Results for a potential Candidate Management Procedure for the Toothfish (*Dissostichus eleginoides*) Resource in the Prince Edward Islands vicinity

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ABSTRACT

Brandão and Butterworth (2019a) investigated various target-based Candidate Management Procedures (CMPs); however, their performances under operating models OM17 and OM18 were not satisfactory so that further investigation/adjustment of these CMPs was needed. An adjusted form of CMP(mean+tag) of Brandão and Butterworth (2019a), which incorporates trends in the cumulative number of recaptured tags as well as the recent mean of the trotline CPUE, is considered in this paper. This CMP seems to perform satisfactorily under most of the OMs, in that median catches increase for most of the projection period while catch rates keep increasing and the median final depletion remains above the specified target value under OM10. However, the performance of the CMP under OM17 is still not satisfactory. It might be that it will not be possible to improve the performance of the CMP under OM17 without decreasing TACs under other scenarios for which the status of the resource does not necessitate lower catches. However, as this OM assumes quite an extreme tag loss, perhaps less weight should be accorded to the performance of the CMP under this scenario, even perhaps considering it as a robustness test rather than part of this Reference Set.

INTRODUCTION

A modified version of one of the simple empirical Candidate Management Procedure (CMP) proposed by Brandão and Butterworth (2019a) for computing future TACs for toothfish in the Prince Edward Islands region is investigated in this paper. This CMP (referred to as CMP(mean+tag)) incorporates trends in the cumulative number of recaptured tags as well as the recent mean of the trotline CPUE .

The parameters of this CMP are tuned to achieve a target median final depletion level of 40% under OM10, and results are then shown for the Reference Set (RS) of Operating Models (OMs).

OPERATING MODELS AND PROJECTIONS

Assessment component

Brandão and Butterworth (2019b) presented the conditioning of a RS of OMs to be used to generate future data to test Candidate Management Procedures (CMPs). Table 1 lists the final RS 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 corresponding to 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 are given in Appendix 1.

Projections component

The four CMPs investigated here assume that commercial trotline CPUE data will continue to be available annually, and one of these CMPs also assumes that tag-recapture data from trotlines will be available in the future. Details on the future level of tagging assumed is discussed below under item (5). The current level of cetacean predation assumed for trotlines by each OM is also 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 CPUE and tag-recapture 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 calculated by applying equations (A1.1)–(A1.3). To allow for initial variation in biomass projections (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 $\mathrm{N}\left(0,\sigma_R^2\right)$, 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 equations (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 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-normally distributed 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 index values well; as a result future projected CPUE indices are much higher than those observed recently. To take this into account, the projected CPUE indices have been multiplied by the ratio of the average of the last two CPUE indices observed 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 approach has been adopted to take the actual TACs already set for 2018 and 2019 into account

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

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 ($C_{y'}$) (removal from the population) 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 in the OM concerned. 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 proportion of the TAC that is being allocated (0.886). The numbers-at-age for year y' are projected forward under this true catch (removal); the operating model is used to obtain values for $C_{y',a}$ and $N_{y'+1,a}$. The same assumptions about the commercial selectivity function and recruitment fluctuations as made in step (1) above are also made for these projections.

5. The number of tags released each year is assumed to be constant in the future (assumed to be 400 in this paper). The age distribution of tags released in year y′ $\left(R_{y',a}\right)$, given the abundance of toothfish $N_{y',a}$, is generated as

$$R_{y',a} = 400 \frac{N_{y',a} \overline{R_a} / \overline{N_a}}{\sum_a \left(N_{y',a} \overline{R_a} / \overline{N_a} \right)},$$

where

$\overline{R_a}$ is the average number (over the period 2005 to 2017) of tags released on fish of age a, and

$\overline{N_a}$ is the average number (over the period 2005 to 2017) in the population of age a.

Given the fishing mortality for toothfish in year *y′* of age *a* for fleet *f* $\left(F_{y',a}^{f}\right)$, equation (A1.38) is used to compute the estimated numbers of tags recaptured from trotlines $\left(\hat{r}_{y',a}\right)$. Future age aggregated numbers of tags recaptured from trotlines $\left(r_{y'}\right)$ are then generated as realisations from a Poisson $\left(\hat{r}_{y'}\right)$ distribution, where $\hat{r}_{y'} = \sum_{a} r_{y',a}$. The cumulative recapture numbers are then calculated from the age aggregated generated numbers of recaptured tags.

6. Steps (2)–(4) are repeated for each future year considered.
7. 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 (which in turn affect future catches and consequently numbers in the population and the number of recaptures).

The updated GLMM-standardised trotline CPUE estimate for 2018[1] (0.906 see Brandão and Butterworth, 2019c), and the observed number of tags released together with the number of tag-recaptures observed for 2018 are used as the starting point inputs in the projections.

THE CMP CONSIDERED

The CMP considered in this paper, where the TAC is modified in synchrony with the trends in resource abundance indices (such as CPUE and tag recapture data) is specified as

$$\text{CMP(mean+tag):} \quad TAC_{y+1} = TAC_y \left[1 + \phi \left(\frac{\mu_y^{CPUE} - t^*}{t^*} \right) \right] \left[1 - \gamma \left(s_y^{cum(recap)} - s_t^* \right) \right] \tag{1}$$

where μ_y^{CPUE} is the mean trotline CPUE for the previous three years, $s_y^{cum(recap)}$ is the slope of a linear regression of the cumulative number of recaptured tags against time for the previous five years and ϕ, γ, t^* and s_t^* are control parameters. The difference between this CMP and the one of Brandão and Butterworth (2019a) is that previously $s_y^{cum(recap)}$ was defined as the slope of a log-linear (rather than a linear) regression of the cumulative number of recaptured tags against time. Thus the CMP output becomes more sensitive to the number of tags recaptured in absolute terms, which provide a better reflection of resource status.

This CMP also constrains TACs to a maximum inter-annual change of 15%.

RESULTS AND DISCUSSION

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

[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*.

Catches achieved

Average annual catch: $\overline{C^s} = \frac{1}{20}\sum_{y=2019}^{2038} C_y^s$, where *s* represents simulation *s;* averages of annual catch for different periods within these projections are also considered.

Risk to resource

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

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

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

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 control parameters led to the following selection for the CMP, given a target of 40% of the median final depletion under OM10:

CMP(mean+tag): $\phi=1,\ \gamma=1,\ t^*=0.78\ \ and\ \ s_t^*=45$.

Testing this CMP for the OMs of the Reference Set yields the results shown in Table 2. Results for the performance statistics are shown calculated for each individual OM as well as for combining the outputs from all OMs together. Figure 1 compares the performance of this CMP under the Reference Set OMs.

Table 3 reports various catch statistics, while Table 4 gives results based on CPUE statistics. Median projections for some performance statistics under each individual OM are shown in Figures 2a to 2b. Figure 3 shows results when combining all the outputs from the 15 OMs together and calculating the performance statistics on the 15x100 simulations. Figure 3 also shows one randomly selected worm trajectory from each of the OMs.

Under most OMs, the performance of this simple empirical CMP seems to be satisfactory in that median catches increase for most of the projection period, while catch rates also keep increasing and the median final depletion remains above the specified target value under OM10. Under OM03 and OM15, the median final depletion is only slightly below this target value. 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, the CMP still falls well below the target value for median final depletion.

If no bias is incorporated in the projections of CPUE (OM18), the CMP exhibits much better performance than was shown by previous CMPs reported by Brandão and Butterworth (2019a), except for CMP(slope). The CMP reacts appropriately by not sharply increasing catches and consequently maintains the resource biomass just below the target value for median final depletion and current (2017) value.

With the adjustment made to the form of the CMP, attempts to incorporate the cumulative numbers of tag returns in the CMP seem to have been successful in improving performance for OM18 which showed problematic resource trends with previous CMPs (Brandão and Butterworth, 2019a). The performance of the CMP under OM17 is still not satisfactory. It might be that it will not be possible to improve the performance of the CMP under OM17 without decreasing TACs under other scenarios in which the status of the resource does not necessitate lower catches. However, as this OM assumes quite an extreme tag loss, perhaps less weight should be accorded to the performance of the CMP under this scenario, even perhaps considering it as a robustness test rather than part of the Reference Set.

Of all the CMPs considered in Brandão and Butterworth (2019a), only one showed an improvement in some respects under OM17. This is CMP(dep t) , which is based on the average of recent CPUE indices and allows for a time-dependent target value. An initial attempt at the incorporation of the tag recapture information in the specification of this CMP (i.e. specifying CMP(dep t+tag) in a similar manner as in CMP(mean+tag)), did not result in an improvement in the performance under OM17, so that this approach was not pursued further.

The form of CMP(mean+tag) in Brandão and Butterworth (2019a) had the added unsatisfactory behaviour under most OMs in that there is a drop in TACs for about the first ten years. With the adjustment made to the CMP reported here, this is no longer the case. Under most OMs, there is now an increase in TACs initially before a later drop in TACs, but for most OMs this drop still keeps the TAC above its present value.

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. Length related units are in terms of cm.

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	ℓ_∞= 174.5 κ = 0.0425 t_{o} = -1.4575	ℓ_∞= 152.0 κ = 0.067 t_{o} = -1.49
OM13†	c = 4.09x10^{-9} d = 3.196	c = 2.54x10^{-8} d = 2.8
OM14†	c = 4.17x10^{-9} d = 3.206	c = 2.54x10^{-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 mass at length conversion is given in terms of cm to tonnes.
* OM18 is a robustness test and is not part of the Reference Set of OMs.

Table 2. Medians of the distributions of several performance statistics under the simple CMP considered for the selected Reference Set OMs, together with their 90% probability intervals. The last row reports these performance statistics as medians across all simulations for all 15 RS OMs, giving equal weight to each OM.

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)	0.45 (0.38; 0.53)	1.06 (0.90; 1.25)	1.83 (1.55; 2.16)	1.42 (1.40; 1.44)	763 (584; 945)	671 (620; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM02 (M = 0.1)	0.53 (0.46; 0.62)	1.01 (0.88; 1.18)	2.09 (1.81; 2.44)	1.83 (1.82; 1.84)	616 (493; 761)	659 (606; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM03 (M=0.16)	0.39 (0.33; 0.49)	1.05 (0.87; 1.31)	1.65 (1.37; 2.06)	1.19 (1.17; 1.22)	902 (695; 1088)	678 (626; 678)	0.14 (0.11; 0.16)	0.25 (0.22; 0.25)
OM04 (h = 0.6)	0.41 (0.35; 0.48)	1.02 (0.87; 1.20)	1.33 (1.14; 1.57)	1.07 (1.06; 1.09)	688 (529; 853)	667 (613; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM05 (h = 0.9)	0.47 (0.40; 0.56)	1.08 (0.92; 1.28)	2.83 (2.40; 3.35)	2.14 (2.12; 2.17)	829 (638; 1012)	674 (622; 678)	0.14 (0.11; 0.16)	0.25 (0.22; 0.25)
OM06 ($P_{longline}$ = +30%)	0.45 (0.38; 0.54)	1.06 (0.90; 1.27)	1.83 (1.55; 2.19)	1.42 (1.41; 1.44)	791 (607; 970)	674 (622; 678)	0.14 (0.11; 0.16)	0.25 (0.22; 0.25)
OM07 ($P_{trotline}$ = +0%)	0.45 (0.38; 0.53)	1.06 (0.90; 1.26)	1.82 (1.55; 2.15)	1.40 (1.39; 1.42)	787 (603; 973)	674 (622; 678)	0.14 (0.11; 0.16)	0.25 (0.22; 0.25)
OM08 ($P_{trotline}$ = +10%)	0.45 (0.38; 0.54)	1.05 (0.90; 1.26)	1.84 (1.56; 2.19)	1.43 (1.41; 1.45)	751 (575; 922)	670 (616; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM09 (w_{CPUE} = 5)	0.42 (0.35; 0.49)	0.99 (0.84; 1.16)	1.71 (1.45; 2.00)	1.29 (1.28; 1.32)	748 (574; 891)	655 (599; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM10 (w_{CPUE} = 10)	0.40 (0.34; 0.47)	0.89 (0.75; 1.03)	1.67 (1.42; 1.94)	1.30 (1.28; 1.32)	672 (524; 810)	629 (571; 678)	0.14 (0.11; 0.16)	0.23 (0.21; 0.25)
OM12 (alt growth)	0.44 (0.38; 0.55)	0.69 (0.60; 0.86)	1.76 (1.54; 2.20)	1.81 (1.80; 1.82)	739 (560; 906)	595 (563; 632)	0.14 (0.11; 0.16)	0.23 (0.20; 0.24)
OM13 (mass at lt Area 48.4)	0.45 (0.38; 0.53)	1.05 (0.90; 1.25)	1.76 (1.51; 2.10)	1.37 (1.36; 1.39)	741 (565; 911)	663 (612; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM14 (mass at lt Area 58.5.2)	0.45 (0.38; 0.54)	1.05 (0.90; 1.26)	1.76 (1.51; 2.12)	1.37 (1.36; 1.39)	740 (566; 910)	663 (612; 678)	0.14 (0.11; 0.16)	0.24 (0.22; 0.25)
OM15 (tag report rate = 0.8)	0.37 (0.31; 0.45)	0.95 (0.80; 1.16)	1.50 (1.25; 1.82)	1.25 (1.23; 1.27)	801 (612; 969)	677 (624; 678)	0.14 (0.11; 0.16)	0.25 (0.22; 0.25)
OM17 (tag loss = 0.5)	0.07 (0.00; 0.15)	0.32 (0.01; 0.64)	0.31 (0.01; 0.61)	0.56 (0.52; 0.60)	627 (467; 809)	678 (636; 678)	0.15 (0.12; 0.17)	0.25 (0.22; 0.25)
OM18 (no CPUE bias)	0.37 (0.30; 0.44)	0.87 (0.71; 1.04)	1.51 (1.23; 1.79)	1.42 (1.40; 1.44)	950 (789; 1115)	678 (678; 678)	0.15 (0.13; 0.16)	0.25 (0.25; 0.25)
Combined OMs	0.39 (0.02; 0.51)	0.88 (0.07; 1.20)	1.59 (0.07; 2.08)	1.30 (0.53; 1.43)	686 (503; 902)	663 (591; 678)	0.15 (0.11; 0.17)	0.24 (0.21; 0.25)

Table 3. Projected distribution 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 selected Reference Set OMs, together with their 90% probability intervals. The last row reports these performance statistics as medians across all simulations for all 15 RS OMs, giving equal weight to each OM.

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)	798 (610; 988)	762 (569; 916)	720 (554; 921)	689 (634; 695)	981 (535; 1720)	839 (478; 1279)	672 (424; 1138)	840 (636; 867)
OM02 (M = 0.1)	643 (514; 796)	640 (491; 779)	646 (505; 802)	676 (621; 695)	676 (336; 1324)	614 (338; 972)	549 (360; 892)	789 (611; 867)
OM03 (M=0.16)	944 (726; 1139)	870 (628; 1066)	823 (614; 1057)	695 (641; 695)	1183 (665; 2000)	1007 (560; 1536)	856 (507; 1483)	867 (653; 867)
OM04 (h = 0.6)	719 (552; 892)	700 (531; 847)	693 (534; 869)	684 (628; 695)	799 (436; 1489)	740 (403; 1121)	611 (399; 1043)	823 (623; 867)
OM05 (h = 0.9)	867 (666; 1059)	802 (598; 963)	741 (574; 961)	691 (637; 695)	1059 (588; 1979)	951 (531; 1394)	725 (457; 1227)	851 (637; 867)
OM06 ($P_{longline}$ = +30%)	827 (634; 1016)	780 (581; 938)	732 (570; 940)	692 (636; 695)	994 (542; 1790)	875 (482; 1346)	701 (449; 1187)	852 (639; 867)
OM07 ($P_{trotline}$ = +0%)	784 (600; 970)	742 (555; 897)	699 (535; 893)	658 (606; 662)	933 (519; 1734)	844 (469; 1275)	668 (428; 1118)	809 (607; 826)
OM08 ($P_{trotline}$ = +10%)	823 (629; 1011)	778 (584; 947)	746 (571; 940)	720 (661; 729)	993 (539; 1790)	870 (485; 1329)	689 (439; 1149)	874 (660; 908)
OM09 (w_{CPUE} = 5)	782 (599; 932)	708 (534; 860)	666 (521; 855)	671 (613; 695)	969 (552; 1588)	902 (483; 1270)	636 (387; 1067)	779 (597; 867)
OM10 (w_{CPUE} = 10)	702 (547; 847)	630 (471; 777)	577 (473; 774)	644 (583; 695)	880 (506; 1436)	833 (475; 1235)	572 (320; 855)	677 (548; 867)
OM12 (alt growth)	772 (585; 948)	654 (506; 842)	545 (478; 674)	609 (575; 647)	1118 (647; 1845)	990 (595; 1436)	620 (357; 947)	586 (528; 675)
OM13 (mass at lt Area 48.4)	775 (590; 953)	730 (547; 893)	697 (546; 879)	680 (626; 695)	953 (514; 1681)	829 (476; 1247)	635 (407; 1108)	806 (620; 867)
OM14 (mass at lt Area 58.5.2)	774 (591; 952)	730 (547; 895)	696 (546; 878)	680 (626; 695)	956 (519; 1694)	831 (475; 1258)	629 (406; 1104)	806 (620; 867)
OM15 (tag report rate = 0.8)	838 (639; 1014)	784 (576; 969)	744 (577; 968)	694 (639; 695)	967 (507; 1818)	882 (464; 1407)	715 (446; 1279)	862 (642; 867)
OM17 (tag loss = 0.5)	655 (487; 846)	698 (524; 914)	792 (580; 1019)	695 (652; 695)	344 (150; 1041)	448 (231; 943)	658 (375; 1133)	867 (691; 867)
OMP18 (no CPUE bias)	994 (826; 1168)	960 (773; 1122)	911 (783; 1092)	695 (695; 695)	1088 (645; 1669)	1084 (644; 1634)	964 (599; 1465)	867 (867; 867)
Combined OMs	717 (525; 944)	693 (504; 908)	680 (498; 970)	680 (604; 695)	805 (180; 1518)	708 (294; 1241)	634 (352; 1100)	804 (578; 867)

Table 4. Projected distribution median CPUE indices relative to the 2017 CPUE index after several years of projections, and the distribution median CPUE index in 2038 as a proportion of the average of the 2015 to 2017 CPUE indices. The probabilities of the CPUE index in 2038 being less than this average under the simple CMP considered for the selected Reference Set OMs, together with their 90% probability intervals are also reported. The last row reports these performance statistics as medians across all simulations for all 15 RS OMs, giving equal weight to each OM.

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)	1.54 (1.04; 2.44)	1.55 (0.99; 2.51)	1.42 (0.94; 2.02)	1.33 (0.85; 1.86)	1.29 (0.87; 2.04)	0.18
OM02 (M = 0.1)	1.35 (0.88; 2.19)	1.36 (0.84; 2.25)	1.27 (0.84; 1.82)	1.26 (0.77; 1.79)	1.13 (0.74; 1.83)	0.33
OM03 (M=0.16)	1.65 (1.13; 2.54)	1.61 (1.11; 2.58)	1.52 (1.00; 2.14)	1.42 (0.94; 1.94)	1.38 (0.94; 2.13)	0.10
OM04 (h = 0.6)	1.44 (0.98; 2.27)	1.45 (0.93; 2.36)	1.36 (0.90; 1.92)	1.30 (0.83; 1.82)	1.21 (0.82; 1.90)	0.25
OM05 (h = 0.9)	1.61 (1.08; 2.55)	1.62 (1.04; 2.60)	1.48 (0.99; 2.09)	1.35 (0.86; 1.88)	1.34 (0.91; 2.13)	0.13
OM06 ($P_{longline}$ = +30%)	1.53 (1.04; 2.43)	1.55 (0.99; 2.50)	1.42 (0.96; 2.02)	1.33 (0.85; 1.87)	1.28 (0.87; 2.03)	0.19
OM07 ($P_{trotline}$ = +0%)	1.55 (1.05; 2.45)	1.56 (1.01; 2.54)	1.44 (0.97; 2.04)	1.34 (0.86; 1.87)	1.30 (0.88; 2.05)	0.17
OM08 ($P_{trotline}$ = +10%)	1.53 (1.04; 2.42)	1.54 (0.99; 2.49)	1.41 (0.95; 2.00)	1.32 (0.85; 1.85)	1.28 (0.87; 2.02)	0.19
OM09 (w_{CPUE} = 5)	1.72 (1.20; 2.68)	1.69 (1.16; 2.68)	1.58 (1.05; 2.21)	1.39 (0.92; 1.89)	1.43 (1.00; 2.24)	0.05
OM10 (w_{CPUE} = 10)	1.85 (1.34; 2.69)	1.83 (1.32; 2.78)	1.72 (1.17; 2.44)	1.40 (0.99; 1.89)	1.55 (1.12; 2.25)	0.03
OM12 (alt growth)	1.56 (1.21; 2.17)	1.64 (1.17; 2.37)	1.49 (1.11; 1.91)	1.10 (0.84; 1.40)	1.31 (1.01; 1.81)	0.05
OM13 (mass at lt Area 48.4)	1.51 (1.03; 2.41)	1.54 (0.99; 2.44)	1.40 (0.95; 1.98)	1.29 (0.83; 1.80)	1.26 (0.86; 2.01)	0.17
OM14 (mass at lt Area 58.5.2)	1.51 (1.03; 2.40)	1.54 (0.98; 2.44)	1.40 (0.96; 1.98)	1.29 (0.83; 1.80)	1.26 (0.86; 2.01)	0.17
OM15 (tag report rate = 0.8)	1.50 (1.04; 2.32)	1.51 (0.99; 2.45)	1.40 (0.92; 1.95)	1.34 (0.87; 1.86)	1.25 (0.87; 1.94)	0.22
OM17 (tag loss = 0.5)	0.80 (0.19; 1.53)	0.93 (0.23; 1.70)	0.83 (0.45; 1.51)	1.29 (0.91; 1.76)	0.67 (0.16; 1.28)	0.86
OM18 (no CPUE bias)	1.98 (1.32; 3.01)	1.98 (1.27; 3.19)	1.86 (1.22; 2.73)	1.89 (1.21; 2.65)	1.65 (1.11; 2.52)	0.04
Combined OMs	1.47 (0.44; 2.44)	1.46 (0.41; 2.54)	1.39 (0.52; 2.19)	1.34 (0.91; 1.85)	1.23 (0.37; 2.04)	0.36

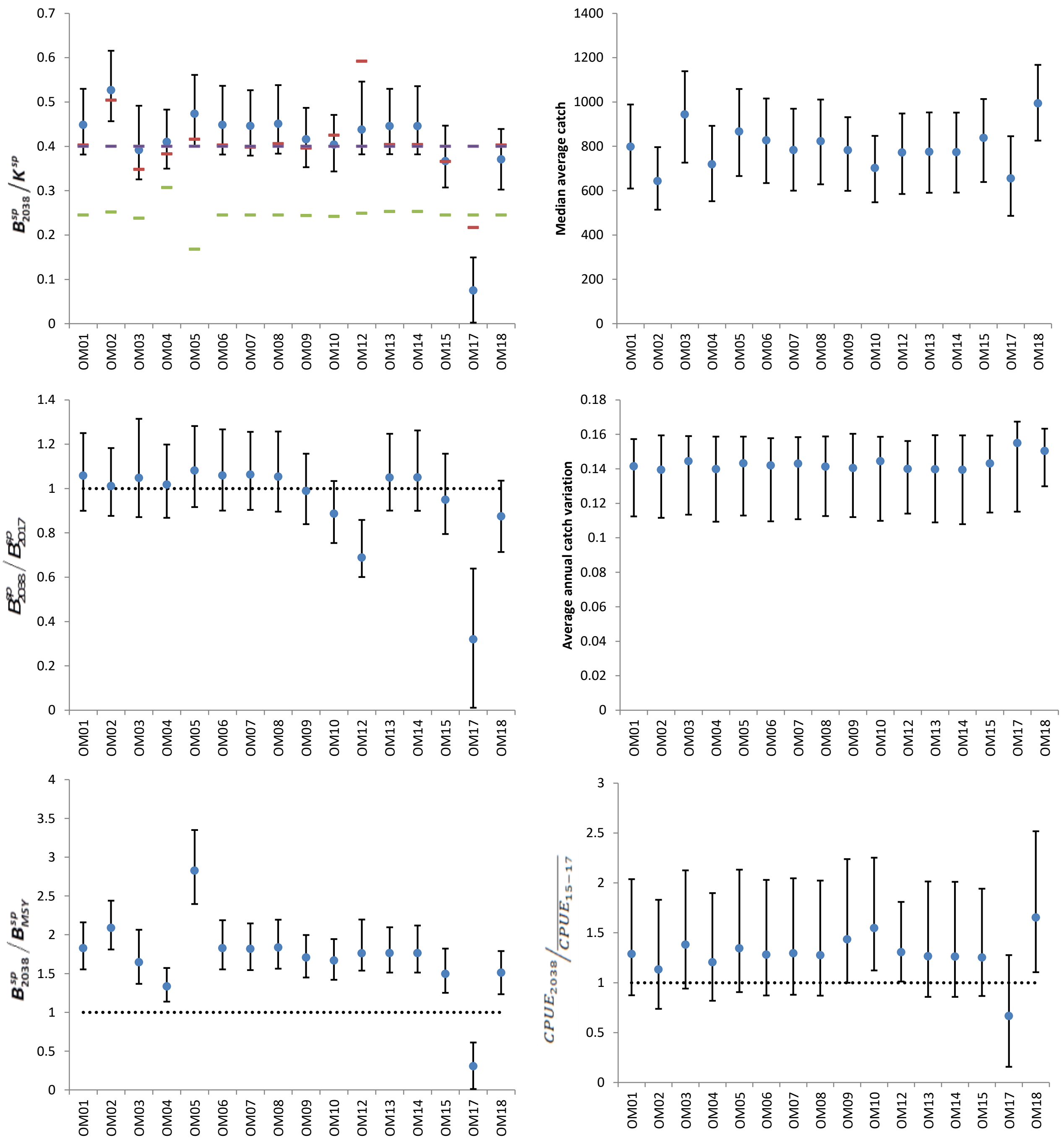

Figure 1. Zeh plots for some of the performance statistics reported in the Tables for each OM for CMP(mean+tag), which has been tuned to achieve a median final depletion of 40% under OM10. These are the spawning biomass depletion at the start of 2038 relative to K, to the spawning biomass in 2017 and 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. The red dashes represent the current (2018) spawning biomass depletion for each OM, the purple dashes represent the final depletion value under OM10 to which the CMP was tuned and the green dashes represent the MSYL (relative to *K*).

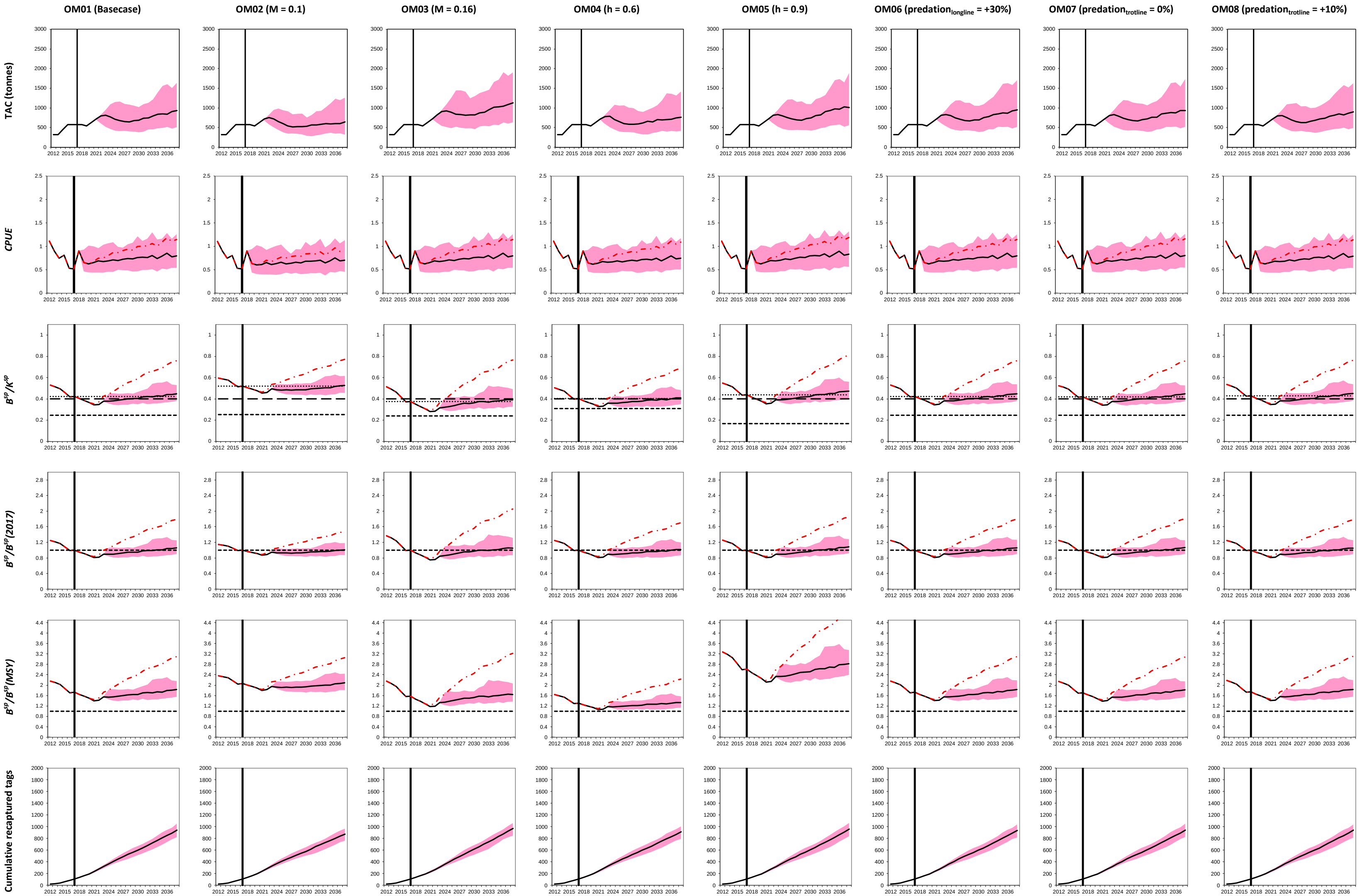

Figure 2a. Median trajectories of the TAC (in tonnes), CPUE trend, spawning biomass depletion, spawning biomass relative to the 2017 value, the spawning biomass relative to B_{MSY} and the cumulative number of recaptured tags under CMP(mean+tag). That CMP is based on the recent mean of the trotline CPUE and the recent trend in the cumulative number of recaptured tags for **OM01 to OM08**. Projections commence to the right of the thick vertical lines, and the shaded areas represent 90% probability envelopes. For the middle row of plots, the large dashed line is the value ($0.4K^{sp}$) to which the CMP was tuned under OM10 and the dotted line is the current (2018) spawning biomass depletion, while the small dash line is the MSYL (relative to *K*). The red lines represent the median trajectories under a zero catch scenario.

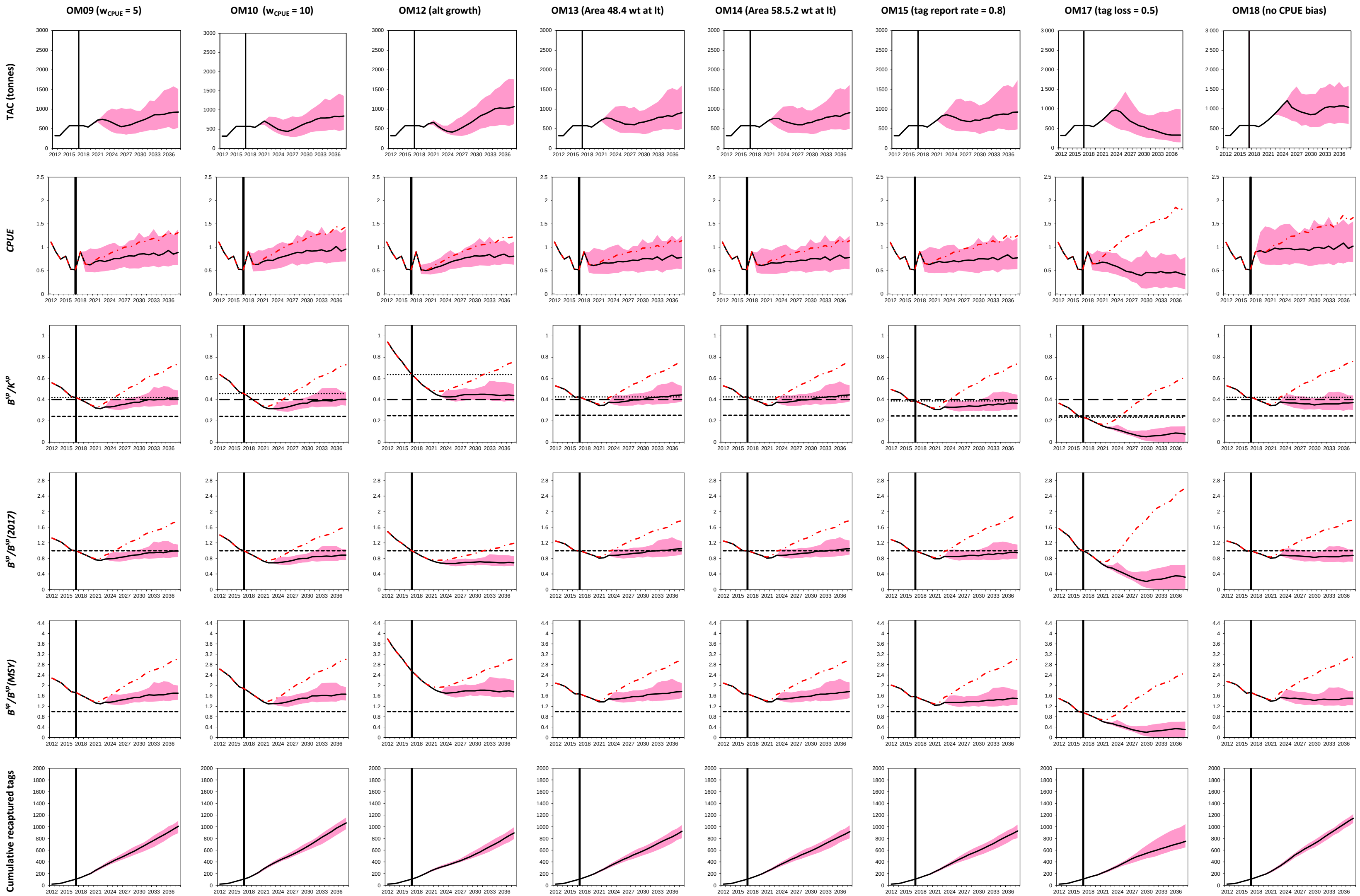

Figure 2b. Projection results as in Figure 2a, but here for **OM09 to OM18**.

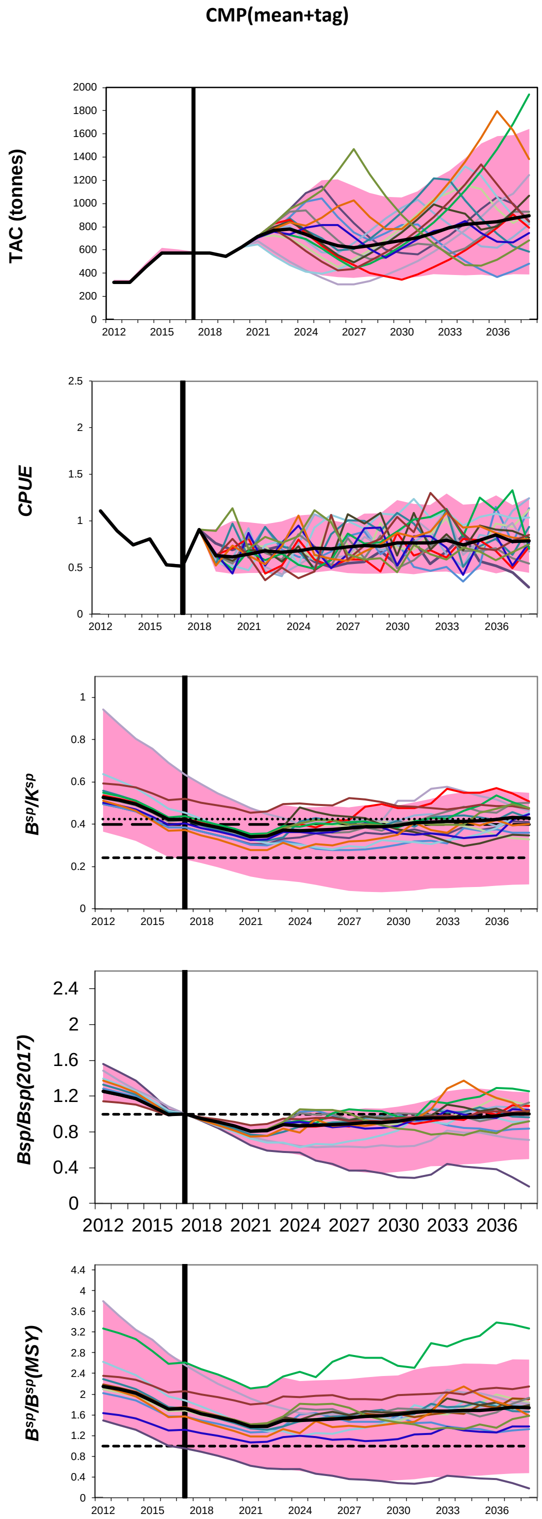

Figure 3. Median trajectories (thick black lines) of the TAC (in tonnes), CPUE trends, spawning biomass depletion, spawning biomass relative to the 2017 value and spawning biomass relative to B_{MSY} under CMP(mean+tag) across all simulations for all 15 RS OMs, giving equal weight to each OM. Projections commence to the right of the vertical lines and the shaded areas represent 90% probability envelopes. A random selection of worm plots, one from each of the 15 OMs, is also shown (coloured lines). For the middle plot, the large dashed line is the value to which this CMP was tuned 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.

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations

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

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

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

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 model 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

$$C_{y,a} = \sum_{f=1}^{3} C^f_{y,a} \ , \tag{A1.4}$$

where

$$C^f_{y,a} = N_{y,a} S^f_{y,a} F^f_y \tag{A1.5}$$

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.

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

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

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

$$C_y^f = \sum_{a=0}^{m} w_a C_{y,a}^f = \sum_{a=0}^{m} w_a S_{y,a}^f F_y^f N_{y,a} \tag{A1.8}$$

which can be re-written as

$$F_y^f = \frac{C_y^f}{\sum_{a=0}^{m} w_a S_{y,a}^f N_{y,a}} \tag{A1.9}$$

FISHING SELECTIVITY

The fleet-specific commercial fishing selectivity, $S_{y,a}^f$, 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

$$S_{y,a}^f = \begin{cases} \left[1+e^{-\left(a-a_{50,y}^f\right)/\delta_y^f}\right]^{-1} & \text{for } a \le a_c \\ \left[1+e^{-\left(a-a_{50,y}^f\right)/\delta_y^f}\right]^{-1} e^{-\omega_y^f (a-a_c)} & \text{for } a > a_c \end{cases} \tag{A1.10}$$

where

$a_{50,y}^f$ is the age-at-50% selectivity (in years) for year y for fleet f,

δ_y^f defines the steepness of the ascending part of the selectivity curve (in years^{-1}) for year y for fleet f, and

ω_y^f defines the steepness of the descending part 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_y^f > 0.9 for a future year, i.e. the available biomass is near to being less than the proposed catch for that year, F_y^f 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 ($S_{y,a}^f F_y^f$) for 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_y^f, is computed as usual using equation (A1.9). If $F_y^f \le 0.9$ no change is made to the computation of the total catch, C_y^f, given by equation (A1.8). If F_y^f > 0.9, compute the total catch from

$$C_y^f = \sum_{a=0}^{m} w_a g(S_{y,a}^f F_y^f) N_{y,a}\,. \tag{A1.11}$$

Denote the modified selectivity by $S^{f*}_{y,a}$, where

$$S^{f*}_{y,a} = \frac{g(S^f_{y,a} F^f_y)}{F^f_y}, \qquad \text{(A1.12)}$$

so that $C^f_y = \sum_{a=0}^{m} w_a S^{f*}_{y,a} F^f_y N_{y,a}$, where

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

Now F^f_y is not bounded at one, but $g\left(S^f_{y,a} F^f_y\right) \le 1$ hence $C^f_{y,a} = g(S^f_{y,a} F^f_y) N_{y,a} \le N_{y,a}$ as required.

STOCK-RECRUITMENT RELATIONSHIP

The spawning biomass in year *y* is given by

$$B^{sp}_y = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \qquad \text{(A1.14)}$$

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^{sp}_y, by a Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment)

$$R(B^{sp}_y) = \frac{\alpha\, B^{sp}_y}{\beta + B^{sp}_y}. \qquad \text{(A1.15)}$$

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.

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

from which it can be shown that

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

Rearranging equation (A1.17) gives

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

and solving equation (A1.15) for α gives

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

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

$$\gamma K^{sp} = R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{A1.19}$$

where

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

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 corresponds to equilibrium, it follows that

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

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

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

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

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

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:

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

where

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

$\widehat{I}_y^f$ $= \frac{1}{\phi}\widehat{q}^f \widehat{B}_y^{\exp}(f)$ 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 would mean that $\phi = 1.05$),

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

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

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 catches-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 then 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.

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

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 all these cells (hence no numerical problems arise for $p^{obs}_{y,\ell}(f)$ values of zero).

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

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

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

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

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 are assumed to be governed by a Poisson distribution and therefore the following term is added to the negative log-likelihood of equation (A1.27)

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

where

$r_{y,a}^f$ 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

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

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

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 $F_{y,a}^f$,

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

ξ is the tag loss rate (in yr^{-1}),

$\eta_{y,a}$ is the proportion of tags reported 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 $F_{y-k,a-k}$.