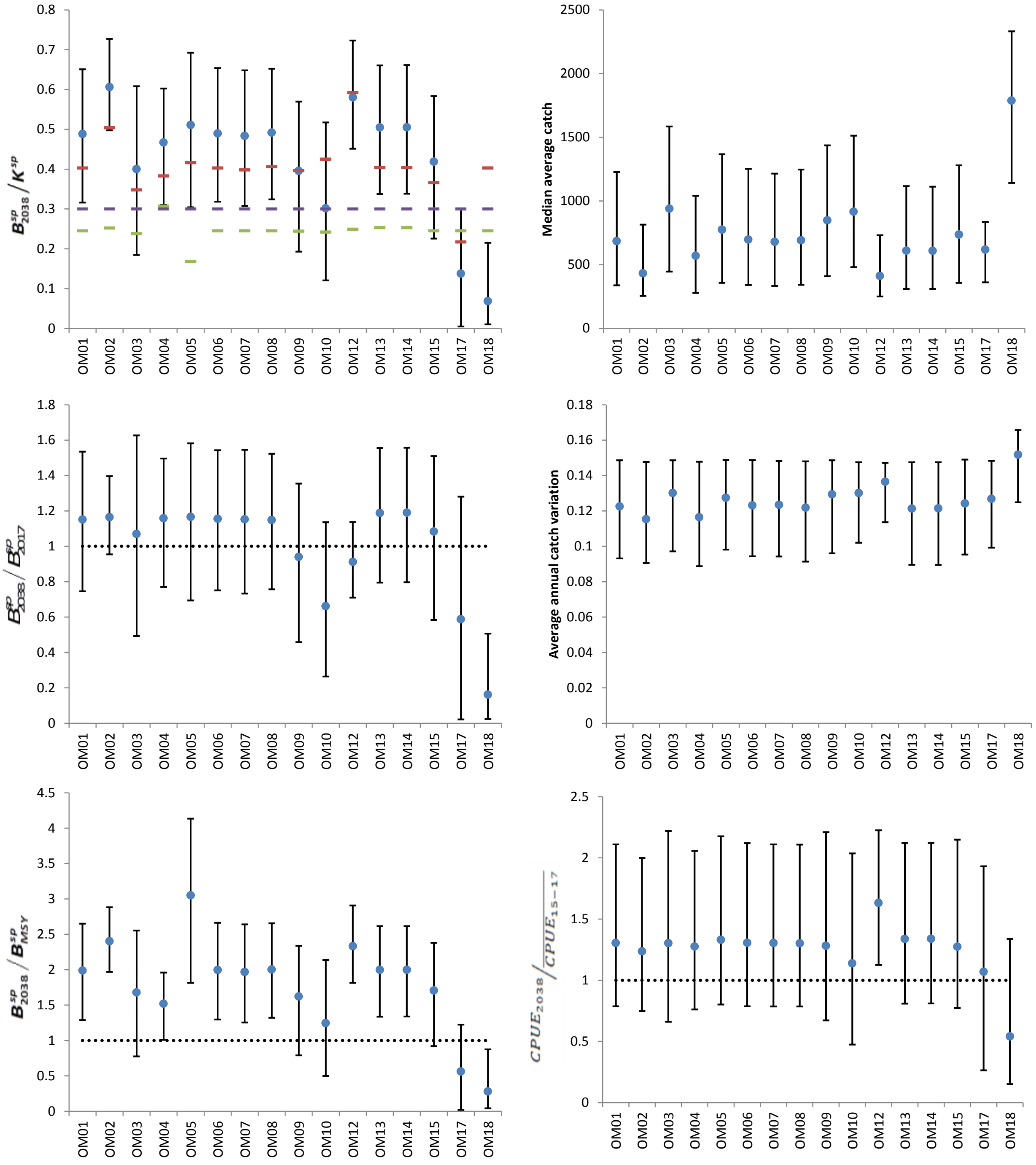


Figure 1. Zeh plots for some of the performance statistics reported in the Tables for each OM for **CMP30 which is tuned to achieve a final depletion of 30% under OM10**. These are the spawning biomass depletion at the start of 2038 relative to K, to the spawning biomass in 2017 and to the spawning biomass at MSY, the projected median of the average annual legal (trotline) catches of toothfish (in tonnes) for the period 2019 to 2038, the average annual variation in catch and the CPUE index in 2038 as a proportion of the average of the 2015 to 2017 CPUE indices for the 15 OMs. The red dashes represents the current (2018) spawning biomass depletion for each OM, the green dashes represents the MSYL (relative to *K*), while the purple dashes represent the final depletion value under OM10 to which the CMP was tuned to. Results for the robustness test OM18 are also shown.

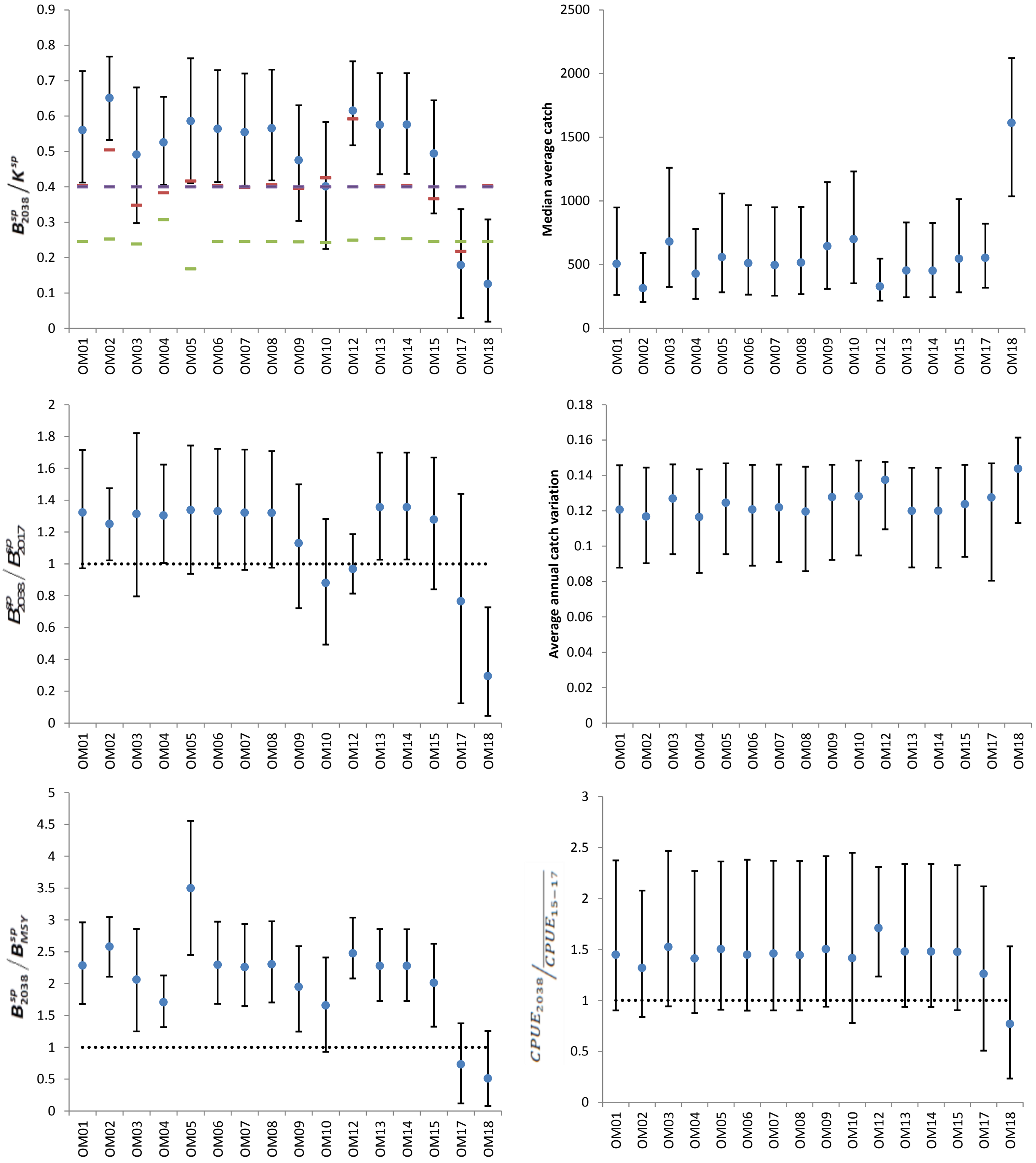


Figure 2. Zeh plots as for Figure 1, but for **CMP40 which is tuned to achieve a final depletion of 40% under OM10**.

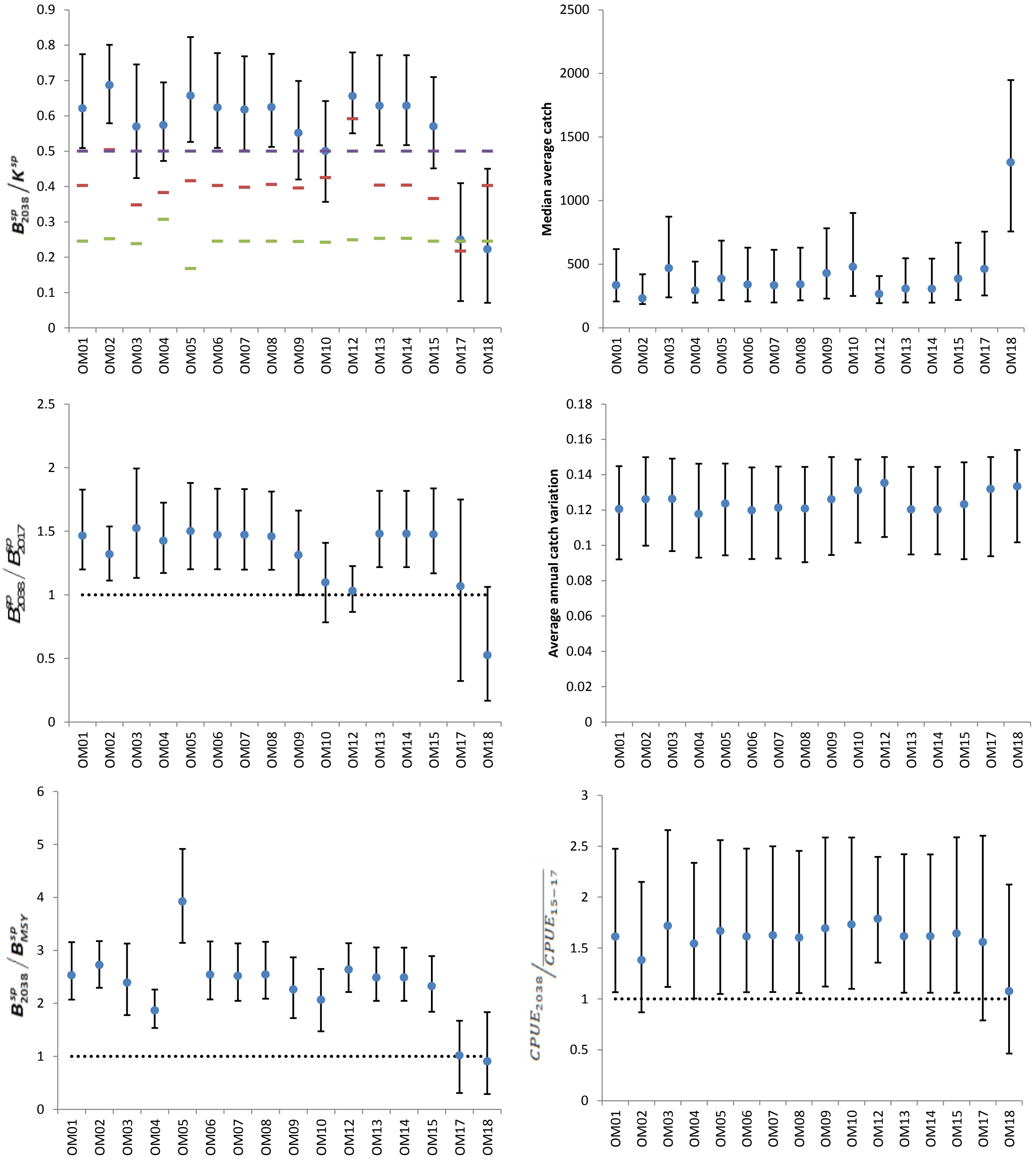


Figure 3. Zeh plots as for Figure 1, but for **CMP50 which is tuned to achieve a final depletion of 50% under OM10**.

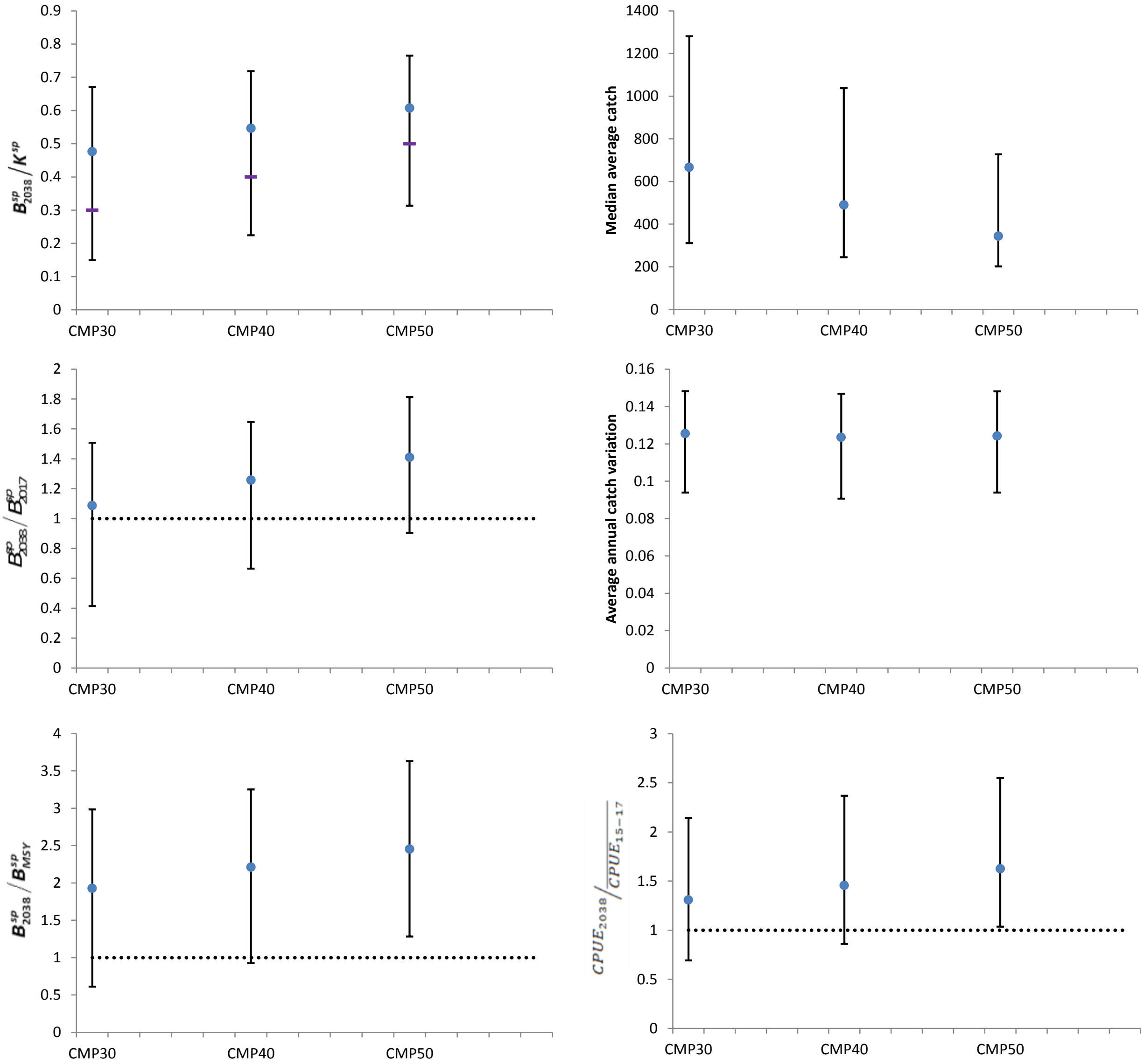


Figure 4. Zeh plots for some of the performance statistics reported in the Tables across all simulations for all 15 RS OMs giving equal weight to each OM (i.e. medians over 15x100 simulations) for the three CMPs considered. The purple dashes represent the final depletion value under OM10 to which each CMP was tuned.

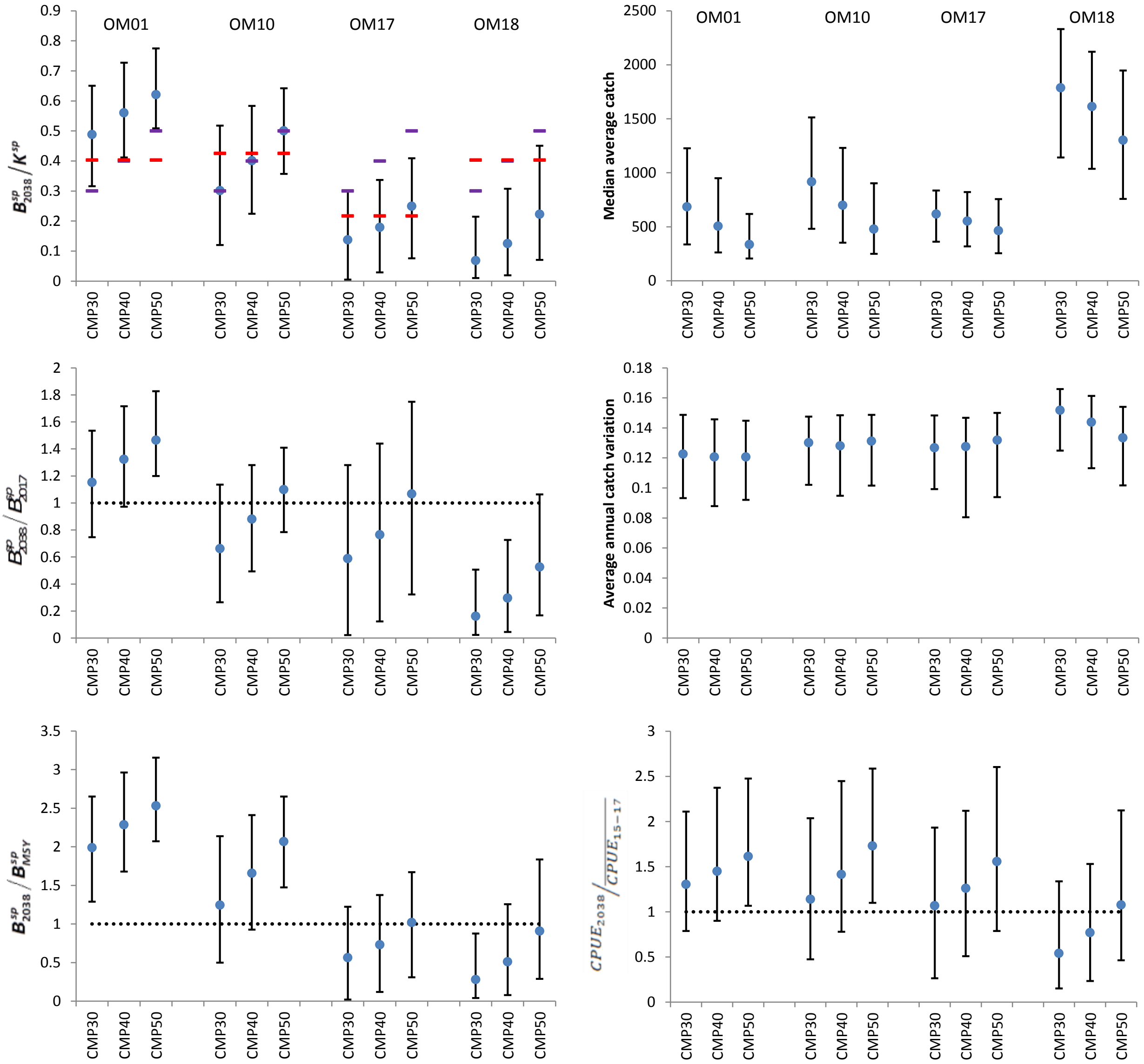


Figure 5. Zeh plots for some of the performance statistics reported in the Tables for OM01, OM10, OM17 and OM18 for CMP30, CMP40 and CMP50 which are tuned to achieve a median final depletion of 30, 40 and 50% respectively under OM10. These are the spawning biomass depletion at the start of 2038 relative to K, to the spawning biomass in 2017 and to the spawning biomass at MSY, the projected median of the average annual legal (trotline) catches of toothfish (in tonnes) for the period 2019 to 2038, the average annual variation in catch and the CPUE index in 2038 as a proportion of the average of the 2015 to 2017 CPUE indices for the 15 OMs. The red dashes represents the current (2018) spawning biomass depletion for each OM and the purple dashes represent the final depletion value under OM10 to which each CMP was tuned.

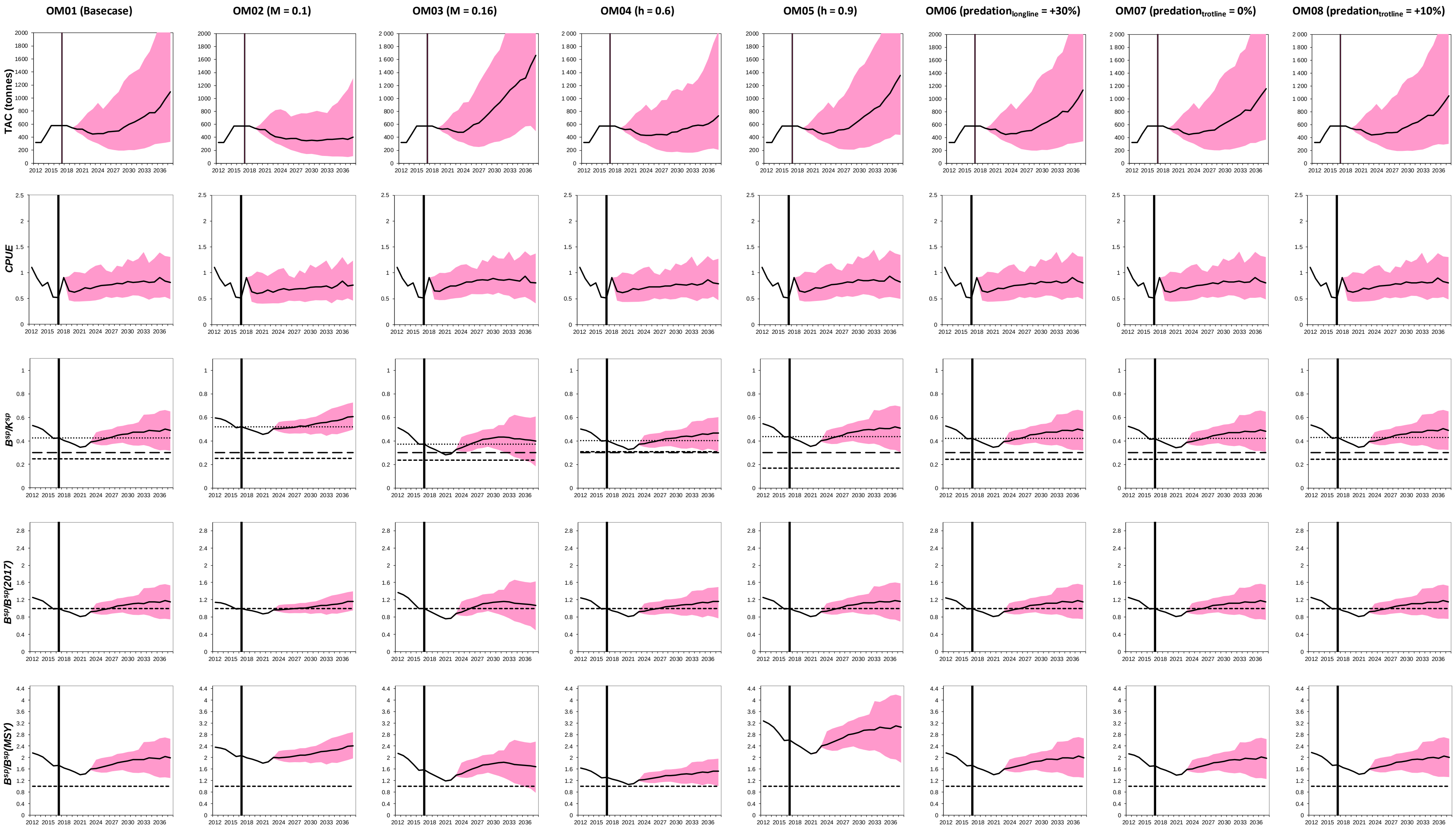


Figure 6a. Median trajectories of TAC (in tonnes), CPUE trends, spawning biomass depletion, spawning biomass relative to the 2017 value and spawning biomass relative to B_{MSY} under **CMP30 (which is tuned to achieve a final depletion of 30% under OM10)** for **OM01 to OM08**. Projections commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. For the middle row of plots, the large dash line is the value the CMP was tuned to under OM10, the dotted line is the current (2018) spawning biomass depletion, while the small dash line is the MSYL (relative to *K*).

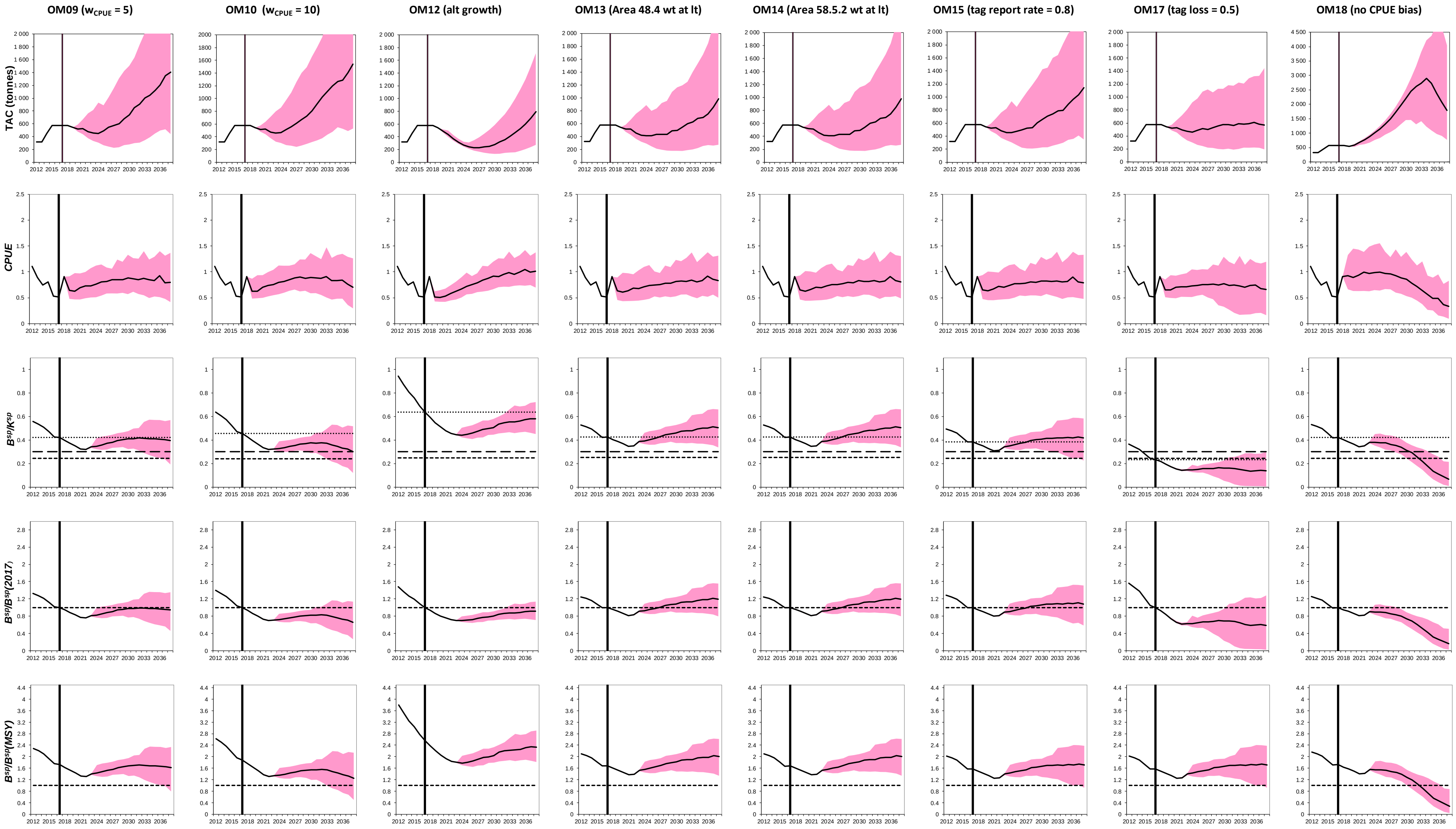


Figure 6b. Projection results as for Figure 5a, but for **OM09 to OM18**.

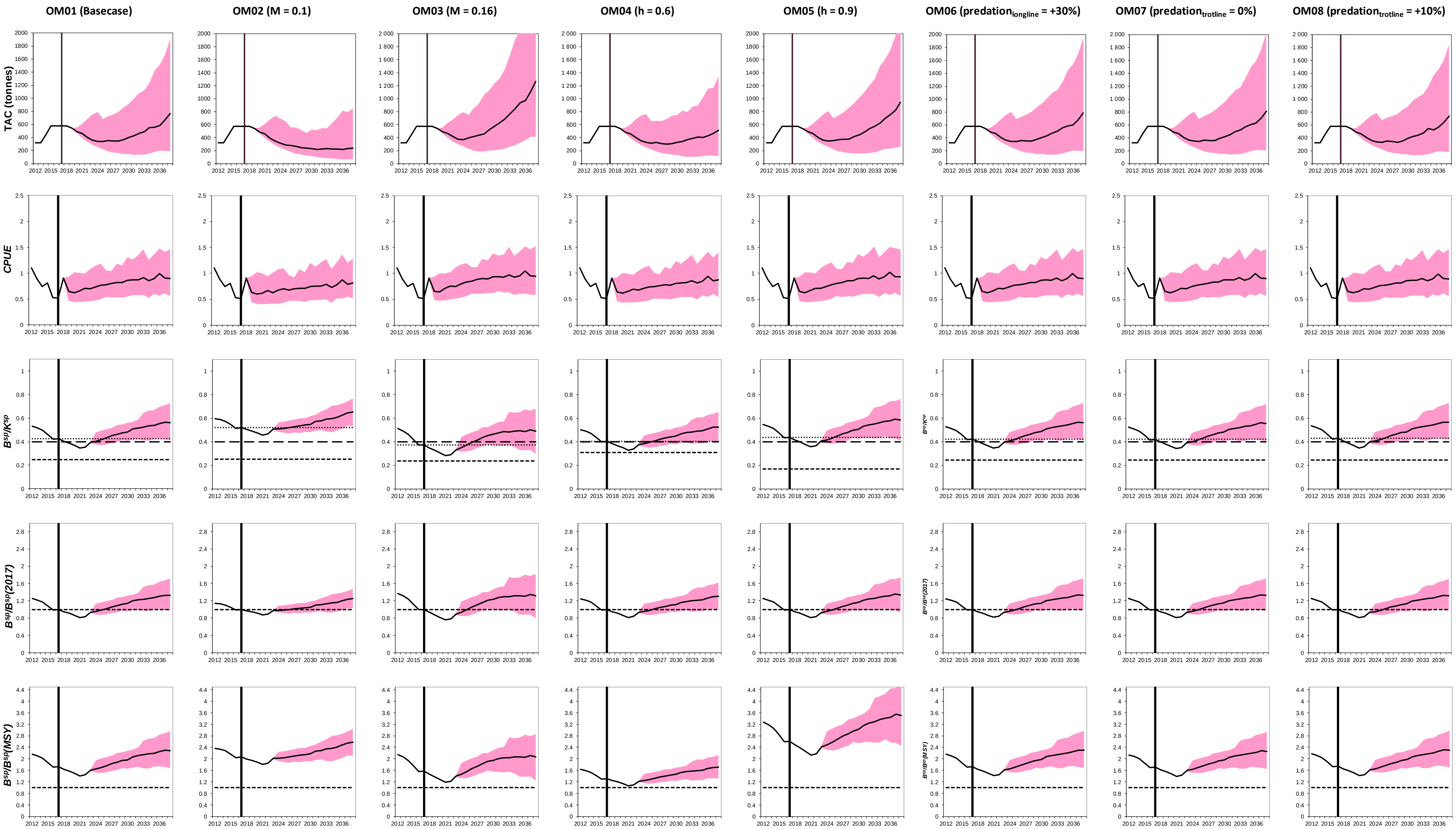


Figure 7a. Median trajectories as for Figure 6a, for **CMP40 which is tuned to achieve a final depletion of 40% under OM10.**

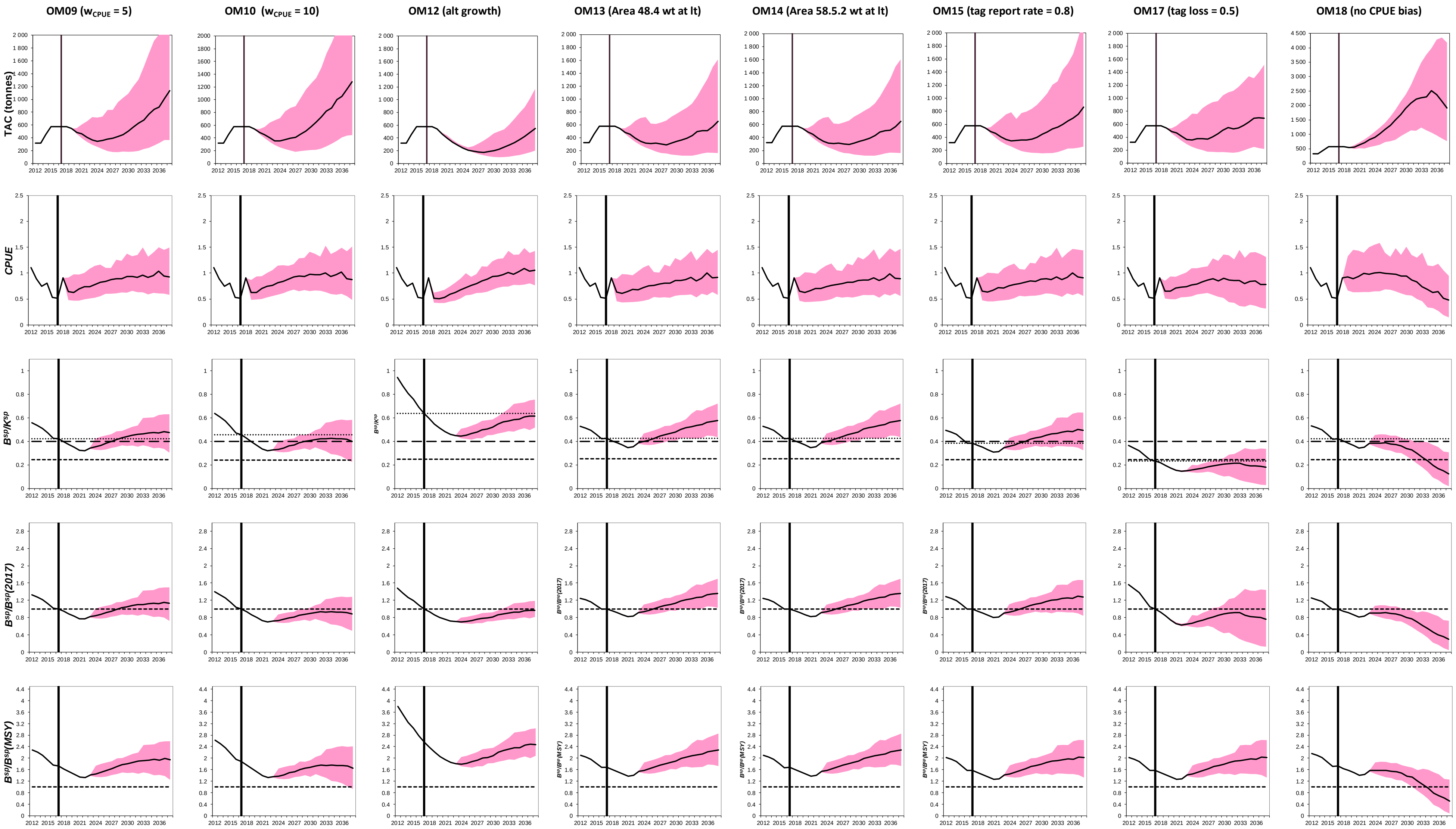


Figure 7b. Projection results as for Figure 7a, but for **OM09 to OM18**.

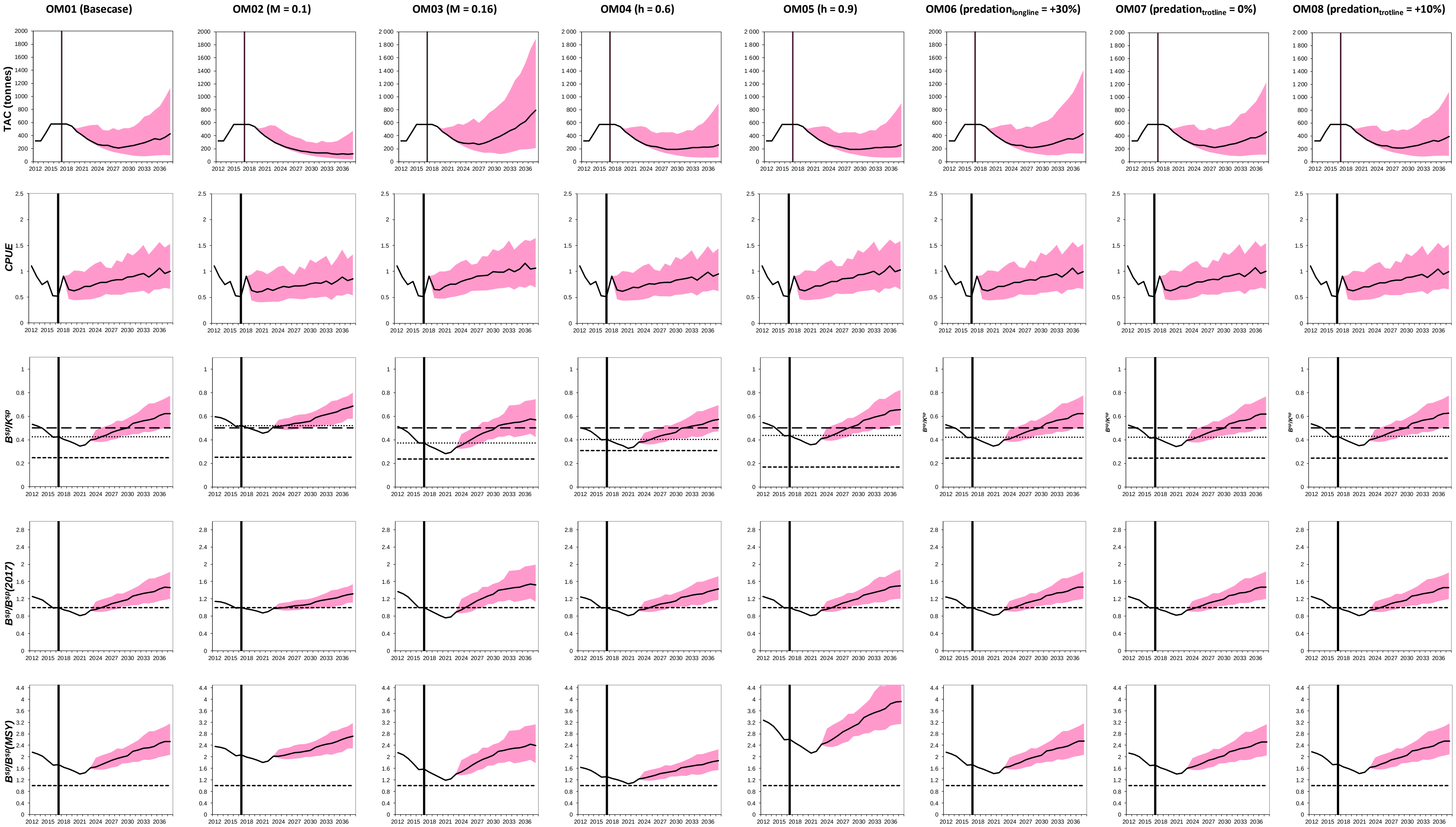
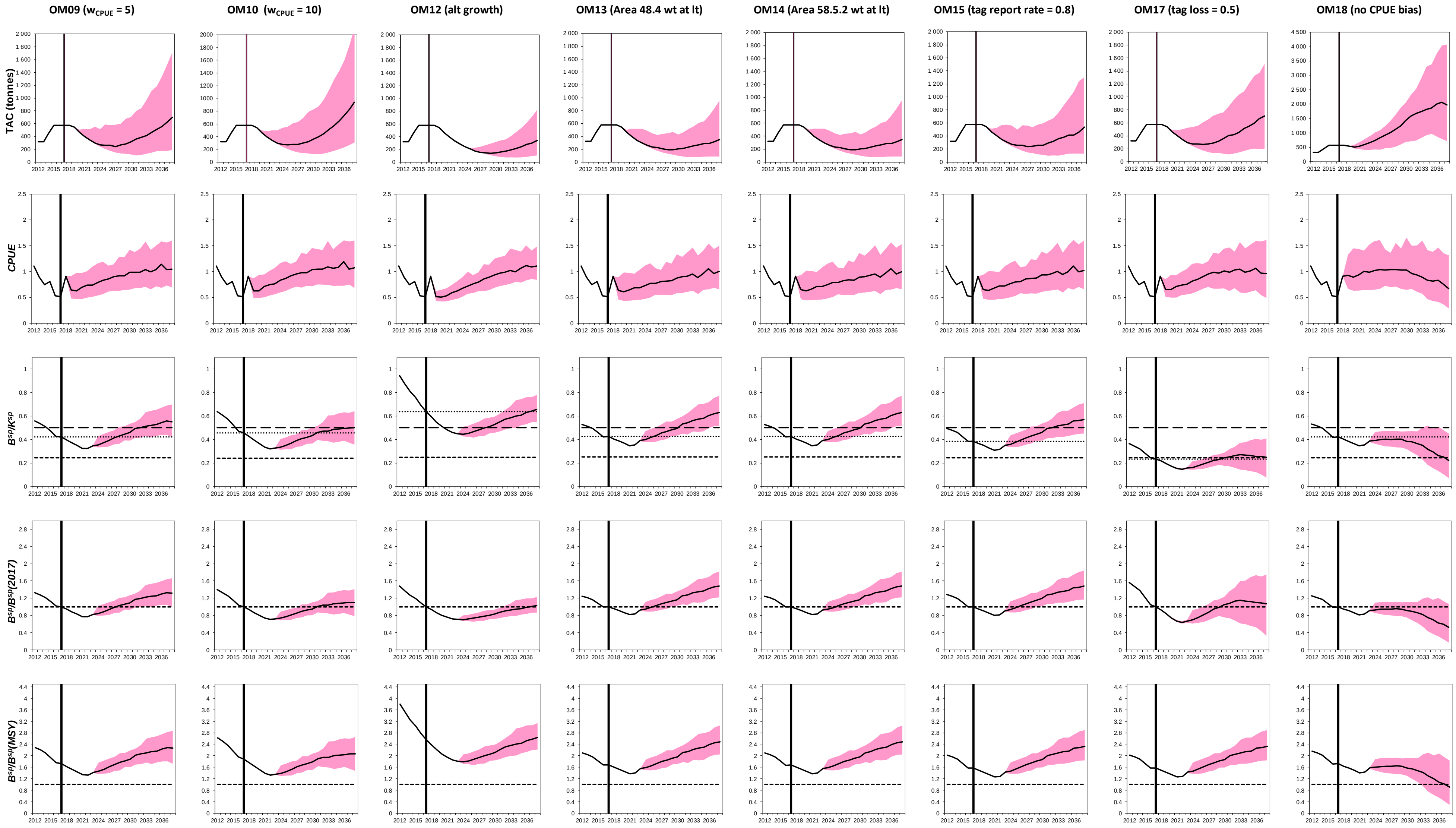


Figure 8a. Median trajectories as for Figure 6a, for **CMP50 which is tuned to achieve a final depletion of 50% under OM10.**



OM09 ($w_{CPUE} = 5$)

OM10 ($w_{CPUE} = 10$)

OM12 (alt growth)

OM13 (Area 48.4 wt at lt)

OM14 (Area 58.5.2 wt at lt)

OM15 (tag report rate = 0.8)

OM17 (tag loss = 0.5)

OM18 (no CPUE bias)

Figure 8b. Projection results as for Figure 8a, but for **OM09 to OM18**.

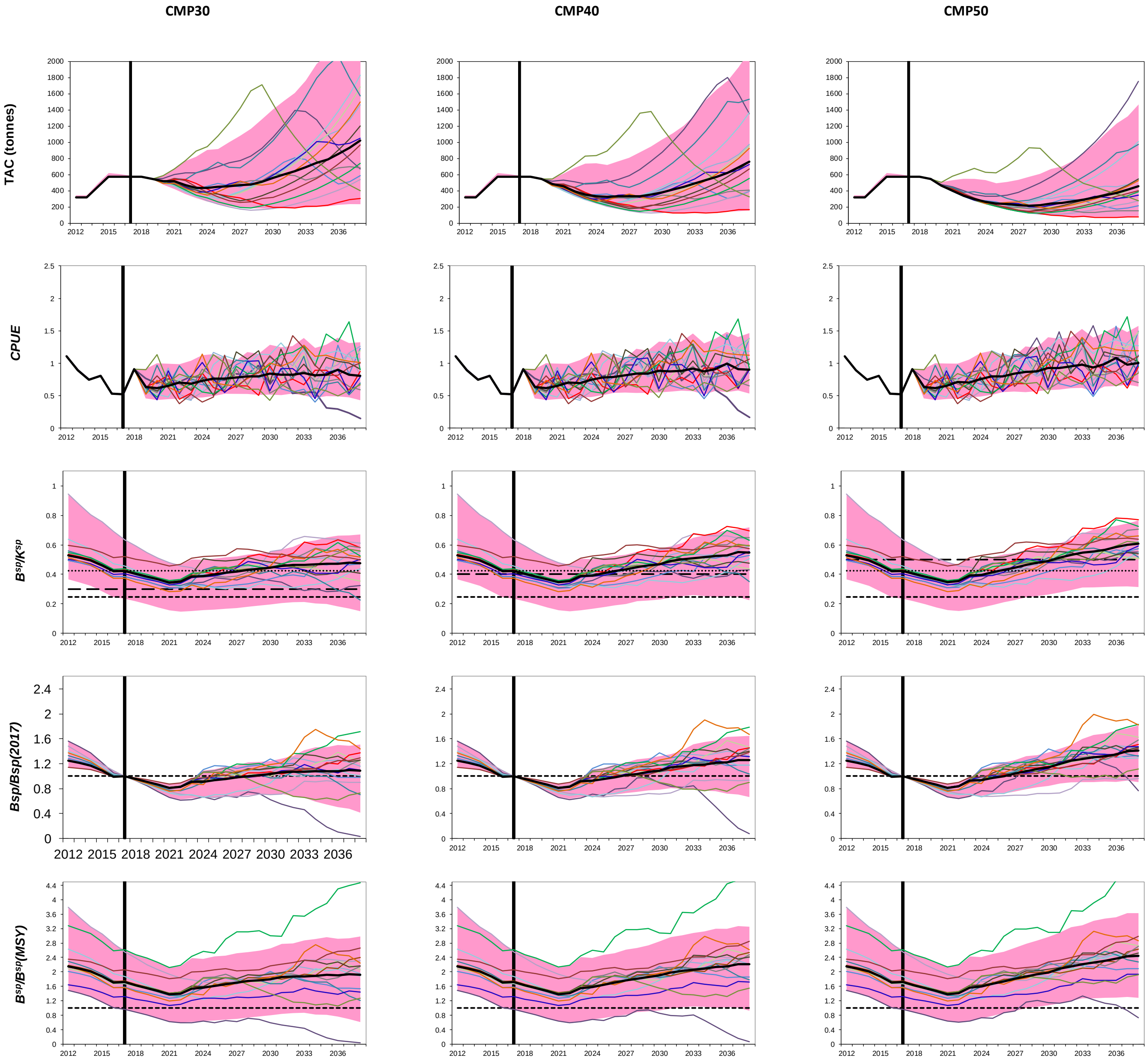


Figure 9. Median trajectories (thick black line) of TAC (in tonnes), CPUE trends, spawning biomass depletion, spawning biomass relative to the 2017 value and spawning biomass relative to B_{MSY} under the CMP across all simulations for all 15 RS OMs giving equal weight to each OM, for the three CMPs considered. Projections commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. A random selection of worm lots, one from each of the 15 OMs, is also shown (coloured lines). For the middle row of plots, the large dash line is the value the CMP was tuned to under OM10, the dotted line is the median current (2018) spawning biomass depletion, while the small dash line is the average MSYL (relative to *K*) over all 15 RS OMs.

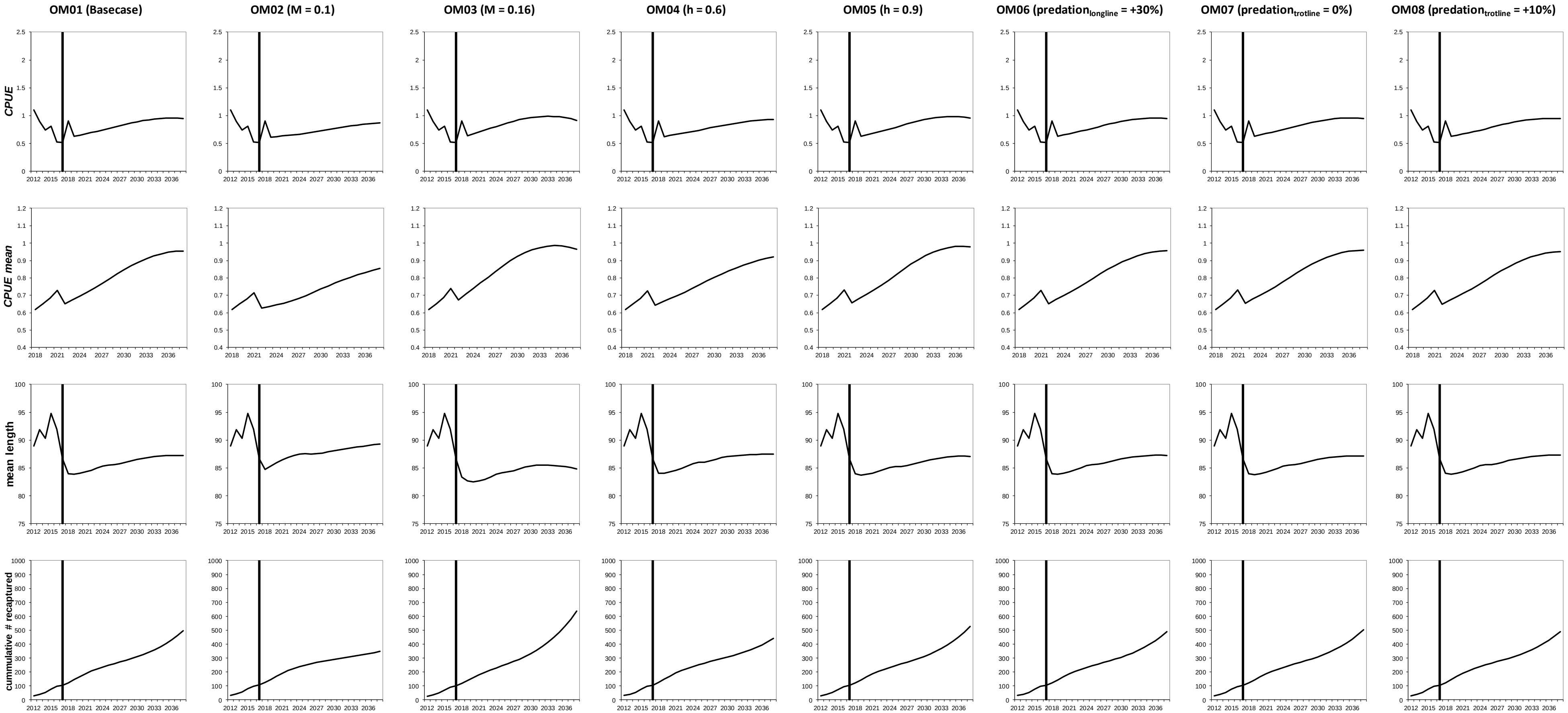


Figure 10a. Deterministic projections (shown to the right of the vertical line) of CPUE, CPUE mean $\left(\mu_{CPUE}\right)$, mean length (in cm) and the cumulative number of recaptured tag trends under **CMP40 (which is tuned to achieve a final depletion of 40% under OM10)** for **OM01 to OM08**. The values to the left of the vertical line reflect past data from trotline operations.

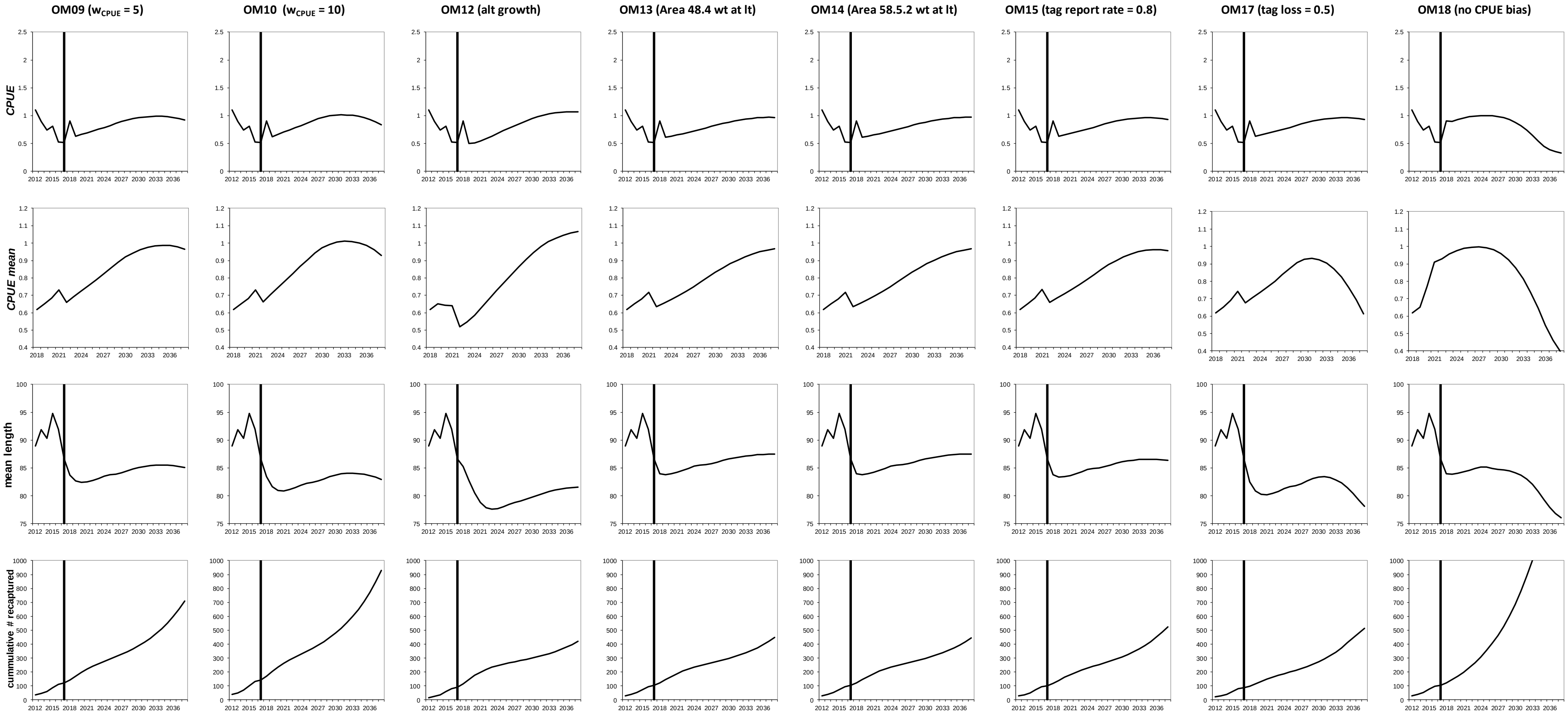


Figure 10b. Deterministic projections as for Figure 10a, but for **OM09 to OM18.**

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

$$N_{y+1,0} = R(B^{sp}_{y+1}) \qquad (A1.1)$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})\, e^{-M} \qquad 0 \leq a \leq m\text{-}2 \qquad (A1.2)$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})\, e^{-M} + (N_{y,m-1} - C_{y,m-1})\, e^{-M} \qquad (A1.3)$$

where:

$N_{y,a}$ is the number of toothfish of age *a* at the start of year *y*,

$C_{y,a}$ is the number of toothfish of age *a* taken by the fishery in year *y*,

$R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A1.10) below,

B^{sp} is the spawning biomass at the start of year *y*,

M is the natural mortality rate of fish (assumed to be independent of age), and

m is the maximum age considered (i.e. the “plus group”), taken here to be *m* = 35.

Note that in the interests of simplicity this approximates the fishery as a pulse fishery at the start of the year. Given that toothfish are relatively long-lived with low natural mortality, such an approximation would seem adequate.

For a three-gear (or “fleet”) fishery, the total predicted number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = \sum_{f=1}^{3} C^{f}_{y,a}\ , \qquad (A1.4)$$

where:

$$C^{f}_{y,a} = N_{y,a} S^{f}_{y,a} F^{f}_{y} \qquad (A1.5)$$

and:

F^{f}_{y} is the proportion of the resource above age *a* harvested in year *y* by fleet *f*, and

$S^{f}_{y,a}$ is the commercial selectivity at age *a* in year *y* for fleet *f*.

The mass-at-age is given by the combination of a von Bertalanffy growth equation $\ell(a)$ defined by constants ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ refers to standard length.

$$\ell(a) = \ell_\infty[1 - e^{-\kappa(a-t_0)}] \qquad (A1.6)$$

$$w_a = c\left[\ell(a)\right]^d \qquad (A1.7)$$

where:

w_a is the mass of a fish at age a.

The fleet-specific total catch (given by the sum of the observed legal catch and any assumed illegal component, together with the assumed level of cetacean depredation) by mass in year y is given by:

$$C^f_y = \sum_{a=0}^{m} w_a C^f_{y,a} = \sum_{a=0}^{m} w_a S^f_{y,a} F^f_y N_{y,a} \tag{A1.8}$$

which can be re-written as:

$$F^f_y = \frac{C^f_y}{\sum_{a=0}^{m} w_a S^f_{y,a} N_{y,a}} \tag{A1.9}$$

FISHING SELECTIVITY

The fleet-specific commercial fishing selectivity, $S^f_{y,a}$, is assumed to be described by a logistic curve, modified by a decreasing selectivity for fish older than age a_c. This is given by:

$$S^f_{y,a} = \begin{cases} \left[1+e^{-\left(a-a^f_{50,y}\right)/\delta^f_y}\right]^{-1} & \text{for } a \le a_c \\ \left[1+e^{-\left(a-a^f_{50,y}\right)/\delta^f_y}\right]^{-1} e^{-\omega^f_y (a-a_c)} & \text{for } a > a_c \end{cases} \tag{A1.10}$$

where

$a^f_{50,y}$	is the age-at-50% selectivity (in years) for year y for fleet f,
δ^f_y	defines the steepness of the ascending section of the selectivity curve (in years^{-1}) for year y for fleet f, and
ω^f_y	defines the steepness of the descending section of the selectivity curve for fish older than age a_c for year y for fleet f (for all the results reported in this paper, a_c is fixed at 8 yrs).

In cases where equation (A1.9) yields a value of F^f_y > 0.9 for a future year, i.e. the available biomass is less than the proposed catch for that year, F^f_y is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch. This procedure makes no adjustment to the exploitation rate ($S^f_{y,a}$ F^f_y) of other ages. To avoid the unnecessary reduction of catches from ages where the TAC could have been taken if the selectivity for those ages had been increased, the following procedure is adopted (CCSBT, 2003):

The fishing mortality, F^f_y, is computed as usual using equation (A1.9). If $F^f_y \le 0.9$ no change is made to the computation of the total catch, C^f_y, given by equation (A1.8). If F^f_y > 0.9, compute the total catch from:

$$C^f_y = \sum_{a=0}^{m} w_a g(S^f_{y,a} F^f_y) N_{y,a} \, . \tag{A1.11}$$

Denote the modified selectivity by $S_{y,a}^{f*}$, where:

$$S_{y,a}^{f*} = \frac{g(S_{y,a}^{f} F_{y}^{f})}{F_{y}^{f}}, \tag{A1.12}$$

so that $C_{y}^{f} = \sum_{a=0}^{m} w_a S_{y,a}^{f*} F_{y}^{f} N_{y,a}$, where

$$g(x) = \begin{cases} x & x \le 0.9 \\ 0.9 + 0.1\left[1 - e^{(-10(x-0.9))}\right] & 0.9 < x \le \infty \end{cases}. \tag{A.1.13}$$

Now F_{y}^{f} is not bounded at one, but $g\left(S_{y,a}^{f} F_{y}^{f}\right) \le 1$ hence $C_{y,a}^{f} = g(S_{y,a}^{f} F_{y}^{f}) N_{y,a} \le N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

The spawning biomass in year *y* is given by:

$$B_{y}^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \tag{A1.14}$$

where:

f_a = the proportion of fish of age *a* that are mature (assumed to be knife-edge at age a_m).

The number of recruits at the start of year *y* is assumed to relate to the spawning biomass at the start of year *y*, B_{y}^{sp}, by a Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment):

$$R(B_{y}^{sp}) = \frac{\alpha\, B_{y}^{sp}}{\beta + B_{y}^{sp}}. \tag{A1.15}$$

The values of the parameters α and β can be calculated given the unexploited equilibrium (pristine) spawning biomass K^{sp} and the steepness of the curve *h*, using equations (A1.15)–(A1.19) below. If the pristine recruitment is $R_0 = R(K^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2K^{sp}) \tag{A1.16}$$

from which it can be shown that:

$$h = \frac{0.2(\beta + K^{sp})}{\beta + 0.2K^{sp}}. \tag{A1.17}$$

Rearranging equation (A1.16) gives:

$$\beta = \frac{0.2K^{sp}(1-h)}{h-0.2} \tag{A1.18}$$

and solving equation (A1.14) for α gives:

$$\alpha = \frac{0.8hR_0}{h-0.2}.$$

In the absence of exploitation, the population is assumed to be in equilibrium. Therefore R_0 is equal to the loss in numbers due to natural mortality when $B^{sp} = K^{sp}$, and hence:

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \qquad \text{(A1.19)}$$

where:

$$\gamma = \left\{ \sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right\}^{-1}. \qquad \text{(A1.20)}$$

PAST STOCK TRAJECTORY AND FUTURE PROJECTIONS

Given a value for the pre-exploitation equilibrium spawning biomass (K^{sp}) of toothfish, and the assumption that the initial age structure is at equilibrium, it follows that:

$$K^{sp} = R_0 \left(\sum_{a=1}^{m-1} w_a f_a e^{-Ma} + \frac{w_m f_m e^{-Mm}}{1-e^{-M}} \right) \qquad \text{(A1.21)}$$

which can be solved for R_0.

The initial numbers at each age *a* for the trajectory calculations, corresponding to the deterministic equilibrium, are given by:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \qquad \text{(A1.22)}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1.1)-(A1.5) and (A1.8)-(A1.14) under the series of annual catches given.

The model estimate of the fleet-specific exploitable component of the biomass is given by:

$$B_y^{\exp}(f) = \sum_{a=0}^{m} w_a S_{y,a}^f N_{y,a} \qquad \text{(A1.23)}$$

THE LIKELIHOOD FUNCTION

The age-structured production model (ASPM) is fitted to the fleet-specific GLM standardised CPUE to estimate model parameters. The likelihood is calculated assuming that the observed (standardised) CPUE abundance indices are lognormally distributed about their expected value:

$$I_y^f = \hat{I}_y^f e^{\varepsilon_y^f} \text{ or } \varepsilon_y^f = \ln\left(I_y^f\right) - \ln\left(\hat{I}_y^f\right), \qquad \text{(A1.24)}$$

where

I_y^f is the standardised CPUE series index for year *y* corresponding to fleet *f*,

$\hat{I}_y^f$ $= \frac{1}{\phi}\hat{q}^f \hat{B}_y^{\exp}(f)$ is the corresponding model estimate, where:

$\widehat{B}_y^{\exp}(f)$ is the model estimate of exploitable biomass of the resource for year *y* corresponding to fleet *f*,

ϕ is a multiplier to account for the effect of cetacean depredation (e.g. a 5% increase due to cetacean depredation means that $\phi = 1.05$), and

q^f is the catchability coefficient for the standardised commercial CPUE abundance indices for fleet *f*, whose maximum likelihood estimate is given by:

$$\ln\hat{q}^f = \frac{1}{n^f}\sum_y \left(\ln I_y^f - \ln\hat{B}_y^{\exp}(f)\right), \tag{A1.25}$$

where:

n^f is the number of data points in the standardised CPUE abundance series for fleet *f*, and

ε_y^f is normally distributed with mean zero and standard deviation σ^f (assuming homoscedasticity of residuals), whose maximum likelihood estimate is given by:

$$\hat{\sigma}^f = \sqrt{\frac{1}{n^f}\sum_y \left(\ln I_y^f - \ln\hat{q}^f\hat{B}_y^{\exp}(f)\right)^2}\ . \tag{A1.26}$$

The negative log likelihood function (ignoring constants) which is minimised in the fitting procedure is thus:

$$-\ln L = \sum_f \left\{ \sum_y \left[\frac{1}{2(\sigma^f)^2}\ \left(\ln I_y^f - \ln\left(q^f\ B_y^{\exp}(f)\right)\right)^2 \right] + n^f\left(\ln\sigma^f\right) \right\}. \tag{A1.27}$$

The estimable parameters of this model are q^f, K^{sp}, and σ^f, where K^{sp} is the pre-exploitation mature biomass. Note that the summation over *f* does not include the pot fishery for which no CPUE data are available.

EXTENSION TO INCORPORATE CATCH-AT-LENGTH INFORMATION

The model above provides estimates of the catch-at-age ($C_{y,a}^f$) by number made by the each fleet in the fishery each year from equation (A1.5). These in turn can be converted into proportions of the catch of age *a*:

$$p_{y,a}^f = C_{y,a}^f \Big/ \sum_{a'} C_{y,a'}^f\ . \tag{A1.28}$$

Using the von Bertalanffy growth equation (A1.6), these proportions-at-age can be converted to proportions-at-length – here under the assumption that the distribution of length-at-age remains constant over time:

$$p_{y,\ell}^f = \sum_a p_{y,a}^f A_{a,\ell}^f \tag{A1.29}$$

where $A_{a,\ell}^f$ is the proportion of fish of age *a* that fall in length group ℓ for fleet *f*. Note that therefore:

$$\sum_\ell A_{a,\ell}^f = 1 \qquad \text{for all ages } a. \tag{A1.30}$$

The *A* matrix has been calculated here under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$\ell(a) \sim \mathrm{N}^*\left[\ell_\infty\left\{1-e^{-\kappa(a-t_0)}\right\};\theta^f(a)^2\right] \tag{A1.31}$$

where

N* is a normal distribution truncated at ± 3 standard deviations (to avoid negative values), and

$\theta^f(a)$ is the standard deviation of length-at-age *a* for fleet *f*, which is modelled here to be proportional to the expected length at age *a*, i.e.:

$$\theta^f(\mathrm{a}) = \beta^f\ell_\infty\left\{1-e^{-\kappa(a-t_0)}\right\} \tag{A1.32}$$

with β^f a parameter estimated in the model fitting process.

Note that since the model of the population's dynamics is based upon a one-year time step, the value of β^f and hence the $\theta^f(a)$'s estimated will reflect not only the real variability of length-at-age, but also the "spread" that arises from the fact that fish in the same annual cohort are not all spawned at exactly the same time, and that catching takes place throughout the year so that there are differences in the age (in terms of fractions of a year) of fish allocated to the same cohort.

Model fitting is effected by adding the following term to the negative log-likelihood of equation (A1.27):

$$-\ln L_{len} = w_{len}\sum_{f,y,\ell}\left\{\ln\left[\sigma^f_{len}\Big/\sqrt{p^f_{y,\ell}}\right]+\left(p^f_{y,\ell}\Big/\left(2\left(\sigma^f_{len}\right)^2\right)\right)\left[\ln p^{obs}_{y,\ell}(f)-\ln p^f_{y,\ell}\right]^2\right\} \tag{A1.33}$$

where

$p^{obs}_{y,\ell}(f)$ is the proportion by number of the catch in year *y* in length group *ℓ* for fleet *f*, and

σ^f_{len} has a closed form maximum likelihood estimate given by:

$$\left(\hat{\sigma}^f_{len}\right)^2 = \sum_{y,\ell}p^f_{y,\ell}\left[\ln p^{obs}_{y,\ell}(f)-\ln p^f_{y,\ell}\right]^2\Big/\sum_{y,\ell}1. \tag{A1.34}$$

Equation (A1.33) makes the assumption that proportions-at-length data are log-normally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to $p^f_{y,\ell}$ to downweight contributions from expected small proportions which will correspond to small observed sample sizes. This adjustment (known as the Punt-Kennedy approach) is of the form to be expected if a Poisson-like sampling variability component makes a major contribution to the overall variance. Given that overall sample sizes for length distribution data differ quite appreciably from year to year, subsequent refinements of this approach may need to adjust the variance assumed for equation (A1.33) to take this into account.

The w_{len} weighting factor may be set at a value less than 1 to downweight the contribution of the catch-at-length data to the overall negative log-likelihood compared to that of the CPUE data in equation (A1.27). The reason that this factor is introduced is that the $p^{obs}_{y,\ell}(f)$ data for a given year frequently show evidence of strong positive correlation, and so would not be as informative as the independence assumption underlying the form of equation (A1.33) would otherwise suggest.

In the practical application of equation (A1.33), length observations were grouped by 2 cm intervals, with minus- and plus-groups specified below 54 and above 138 cm respectively for the longline fleet, and plus-groups above 176 cm for the pot fleet, to ensure $p^{obs}_{y,\ell}(f)$ values in excess of about 2% for these cells.

ADJUSTMENT TO INCORPORATE RECRUITMENT VARIABILIITY

To allow for stochastic recruitment, the number of recruits at the start of year *y* given by equation (A1.15) is replaced by:

$$R(B^{sp}_y) = \frac{\alpha\, B^{sp}_y}{\beta\ + B^{sp}_y} e^{\left(\zeta_y - \sigma^2_{R/2}\right)}, \tag{A1.35}$$

where ζ_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation σ_R (which is input). The ζ_y are estimable parameters of the model.

The stock-recruitment function residuals are assumed to be log-normally distributed. Thus, the contribution of the recruitment residuals to the negative log-likelihood function is given by:

$$-\ln L_{rec} = \sum_{y=1961} \left\{ \ln\sigma_R + \zeta^2_y \big/ \left(2\sigma^2_R\right) \right\}, \tag{A1.36}$$

which is added to the negative log-likelihood of equation (A1.27) as a penalty (the frequentist equivalent of a Bayesian prior for these parameters). In the present application, it is assumed that the resource is not at equilibrium at the start of the fishery, but rather in such equilibrium in 1960 with zero catches taken until the start of the fishery in 1997 (by which time virtually all "memory" of the original equilibrium has been lost because of subsequent recruitment variability). For the computations reported in this paper $\sigma_R = 0.5$.

EXTENSION TO INCLUDE TAG-RECAPTURE DATA

The approach described by Butterworth *et al.* (2003) has been implemented in this paper to take into account tag-recapture data. The recaptures follow a Poisson distribution and therefore the following term is added to the negative log-likelihood of equation (A1.27):

$$-\ln L_{tag} = \sum_{f,y,a} \left\{ \hat{r}^f_{y,a} - r^f_{y,a} \ln \hat{r}^f_{y,a} \right\} \tag{A1.37}$$

where

$r^f_{y,a}$ is the number of recaptured tags from toothfish of age *a* in year *y* by fleet *f* that have been at large for more than a year, and

$\hat{r}^f_{y,a}$ is the expected number of recaptures of age *a* in year *y* by fleet *f*, given by:

$$\hat{r}^f_{y,a} = \eta_{y,a} \frac{F^f_{y,a}}{M_a + F_{y,a} + \xi} \left\{ 1 - e^{-\left(M_a + F_{y,a} + \xi\right)} \right\} \sum_{k=1}^{a-1} R_{y-k,a-k} e^{-\left(M_{a-k} + F^*_{y-k,a-k} + \xi\right)} \left[\prod_{j=1,k\geq 2}^{k-1} e^{-\left(M_{a-j} + F_{y-j,a-j} + \xi\right)} \right] \tag{A1.38}$$

where

$R_{y-k,a-k}$ is the number of tags released in year *y-k* of age *a-k*,

$F_{y,a}$ is the fishing mortality for toothfish in year *y* of age *a*, which is given by the summation of the fleet specific fishing mortalities $F^f_{y,a}$,

M_a is the natural mortality rate for toothfish of age *a* (assumed to be independent of age),

ξ is the tag loss rate,

$\eta_{y,a}$ is the tag-reporting rate for toothfish in year *y* of age *a*, and

$F^*_{y-k,a-k}$ is the fishing mortality of tagged toothfish in year *y-k* of age *a-k* during the first year at large. This is estimated from the number of tags recaptured by each fleet within the first year that the toothfish are at large. However, in this instance, as there are minimal recaptures for longlines and for trotlines within the first year, these fishing mortalities have been assumed to be the same as $F_{y-k,a-k}$.