Initial results for a simple initial Candidate Management Procedure for the Toothfish (*Dissostichus eleginoides*) Resource in the Prince Edward Islands vicinity

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ABSTRACT

The Operating Models (OMs) presented in Brandão and Butterworth (2019) for the toothfish resource in the Prince Edward Islands region are used for initial trials of a Candidate Management Procedure (CMP) which could provide future TAC recommendations for this resource. The performance of a simple CMP control rule based upon recent trends in CPUE is investigated. This CMP is able to secure an increase in the TAC without adversely affecting the status of the resource under most OMs. However, the performance under OM17, which addresses the concern with the poor fit to the trotline CPUE data in the last two years, is not satisfactory. In order to tune this CMP 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.

INTRODUCTION

In this paper, an initial simple empirical Candidate Management Procedure (CMP) is proposed for computing future TACs for toothfish in the Prince Edward Islands region and its performance is evaluated. This simple empirical CMP is based on recent trends in the trotline CPUE to set TACs.

OPERATING MODELS AND PROJECTIONS

Assessment component

Brandão and Butterworth (2019) 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. 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 initial CMP investigated here assumes that commercial trotline CPUE data will continue to be available annually. The current level of cetacean predation assumed for trotlines in the Base case OM (OM01) is assumed to continue in the future. 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. It is assumed that no IUU catches take place in the future.

The evaluation of the CMP requires 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 $N(0,\sigma_R^2)$, 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 relationship. These fluctuations are computed for each future year simulated by generating $\zeta_{y'}$ factors distributed as $N(0,\sigma_R^2)$, 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 (A1.23); then a log-normal observation error is added to this expected value, i.e.:

$$I_{y'}^{CPUE} = qB_{y'}^{\exp}e^{\varepsilon_{y'}} \ ,$$

   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) to calculate future TACs, the TAC for the starting year 2018 (TAC_{2018}) is set to be 342.7 (the actual catch taken in 2018) or 575 (the TAC set for 2018) tonnes. The decision to consider the TAC for 2018 was to examine the performance of the CMP when calculated from a starting value equal to the TAC that is presently set. For future years (i.e. 2019, 2020, 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 CMP.

4. The numbers-at-age for year y' are projected forward under a true catch given by the sum of $TAC_{y'}$ (the legal component) and any assumed illegal component (taken to be zero), together with the assumed level of cetacean depredation which is taken to remain at its current level of the OM; 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.

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 term 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:

<u>Catches achieved</u>

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.

<u>Risk to resource</u>

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 MSY: $B_{2038}^{sp(s)} / B_{MSY}^{sp(s)}$

<u>Industrial stability</u>

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

<u>Economic viability</u>

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

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 selections $\lambda = 1$ and *t* = 0.694 (the average of the observed CPUE indices for 2014 to 2016) for the CMP of equation (1).

Testing this CMP for the Reference Set scenarios yields the results shown in Tables 2a and b for the two values of catches assumed for 2018 (the actual catch or the TAC set). Results for the performance statistics are shown calculated for each individual OM as well as by combining the outputs from all OMs together. Figures 1 to 3 show the performance of this CMP under the Reference Set OMs.

Tables 3a and b report various catch statistics while Tables 4a and b give results based on CPUE statistics. Median projections for some performance statistics are shown in Figures 4a and b for the CMP when the actual catch in 2018 is used and in Figures 5a and b when the TAC set is used. These Figures show the results for each individual OM, while Figure 6 shows results when combining all the output from the 15 OMs together and calculating the performance statistics on the 15x100 simulations. Figure 6 also shows one randomly selected worm plot from each of the OMs.

Under most OMs, the performance of the simple empirical CPM seems to be satisfactory in that catches increase while catch rates keep increasing and the resource status remains above B_{MSY}. If the TAC calculation for projections begin from the 2018 TAC set rather than the actual catch, the CMP results in declines in the status of the resource under some of the OMs but, in median terms, the resource remains above MSY. The exception is the performance under OM17 in which a better fit to the observed lower trotline CPUE indices in the last two years is achieved. In this case the CMP does not react in dropping TACs in order to maintain either the CPUE or the resource status at minimum at the current levels.

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 satisfactorily react 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 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.

REFERENCES

Brandão, A. and Butterworth, D.S. 2019. Conditioning of the Reference Set of Operating Models for the toothfish resource in the Prince Edward Islands vicinity. Department of Agriculture, Forestry and Fisheries Document: FISHERIES/2019/MAR/SWG-DEM/04.

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	ℓ_∞ = 174.5 κ = 0.0425 t_o = -1.4575	ℓ_∞ = 152.0 κ = 0.067 t_o = -1.49
OM13†	c = 4.09×10^{-9} d = 3.196	c = 2.54×10^{-8} d = 2.8
OM14†	c = 4.17×10^{-9} d = 3.206	c = 2.54×10^{-8} d = 2.8
OM15	Tag reporting rate = 0.8	1
OM17	Annual tag loss/mortality rate = 0.5	0

† The weight at length conversion is given in terms of cm to tonnes.

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 the CMP **assuming the actual catch in 2018** as the intended value when applying equation (1) to compute future TACs. The last two rows report these performance statistics as medians across all simulations for all 15 RS OMs giving equal weight to each OM, when assuming the actual catch in 2018 and when assuming the TAC for 2018 as the starting values for applying equation (1) to compute future TACs.

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	0.50 (0.29; 0.71)	1.18 (0.69; 1.67)	2.03 (1.18; 2.88)	1.49 (1.47; 1.50)	618 (296; 1071)	269 (234; 368)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM02	0.40 (0.33; 0.47)	0.76 (0.64; 0.91)	1.57 (1.33; 1.87)	1.68 (1.66; 1.68)	159 (104; 309)	258 (232; 372)	0.11 (0.09; 0.14)	0.11 (0.06; 0.15)
OM03	0.81 (0.53; 1.16)	2.16 (1.41; 3.11)	3.40 (2.22; 4.88)	1.44 (1.42; 1.45)	944 (577; 1449)	281 (240; 371)	0.14 (0.12; 0.15)	0.11 (0.06; 0.14)
OM04	0.46 (0.29; 0.64)	1.14 (0.71; 1.59)	1.49 (0.93; 2.09)	1.14 (1.12; 1.14)	542 (248; 969)	268 (233; 366)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM05	0.53 (0.29; 0.75)	1.22 (0.67; 1.72)	3.19 (1.76; 4.49)	2.25 (2.22; 2.26)	668 (310; 1135)	270 (234; 368)	0.13 (0.10; 0.14)	0.11 (0.06; 0.14)
OM06	0.50 (0.29; 0.71)	1.19 (0.69; 1.68)	2.05 (1.19; 2.89)	1.50 (1.48; 1.50)	625 (299; 1086)	270 (234; 369)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM07	0.53 (0.33; 0.73)	1.27 (0.79; 1.74)	2.17 (1.36; 2.97)	1.47 (1.46; 1.48)	512 (235; 904)	255 (232; 346)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM08	0.46 (0.25; 0.67)	1.06 (0.58; 1.57)	1.86 (1.00; 2.75)	1.51 (1.49; 1.52)	734 (366; 1256)	286 (237; 397)	0.12 (0.10; 0.14)	0.11 (0.06; 0.14)
OM09	0.43 (0.23; 0.64)	1.03 (0.56; 1.53)	1.78 (0.96; 2.63)	1.37 (1.35; 1.38)	705 (364; 1116)	266 (234; 352)	0.13 (0.11; 0.14)	0.11 (0.06; 0.15)
OM10	0.37 (0.20; 0.58)	0.81 (0.44; 1.27)	1.53 (0.83; 2.40)	1.37 (1.36; 1.38)	736 (400; 1130)	256 (233; 333)	0.13 (0.12; 0.14)	0.11 (0.06; 0.15)
OM12	0.62 (0.48; 0.76)	0.98 (0.76; 1.19)	2.51 (1.95; 3.05)	1.90 (1.90; 1.91)	324 (199; 483)	232 (232; 244)	0.14 (0.11; 0.14)	0.15 (0.12; 0.15)
OM13	0.51 (0.31; 0.71)	1.21 (0.73; 1.67)	2.03 (1.22; 2.80)	1.45 (1.43; 1.45)	559 (269; 976)	263 (232; 355)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM14	0.51 (0.31; 0.71)	1.21 (0.73; 1.67)	2.03 (1.23; 2.80)	1.45 (1.43; 1.45)	557 (268; 973)	262 (232; 354)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM15	0.42 (0.22; 0.63)	1.10 (0.56; 1.64)	1.73 (0.89; 2.58)	1.33 (1.31; 1.34)	671 (328; 1072)	271 (234; 367)	0.13 (0.10; 0.14)	0.11 (0.05; 0.14)
OM17	0.04 (0.00; 0.22)	0.18 (0.02; 0.93)	0.17 (0.02; 0.89)	0.67 (0.66; 0.69)	717 (454; 955)	265 (236; 339)	0.13 (0.11; 0.14)	0.11 (0.06; 0.14)
Actual catch	0.48 (0.11; 0.78)	1.10 (0.40; 1.91)	1.75 (0.36; 3.53)	1.41 (0.58; 2.24)	613 (182; 1124)	264 (232; 367)	0.13 (0.10; 0.14)	0.11 (0.06; 0.15)
TAC	0.40 (0.09; 0.65)	0.91 (0.24; 1.55)	1.62 (0.34; 2.93)	1.39 (0.58; 2.14)	757 (258; 1522)	435 (389; 606)	0.12 (0.09; 0.14)	0.11 (0.06; 0.15)

Table 2b. Results as in Table 2a for the individual OMs, but **assuming the TAC for 2018** as the intended value when applying equation (1) to compute future TACs.

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	0.42 (0.22; 0.61)	0.99 (0.52; 1.44)	1.72 (0.89; 2.48)	1.43 (1.39; 1.44)	801 (385; 1358)	445 (390; 608)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM02	0.37 (0.30; 0.45)	0.72 (0.58; 0.86)	1.48 (1.20; 1.78)	1.62 (1.59; 1.63)	239 (166; 425)	430 (389; 621)	0.11 (0.09; 0.14)	0.11 (0.06; 0.15)
OM03	0.51 (0.18; 0.95)	1.37 (0.47; 2.54)	2.15 (0.74; 3.99)	1.36 (1.33; 1.38)	1483 (848; 2302)	463 (397; 619)	0.14 (0.12; 0.15)	0.11 (0.06; 0.14)
OM04	0.41 (0.24; 0.56)	1.03 (0.60; 1.40)	1.35 (0.79; 1.83)	1.08 (1.06; 1.10)	665 (324; 1200)	443 (389; 607)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM05	0.43 (0.20; 0.65)	0.98 (0.47; 1.48)	2.56 (1.22; 3.88)	2.15 (2.11; 2.18)	862 (432; 1472)	446 (390; 608)	0.13 (0.10; 0.14)	0.11 (0.06; 0.14)
OM06	0.42 (0.22; 0.61)	1.00 (0.52; 1.44)	1.72 (0.89; 2.49)	1.43 (1.40; 1.45)	811 (390; 1373)	446 (390; 610)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM07	0.48 (0.29; 0.65)	1.13 (0.68; 1.56)	1.94 (1.17; 2.66)	1.41 (1.38; 1.42)	649 (308; 1150)	422 (389; 578)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM08	0.36 (0.17; 0.56)	0.85 (0.39; 1.30)	1.48 (0.68; 2.27)	1.44 (1.41; 1.46)	956 (482; 1564)	471 (396; 660)	0.12 (0.10; 0.14)	0.11 (0.06; 0.14)
OM09	0.32 (0.14; 0.54)	0.77 (0.33; 1.28)	1.33 (0.57; 2.21)	1.30 (1.28; 1.32)	930 (485; 1497)	438 (390; 578)	0.13 (0.11; 0.14)	0.11 (0.06; 0.15)
OM10	0.26 (0.09; 0.49)	0.56 (0.20; 1.07)	1.06 (0.38; 2.00)	1.31 (1.29; 1.32)	993 (541; 1514)	420 (389; 555)	0.13 (0.12; 0.14)	0.11 (0.06; 0.15)
OM12	0.56 (0.42; 0.70)	0.89 (0.67; 1.11)	2.26 (1.71; 2.83)	1.83 (1.83; 1.84)	458 (285; 748)	389 (389; 404)	0.14 (0.11; 0.14)	0.15 (0.12; 0.15)
OM13	0.45 (0.25; 0.62)	1.07 (0.59; 1.46)	1.80 (0.99; 2.46)	1.38 (1.36; 1.40)	708 (350; 1218)	435 (389; 592)	0.12 (0.10; 0.14)	0.11 (0.05; 0.15)
OM14	0.46 (0.25; 0.62)	1.07 (0.59; 1.46)	1.80 (0.99; 2.46)	1.38 (1.35; 1.40)	706 (349; 1215)	434 (389; 592)	0.12 (0.10; 0.14)	0.11 (0.06; 0.15)
OM15	0.35 (0.15; 0.53)	0.90 (0.38; 1.38)	1.41 (0.60; 2.17)	1.26 (1.23; 1.28)	837 (425; 1363)	446 (390; 604)	0.13 (0.10; 0.14)	0.11 (0.05; 0.14)
OM17	0.06 (0.00; 0.23)	0.25 (0.01; 0.98)	0.24 (0.01; 0.93)	0.57 (0.54; 0.60)	663 (406; 870)	420 (389; 555)	0.13 (0.11; 0.14)	0.11 (0.06; 0.14)

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 the CMP **assuming the actual catch in 2018** as the intended value when applying equation (1) to compute future TACs. The last two rows report these performance statistics as medians across all simulations for all 15 RS OMs giving equal weight to each OM, when assuming the actual catch in 2018 and when assuming the TAC for 2018 as the intended values when applying equation (1) to compute future TACs.

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	649 (311; 1124)	450 (227; 768)	331 (206; 515)	283 (246; 386)	1452 (555; 2754)	864 (352; 1638)	465 (186; 838)	276 (192; 455)
OM02	167 (109; 325)	198 (132; 349)	231 (169; 384)	271 (244; 390)	57 (19; 242)	94 (39; 268)	163 (81; 406)	245 (188; 458)
OM03	991 (606; 1522)	622 (397; 943)	412 (283; 605)	295 (252; 389)	2715 (1608; 4225)	1350 (799; 2101)	671 (397; 1044)	307 (207; 465)
OM04	569 (260; 1017)	407 (208; 723)	317 (199; 493)	282 (245; 384)	1141 (337; 2332)	701 (260; 1464)	413 (171; 797)	271 (191; 454)
OM05	701 (326; 1192)	460 (241; 794)	337 (210; 529)	284 (246; 387)	1686 (700; 2993)	907 (381; 1721)	482 (195; 865)	279 (192; 456)
OM06	656 (314; 1140)	451 (229; 777)	332 (207; 518)	283 (246; 388)	1476 (569; 2771)	874 (353; 1654)	468 (187; 849)	277 (192; 456)
OM07	538 (246; 949)	372 (193; 650)	292 (187; 436)	268 (244; 363)	1109 (382; 2348)	674 (254; 1320)	368 (152; 697)	244 (188; 429)
OM08	771 (384; 1319)	521 (270; 901)	377 (237; 592)	300 (249; 417)	1850 (796; 3024)	1042 (422; 1959)	566 (234; 998)	313 (201; 481)
OM09	741 (382; 1171)	481 (267; 810)	338 (217; 558)	279 (246; 369)	1856 (904; 3020)	999 (449; 1662)	507 (236; 961)	267 (192; 426)
OM10	773 (420; 1186)	498 (284; 825)	337 (225; 537)	269 (245; 350)	2007 (1073; 3032)	1057 (533; 1773)	530 (265; 913)	255 (189; 411)
OM12	340 (209; 507)	239 (171; 333)	201 (172; 254)	244 (244; 256)	824 (424; 1337)	410 (211; 665)	204 (121; 331)	188 (188; 218)
OM13	586 (282; 1024)	404 (212; 696)	310 (197; 461)	276 (244; 372)	1298 (489; 2490)	765 (314; 1451)	406 (171; 752)	258 (188; 441)
OM14	584 (281; 1022)	403 (212; 694)	309 (197; 460)	276 (244; 372)	1292 (486; 2483)	762 (313; 1445)	404 (171; 749)	257 (188; 440)
OM15	704 (345; 1125)	476 (251; 791)	339 (213; 550)	284 (246; 386)	1611 (749; 2778)	954 (404; 1662)	497 (208; 908)	279 (193; 453)
OM17	753 (476; 1002)	557 (326; 822)	376 (244; 565)	278 (248; 356)	1238 (492; 2091)	1146 (595; 1776)	608 (315; 970)	275 (201; 420)
Actual catch	643 (191; 1180)	437 (189; 821)	325 (189; 559)	277 (244; 385)	1459 (92; 2974)	845 (132; 1725)	451 (135; 951)	265 (188; 450)
TAC catch	795 (271; 1598)	606 (281; 1164)	493 (303; 880)	457 (409; 637)	1474 (104; 3971)	985 (155; 2352)	605 (187; 1409)	419 (315; 742)

Table 3b. Results as in Table 3a for the individual OMs, but **assuming the TAC for 2018** as the intended value when applying equation (1) to compute future TACs.

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	841 (404; 1426)	626 (334; 1127)	508 (324; 797)	467 (409; 638)	1527 (500; 3341)	1050 (397; 1977)	628 (257; 1245)	443 (316; 758)
OM02	251 (174; 447)	299 (214; 505)	367 (279; 600)	451 (409; 652)	64 (29; 241)	117 (60; 293)	228 (125; 554)	395 (315; 759)
OM03	1557 (890; 2417)	978 (587; 1537)	651 (436; 1006)	486 (417; 650)	4183 (2349; 6636)	2096 (1168; 3415)	1053 (581; 1698)	496 (331; 774)
OM04	698 (340; 1260)	556 (303; 1010)	493 (314; 767)	465 (409; 637)	1171 (378; 2693)	813 (292; 1739)	553 (224; 1167)	434 (315; 756)
OM05	905 (453; 1545)	678 (354; 1180)	521 (331; 819)	469 (410; 638)	1838 (650; 3628)	1162 (475; 2294)	680 (283; 1296)	448 (317; 760)
OM06	851 (410; 1442)	633 (338; 1140)	512 (326; 803)	468 (409; 640)	1565 (511; 3409)	1075 (402; 2020)	641 (262; 1264)	446 (316; 761)
OM07	681 (323; 1208)	533 (282; 960)	448 (300; 690)	444 (409; 607)	1294 (434; 2940)	778 (290; 1632)	491 (203; 1035)	391 (315; 712)
OM08	1004 (506; 1642)	746 (396; 1289)	580 (360; 932)	495 (415; 693)	1871 (617; 3870)	1302 (538; 2444)	795 (331; 1524)	505 (332; 804)
OM09	977 (509; 1572)	699 (377; 1181)	529 (334; 862)	459 (410; 607)	1963 (723; 3819)	1281 (578; 2353)	709 (318; 1411)	425 (318; 709)
OM10	1042 (568; 1590)	728 (400; 1154)	517 (342; 885)	441 (409; 583)	1963 (909; 3473)	1399 (659; 2490)	750 (341; 1501)	401 (315; 669)
OM12	481 (299; 785)	351 (261; 524)	316 (283; 389)	409 (409; 424)	1126 (458; 1959)	564 (255; 1017)	287 (164; 506)	315 (315; 349)
OM13	744 (368; 1279)	569 (306; 1033)	476 (312; 732)	457 (409; 622)	1410 (465; 3036)	888 (351; 1766)	547 (230; 1123)	414 (315; 733)
OM14	742 (367; 1276)	567 (306; 1030)	474 (311; 730)	456 (409; 621)	1402 (464; 3026)	883 (350; 1759)	544 (229; 1119)	413 (315; 732)
OM15	879 (447; 1431)	663 (355; 1109)	521 (327; 833)	468 (410; 635)	1612 (513; 3283)	1109 (478; 2088)	653 (277; 1313)	446 (317; 753)
OM17	697 (426; 914)	620 (356; 961)	496 (329; 857)	441 (409; 583)	760 (284; 1688)	813 (406; 1583)	671 (284; 1333)	395 (315; 691)

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 the CMP **assuming the actual catch in 2018** as the intended value when applying equation (1) to compute future TACs. The last two rows reports these performance statistics as medians across all simulations for all 15 RS OMs giving equal weight to each OM, when assuming the actual catch in 2018 and when assuming the TAC for 2018 as the intended values when applying equation (1) to compute future TACs.

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	1.67 (0.98; 2.81)	1.79 (1.20; 2.90)	1.73 (1.14; 2.43)	1.48 (0.95; 2.08)	1.39 (0.82; 2.35)	0.14
OM02	1.11 (0.69; 1.73)	1.12 (0.71; 1.82)	1.12 (0.73; 1.67)	1.24 (0.75; 1.73)	0.93 (0.57; 1.45)	0.67
OM03	2.90 (1.79; 4.58)	2.93 (2.05; 4.56)	2.51 (1.70; 3.66)	1.78 (1.19; 2.41)	2.43 (1.50; 3.83)	0.00
OM04	1.58 (0.96; 2.64)	1.69 (1.13; 2.76)	1.64 (1.09; 2.31)	1.46 (0.93; 2.04)	1.32 (0.81; 2.21)	0.15
OM05	1.73 (0.98; 2.92)	1.87 (1.26; 3.01)	1.79 (1.17; 2.52)	1.50 (0.96; 2.10)	1.44 (0.82; 2.45)	0.13
OM06	1.67 (0.98; 2.82)	1.80 (1.20; 2.91)	1.73 (1.14; 2.44)	1.49 (0.95; 2.08)	1.40 (0.82; 2.36)	0.14
OM07	1.73 (1.02; 2.82)	1.79 (1.18; 2.88)	1.67 (1.12; 2.37)	1.42 (0.91; 1.99)	1.45 (0.85; 2.35)	0.12
OM08	1.60 (0.92; 2.76)	1.78 (1.22; 2.94)	1.79 (1.17; 2.50)	1.55 (0.99; 2.17)	1.34 (0.77; 2.30)	0.17
OM09	1.72 (0.97; 2.80)	1.96 (1.31; 3.00)	1.89 (1.26; 2.68)	1.55 (1.05; 2.10)	1.44 (0.81; 2.34)	0.14
OM10	1.72 (0.93; 2.81)	2.06 (1.35; 3.08)	1.99 (1.40; 2.76)	1.60 (1.14; 2.14)	1.44 (0.78; 2.35)	0.18
OM12	2.11 (1.54; 2.94)	2.05 (1.52; 2.94)	1.79 (1.33; 2.37)	1.24 (0.95; 1.57)	1.76 (1.29; 2.45)	0.00
OM13	1.70 (1.01; 2.80)	1.80 (1.20; 2.87)	1.70 (1.15; 2.39)	1.45 (0.93; 2.01)	1.42 (0.84; 2.34)	0.12
OM14	1.70 (1.01; 2.81)	1.80 (1.20; 2.87)	1.70 (1.15; 2.39)	1.45 (0.93; 2.01)	1.42 (0.84; 2.35)	0.12
OM15	1.62 (0.91; 2.80)	1.82 (1.22; 2.95)	1.80 (1.19; 2.53)	1.52 (0.99; 2.09)	1.36 (0.76; 2.34)	0.16
OM17	0.72 (0.18; 2.11)	1.56 (0.73; 2.73)	1.97 (1.45; 2.67)	1.68 (1.21; 2.21)	0.60 (0.15; 1.77)	0.77
Actual catch	1.68 (0.78; 2.99)	1.83 (1.01; 3.18)	1.77 (1.09; 2.71)	1.49 (0.95; 2.11)	1.40 (0.65; 2.50)	0.20
TAC	1.46 (0.58; 2.68)	1.63 (0.88; 2.94)	1.64 (0.99; 2.53)	1.41 (0.90; 2.02)	1.22 (0.49; 2.24)	0.31

Table 4b. Results as in Table 4a for the individual OMs, but **assuming the TAC for 2018** as the intended value when applying equation (1) to compute future TACs.

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	1.47 (0.89; 2.50)	1.60 (0.99; 2.68)	1.62 (1.08; 2.32)	1.42 (0.91; 2.00)	1.23 (0.74; 2.09)	0.26
OM02	1.08 (0.67; 1.70)	1.06 (0.68; 1.74)	1.06 (0.69; 1.58)	1.19 (0.72; 1.66)	0.90 (0.56; 1.42)	0.69
OM03	2.19 (0.92; 3.77)	2.52 (1.57; 4.13)	2.33 (1.59; 3.42)	1.70 (1.14; 2.33)	1.83 (0.77; 3.15)	0.11
OM04	1.46 (0.89; 2.37)	1.52 (0.93; 2.57)	1.53 (1.03; 2.18)	1.40 (0.89; 1.96)	1.22 (0.75; 1.98)	0.29
OM05	1.48 (0.88; 2.62)	1.67 (1.03; 2.82)	1.68 (1.12; 2.42)	1.44 (0.93; 2.02)	1.24 (0.73; 2.19)	0.25
OM06	1.47 (0.89; 2.51)	1.60 (0.99; 2.69)	1.62 (1.08; 2.32)	1.43 (0.91; 2.00)	1.23 (0.74; 2.10)	0.23
OM07	1.57 (0.96; 2.57)	1.63 (0.99; 2.72)	1.59 (1.04; 2.25)	1.36 (0.87; 1.91)	1.32 (0.80; 2.15)	0.19
OM08	1.41 (0.80; 2.41)	1.55 (0.96; 2.69)	1.64 (1.08; 2.39)	1.49 (0.95; 2.09)	1.18 (0.67; 2.01)	0.33
OM09	1.41 (0.73; 2.49)	1.64 (1.07; 2.78)	1.73 (1.15; 2.54)	1.48 (1.00; 2.02)	1.18 (0.61; 2.08)	0.33
OM10	1.32 (0.43; 2.49)	1.77 (1.00; 2.86)	1.84 (1.30; 2.58)	1.51 (1.07; 2.03)	1.10 (0.36; 2.08)	0.42
OM12	1.96 (1.38; 2.73)	1.96 (1.43; 2.81)	1.71 (1.26; 2.26)	1.19 (0.91; 1.50)	1.64 (1.16; 2.28)	0.02
OM13	1.53 (0.93; 2.51)	1.62 (1.00; 2.69)	1.60 (1.07; 2.25)	1.39 (0.89; 1.93)	1.28 (0.78; 2.10)	0.22
OM14	1.53 (0.93; 2.51)	1.62 (1.00; 2.69)	1.60 (1.07; 2.25)	1.39 (0.89; 1.93)	1.28 (0.78; 2.10)	0.22
OM15	1.37 (0.79; 2.47)	1.59 (1.02; 2.71)	1.66 (1.08; 2.39)	1.45 (0.94; 1.99)	1.15 (0.66; 2.06)	0.34
OM17	0.88 (0.19; 1.98)	1.26 (0.25; 2.55)	1.58 (1.07; 2.39)	1.45 (1.03; 1.91)	0.74 (0.16; 1.65)	0.69

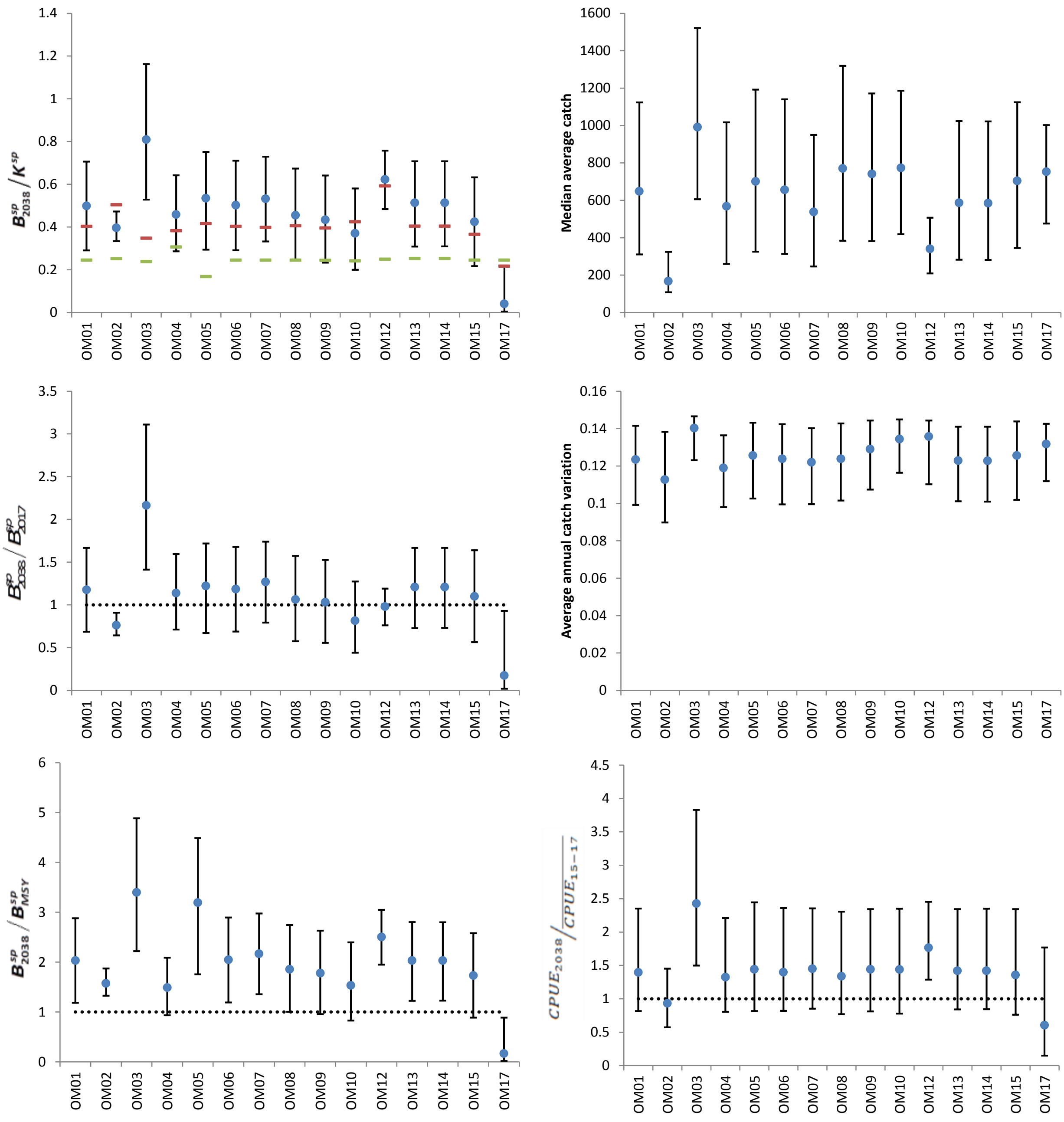

Figure 1. Zeh plots for some of the performance statistics reported in the Tables for each OM when **assuming the actual catch in 2018** as the intended value when applying equation (1) to compute future TACs. These are the spawning biomass depletion at the start of 2038 relative to K, to the spawning 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, while the green dashes represents the MSYL (relative to *K*).

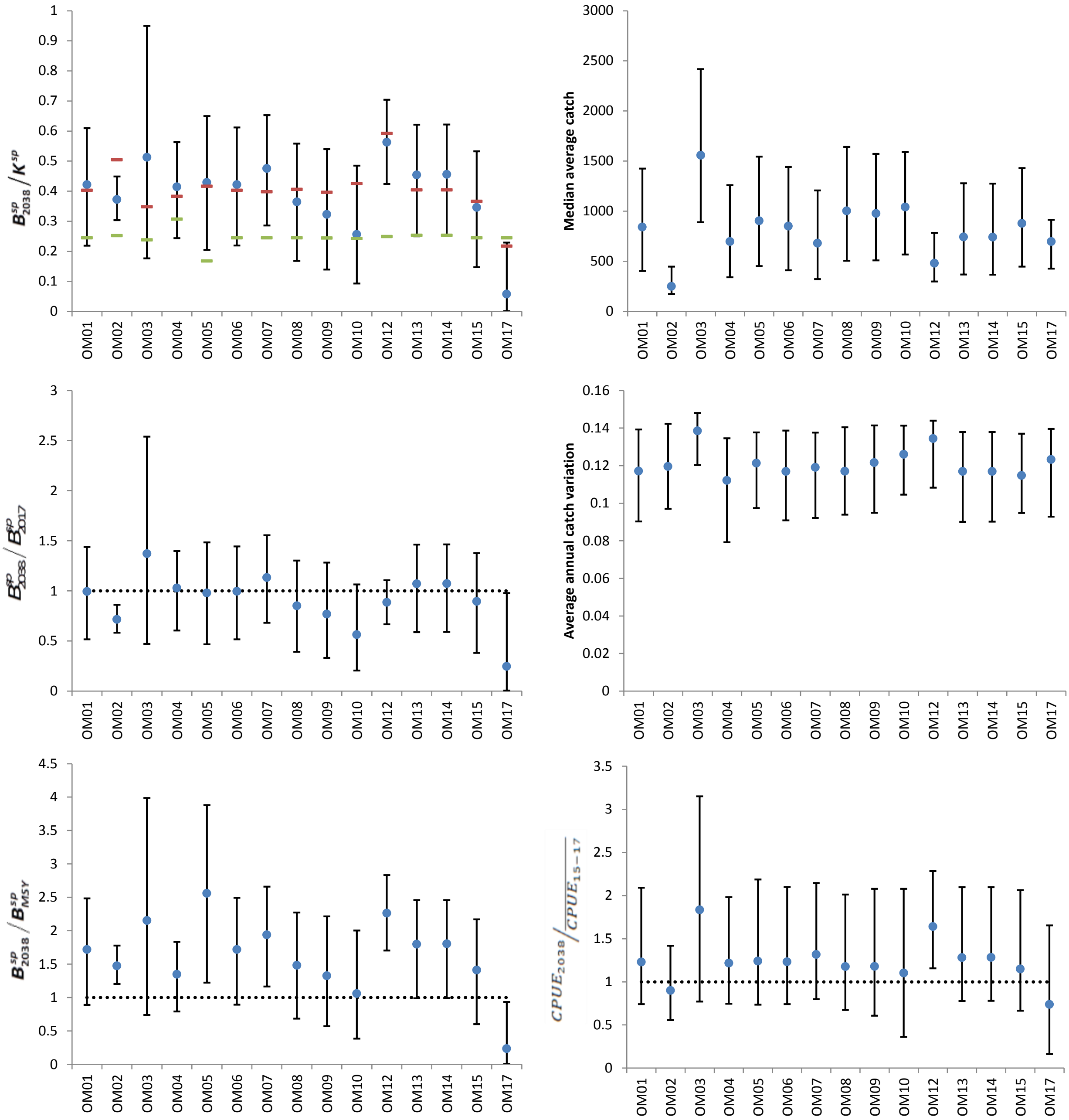

Figure 2. Zeh plots as for Figure 1, but **assuming the TAC for 2018** as the intended value when applying equation (1) to compute future TACs.

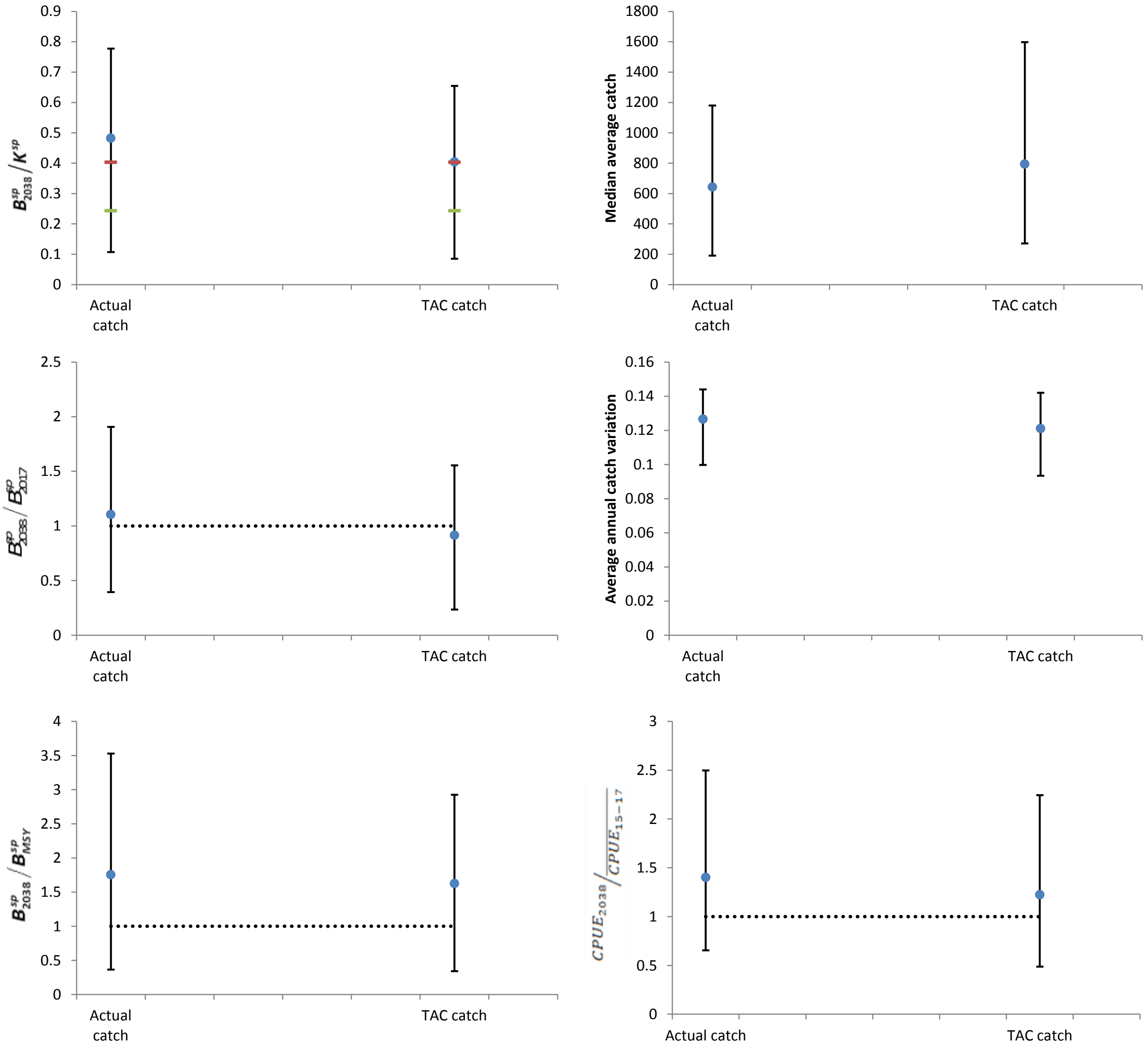

Figure 3. Zeh plots for some of the performance statistics reported in the Tables across all simulations for all 15 RS OMs giving equal weight to each OM (i.e. medians over 15x100 simulations) when assuming the actual catch in 2018 and when assuming the TAC for 2018 as the intended values when applying equation (1) to compute future TACs.

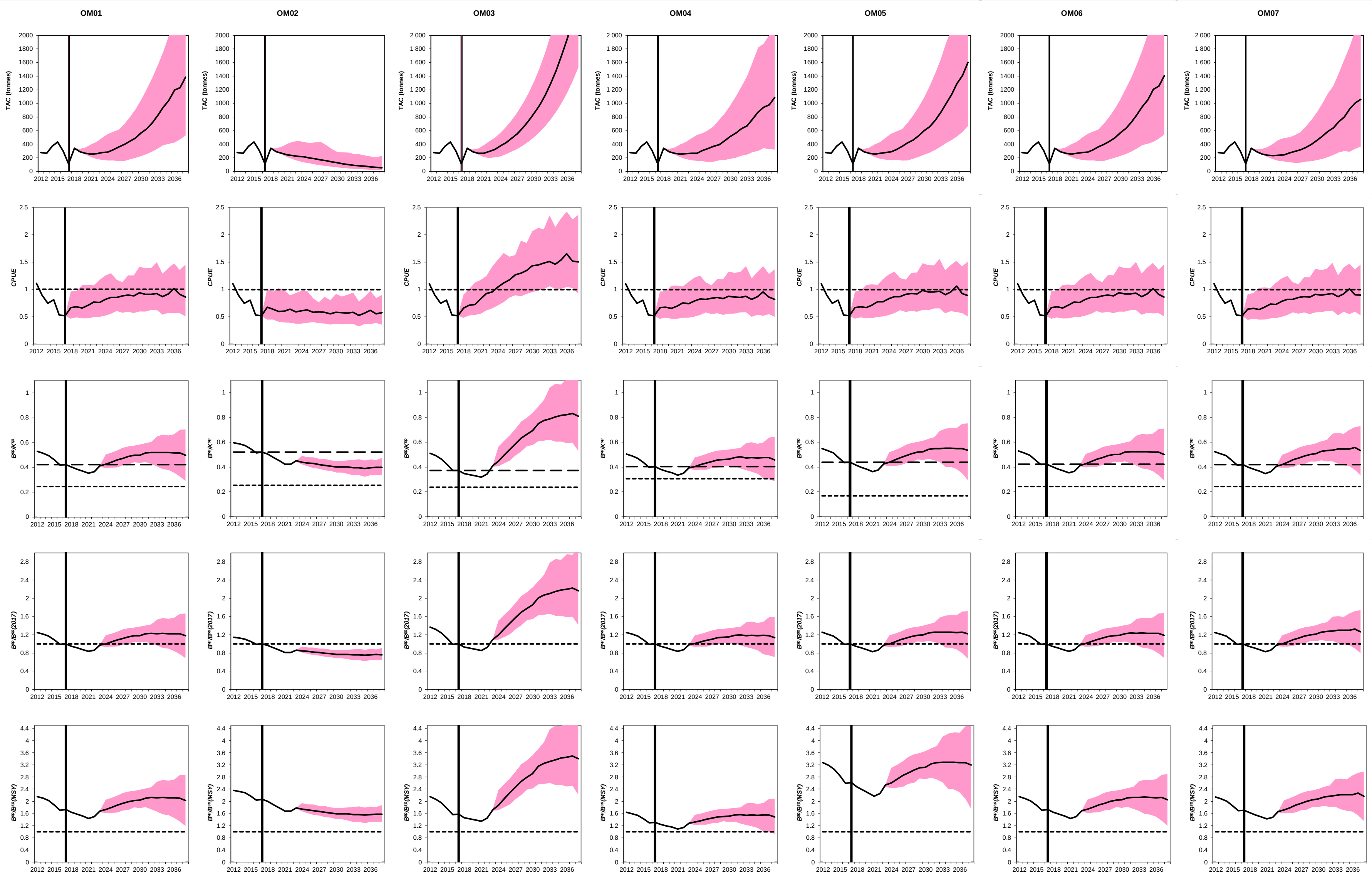

Figure 4a. Median trajectories of TAC (in tonnes), CPUE trends, spawning biomass depletion, spawning biomass relative to the 2017 value and spawning biomass relative to B_{MSY} under the CMP for **OM01 to OM07 assuming the actual catch in 2018** as the intended value when applying equation (1) to compute future TACs**.** 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 current (2018) spawning biomass depletion, while the small dash line is the MSYL (relative to *K*).

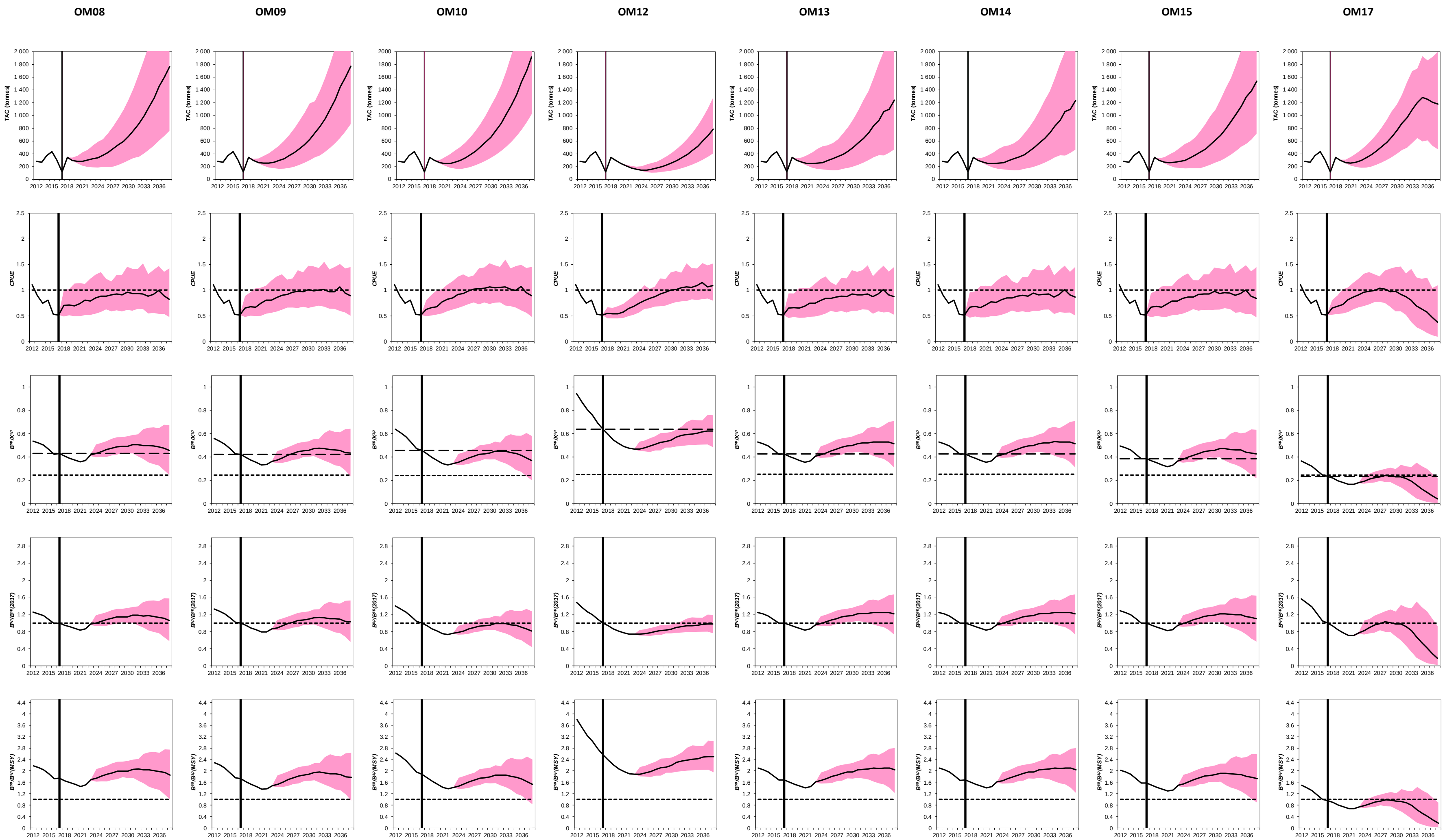

Figure 4b. Projection results as for Figure 4a, but for **OM08 to OM17**.

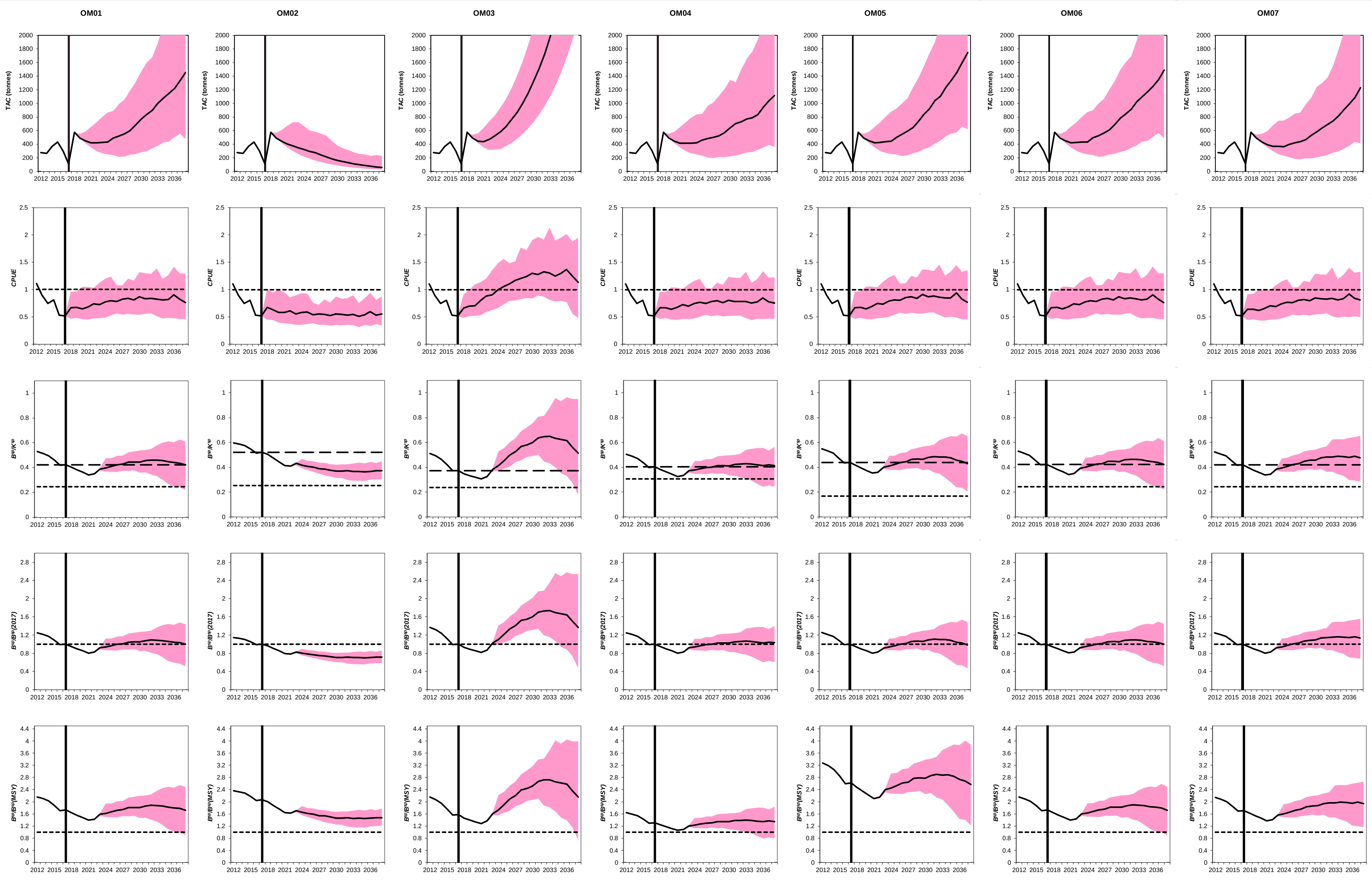

Figure 5a. Median trajectories as for Figure 4a, but **assuming the TAC for 2018** as the intended value when applying equation (1) to compute future TACs.

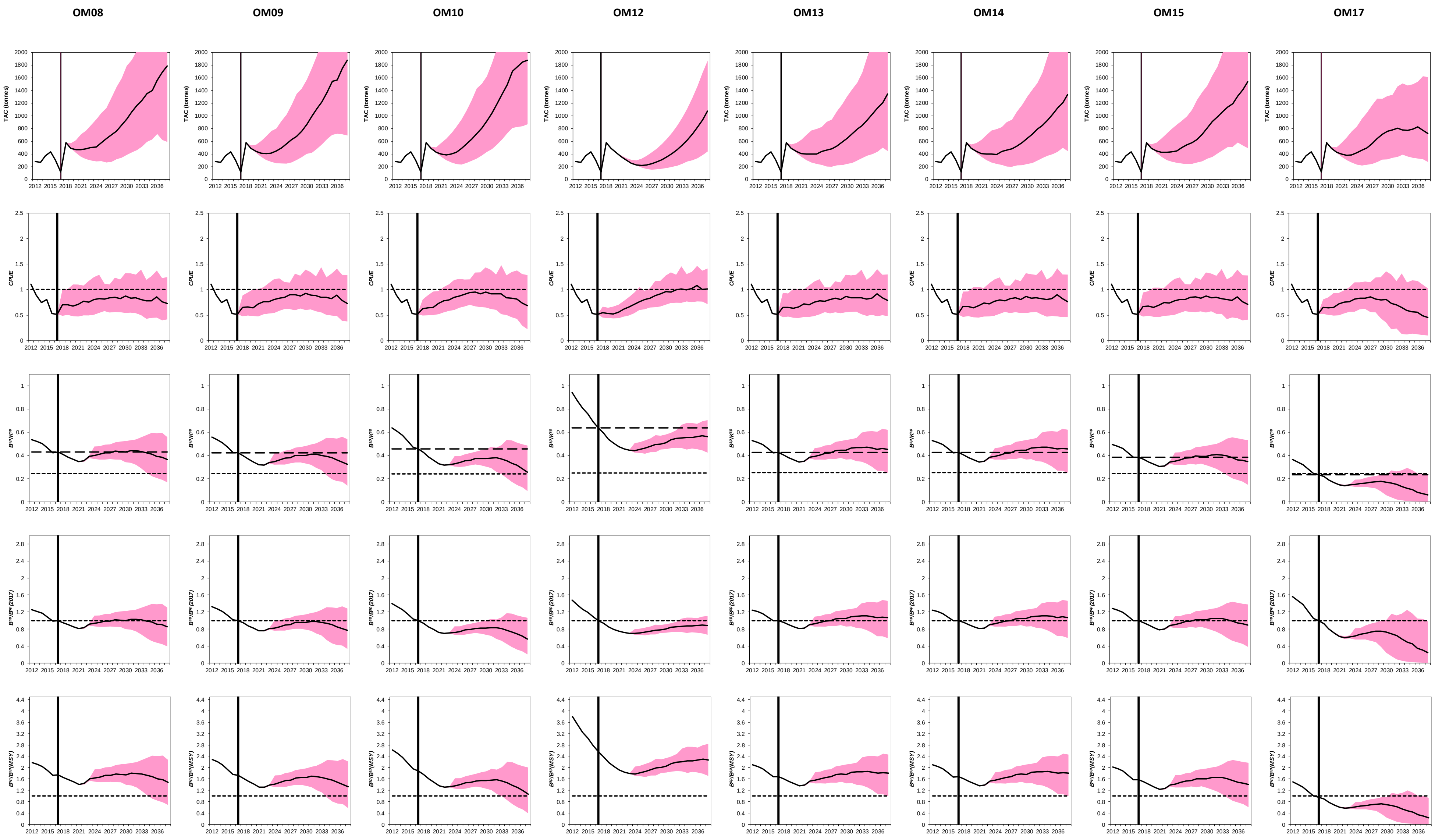

Figure 5b. Projection results as for Figure 5a, but for **OM08 to OM17**.

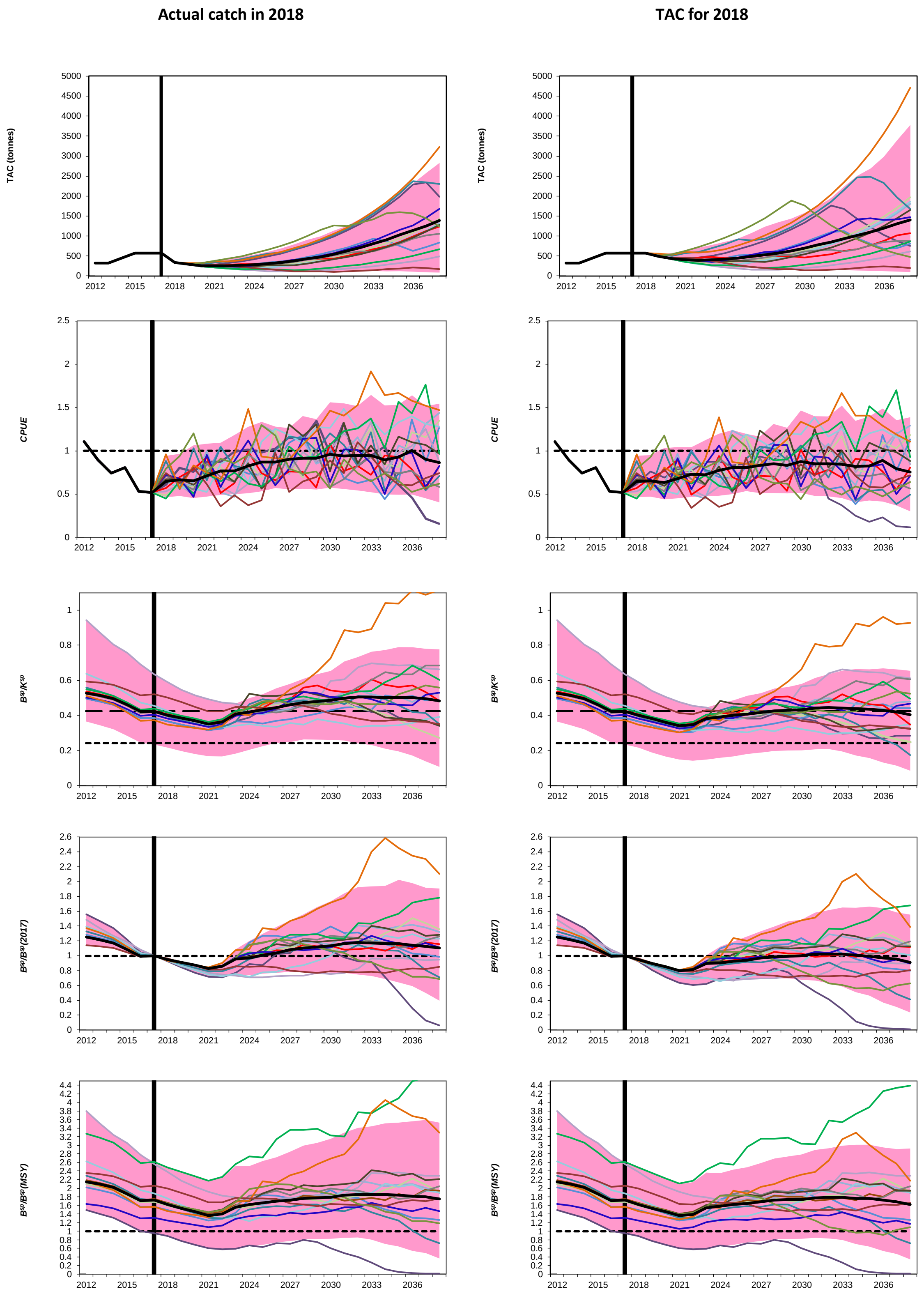

Figure 6. Median trajectories (thick black line) of TAC (in tonnes), CPUE trends, spawning biomass depletion, spawning biomass relative to the 2017 value and spawning biomass relative to B_{MSY} under the CMP across all simulations for all 15 RS OMs giving equal weight to each OM, when assuming the actual catch in 2018 (left) and when assuming the TAC for 2018 (right) as the intended values when applying equation (1) to compute future TACs. 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 plots, the large dash line is the current (2018) spawning biomass depletion, while the small dash line is the MSYL (relative to *K*).

APPENDIX 1

THE AGE STRUCTURED PRODUCTION MODEL (ASPM) ASSESSMENT METHODOLOGY

THE BASIC DYNAMICS

The toothfish population dynamics are given by the equations:

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

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

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

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:

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

where:

$$C^f_{y,a} = N_{y,a} S^f_{y,a} F^f_y \qquad \text{(A1.5)}$$

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.

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

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

where:

w_a is the mass of a fish at age a.

The fleet-specific total catch 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:

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

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 is at equilibrium, it follows that:

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

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,

$\widehat{I}_y^f = \widehat{q}^f \widehat{B}_y^{\exp}(f)$ 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, and

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

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

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:

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

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

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

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:

$$p_{y,a}^f = C_{y,a}^f \Big/ \sum_{a'} C_{y,a'}^f\ . \quad \text{(A1.28)}$$

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:

$$p_{y,\ell}^f = \sum_a p_{y,a}^f A_{a,\ell}^f \quad \text{(A1.29)}$$

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:

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

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.:

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

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:

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

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 follow a Poisson distribution and therefore the following term is added to the negative log-likelihood of equation (A1.27):

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

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:

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

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),

$\zeta_{y,a}$ is the tag-reporting rate for toothfish in year *y* of age *a* (assumed to be 1 in this paper), 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 $F_{y-k,a-k}$.