APPENDIX 4c. PROGRESS ON THE DEVELOPMENT OF CANDIDATE MANAGEMENT PROCEDURES FOR THE CANADIAN POLLOCK IN THE WESTERN COMPONENT (4Xopqrs+5Zc)

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ABSTRACT

Four alternative virtual population analysis (VPA)-based assessments of the Western Component of Canadian pollock are used to provide a Reference Set of Operating Models for an illustrative application of Management Strategy Evaluation (MSE) approach to the associated fishery. Results for future total allowable catches (TACs) and resource trends are shown for a variety of Candidate Management Procedures (feedback catch control rules), which are all based on the direct use on an annual survey-based index of abundance. These results are compared to anticipated outcomes under a constant TAC approach. Suggestions are made regarding aspects that need discussion and further refinement if this approach is to be taken further.

INTRODUCTION

One of the problems for the conventional "best assessment" approach to the provision of management advice (*e.g.,* for a total allowable catch (TAC)) is making a choice between different assessment methods and/or assumptions which can be equally defensible, yet lead to recommendations that differ substantially. For example, Fig. 4 of Rademeyer and Butterworth (2010) show results for four different virtual population analysis (VPA)-based assessments of the Western Component of Canadian pollock which differ appreciably in terms of their estimates of recent abundance.

One advantage of the Management Procedure Approach (or Management Strategy Evaluation – MSE) is that it directly addresses this issue. Feedback control rules that make use of future resource monitoring data (*e.g.*, if abundance indices trend up/down, the TAC is increased/decreased) are simulation tested to ensure that outcomes in terms of catches and risks to the resource remain acceptable across a plausible range of uncertainties in the assessment.

This paper provides an initial illustration of how such a MSE might be applied to the Western Component of Canadian pollock.

METHODOLOGY

MSE is based on the simulated application of the some (feedback) harvest control rule to different Operating Models (OMs) of the resource. These OMs are provided by conventional assessments, and are intended to reflect plausible representations of the underlying dynamics of the actual resource. Often the results of this application are reported integrated over a "Reference Set" (RS) of OMs, which is intended to span a few (typically 2-3) of the major uncertainty "axes" associated with the assessment of the resource. For this illustration for the

Western Component of Canadian pollock, the RS is provided by four VPA-based assessments of the resource (Appendix 4b) which are equally weighted when integrating their results.

MSE requires projections of the resource's dynamics into the future, so as to be able to simulate the impact of alternative series of future catches on the resource. Details of the projection methodology applied are provided in Appendix 4c-A. Of particular importance here is the stock-recruitment relationship assumed for the four OMs that comprise the RS (see Step 4 of that Appendix). Fig. 1 shows results for the somewhat conservative approach, based on the most recent 10 years of spawning biomass and recruitment estimates, that has been used to provide these relationships for projections ("conservative" because generally higher values of recruitment for earlier years are being ignored). The values of the standard deviation of the logged residuals, σ_R, and their auto-correlation, ρ, that characterise the variability about these relationships (see Appendix 4c-A, equations A7 to A10) range from 0.26 to 0.72 and from 0.20 to 0.80, respectively, across the four OMs.

A variety of Candidate Management Procedures (CMPs) have been considered. Appendix 4c-B provides detailed technical specifications. These CMPs are all of the type that is known as "empirical" – they use the resource monitoring data directly as input to simple formulae to provide TAC recommendations, rather than the "model-based" type which first filter these data through a usually relatively simple population dynamics model. The CMPs explored (see Table 1) range from:

- Constant catch (this is included not to imply any serious consideration for adoption, as a feedback-free CMP offers no protection against undue resource depletion, but rather to provide a convenient basis for comparison of performance against other CMPs).
- CMPs based on the slope of the trend in the available index of abundance over recent years (here the survey aggregated weight/tow), such that positive slopes lead to TAC increases and negative slopes to TAC decreases.
- CMPs also based on a target value for the abundance index, such that values above this target will lead to TAC increases, and *vice versa.*
- CMPs that incorporate constraints on the maximum TAC change between years, or place an upper bound ("cap") on the TAC.

Target based CMPs tend to yield more stable TACs over time, though the choice for the target level may raise difficulties. In this case the average value of the index over the 1984 to 1994 period (see Appendix 4c-B) has been used for illustrative purposes.

For ease of comparison of different forms of CMPs, given the ever-present trade-off between larger short term catches and greater medium term resource recovery, it is conventional to "tune" different CMPs to correspond to a common achieved average catch or resource depletion level over a specified time period. This involves adjusting the values of the CMPs control parameters to achieve a pre-specified common goal – in this case the median anticipated catch averaged over the next 10 years has been used for this purpose. The resultant tuning parameter values are reported in Table 1.

The primary objective of the MSE approach is to find the CMP which offers what is considered to be the best trade-off in anticipated performance over the conflicting objectives of:

- maximising future catches (in both the short and the longer term),
- minimising the risk of unintended resource depletion or (where pertinent) inadequate resource recovery, and
- minimising the extent of inter-annual TAC changes in the interests of Industry stability.

The CMP eventually chosen should not only be able to demonstrate this desired performance when tested under the RS of OMs, but also not show appreciable deviations from that performance for other "robustness test" OMs reflecting alternative plausible models of resource dynamics (*i.e.*, one seeks "robust" anticipated performance across the range of plausible OMs).

RESULTS

Projections results for a series of CMPs under the RS are given in Table 2. The CMPs have been tuned (*i.e.*, had their control parameters adjusted) to achieve a median 2011-2020 catch of either 5,000 t, 6,000 t, or 7,000 t. Medians and lower 2.5%iles catch and biomass "trajectories" are compared in Figs. 2 and 3. An example of some actual trajectory realisations is shown in Fig. 4. Note that the "trajectories" shown in Figs. 2 and 3 are not true trajectories but rather lines joining percentiles of the distributions of the various statistics for each future year, so that upper and lower 2.5%iles, for example, would encompass the 95% envelope for future projections.

Shade plots, showing medians and 50%, 75%, and 95% probability intervals (PIs) of a series of Performance Statistics, are shown in Fig. 5 for CMPC5b under the RS.

ROBUSTNESS TESTS

It is important to check that the performance of a CMP is reasonably robust to plausible variations of the OMs that constitute the RS. Three such "robustness tests" have been run for CMPC5b:

Rob1: Recruitment over the first four years of projections is assumed to be at the level of the lowest recruitment over the 2000-2009 period.

Rob2: The stock-recruitment relationship is derived from the last 5 years data rather than the last 10 years (equations A8-A10) (see Fig. 1).

Rob3: Recruitment over the first eight years of projections is assumed to be at the level of the lowest recruitment over the 2000-2009 period.

Results for these three robustness tests for CMPC5b are given in Table 3 and plotted in Fig. 6.

DISCUSSION

Although projections have been taken through to 2031 in this exercise, the focus has been on achieving reasonable performance over the next 10 years. Thus projection results beyond 2021 should not receive much attention – any Management Procedure that might be adopted in the immediate future is likely to have been reviewed and revised before 2021.
Fig. 2 illustrates the enhanced performance that feedback control approaches achieve over a constant catch strategy. Given feedback, resource risk (quantified by the lower 2.5%ile probability envelope for future relative to present abundances) is less (at least in the short to medium term) for the feedback compared to the constant catch approaches.

The trade-off that is typical between greater catches *vs.* additional resource risk is evident from Fig. 3.

While recovery of the resource seems guaranteed under the RS trials, this does not follow for the robustness tests considered (Fig. 6). Although CMPC5b (the CMP for which results are reported there) achieves the desired feedback response of reducing TACs in the face of poorer resource circumstances than anticipated under the RS, this is inadequate to prevent slight downward trends in resource levels for the three robustness tests considered at the lower 2.5%ile level.

Fig. 7 provides a convenient (and commonly used) basis to summarise Performance Statistics and compare them under different operating OMs for the same CMP, or different CMPs under the same OM. This suggests that on the basis of trials to date, there is little to choose amongst the alternative feedback control MP formulations that have been considered in this paper.

ASPECTS FOR POSSIBLE FURTHER INVESTIGATION

There are a number of aspects of the work presented here that warrant discussion in the context of possible future refinement of this MSE approach.

- Appropriate assumptions for projections, including in particular alternative assumptions that might be used in the development of alternative stock-recruitment relationships.
- Variation of features of the CMP not considered thus far, *e.g.*, the period over which the abundance index slope is calculated (currently 9 years – see Appendix 4c-B and Table 1), and the number of years over which abundance index average is taken for comparison with the target value in target-based CMPs (currently 3 years – see Appendix 4c-B).
- Refinement of the medium term objectives which management should seek to achieve for the resource and fishery. This includes consideration of desirable constraints on the maximum extent of the TAC change allowed from year to year, and also perhaps an upper bound on the TAC.
- Extension of the present small set of plausible robustness test OMs of this paper to include other plausible hypotheses for resource dynamics for which CMP robustness should be checked.

With such extensions and refinements, it is likely that greater differences will emerge amongst the anticipated performances of alternative forms of CMP such as those in Table 1. For example, if the extent of resource recovery is deemed inadequate for some robustness tests (see Fig. 7), this can be improved by increasing the value of the λ_{down} control parameter that multiplies the slope of the abundance index in the CMP formula (see Appendix 4c-B, equation B1), but there will be an associated risk of a larger TAC reduction in the short term. Such further results will provide a clearer basis to choose amongst alternative CMPs.

Table 1. Tuning parameter values for each CMP presented (see Appendix 4c-B for definitions of the symbols used).

	Comment	Initial TAC	λ_{up}	λ_{down}	*P*	*a*	*b*	*w*	Interannual change constraints	Cap
C=6000t	Constant catch of 6000t	-	-	-	-	-	-	-	-	-
CMPA10b	Slope-based tuned to 6000t 2011-2020 median catch	5802	1.05	1.05	9	-	-	1.0	+15%; -15%	-
CMPB3b	Slope- and target-based tunned to 6000t 2011-2020 median	4500	1.05	1.05	9	13235	10000	0.5	+15%; -15%	-
CMPC4	Slope- and target-based tunned to 6000t 2011-2020 median	4500	1.10	1.10	9	13320	9000	1.0-0.2*	+15%; -15%	-
CMPC5a	Slope- and target-based tunned to 5000t 2011-2020 median	4500	1.10	1.10	9	12179	10000	1.0-0.2*	+15%; -15%	20000t
CMPC5b	Slope- and target-based tunned to 6000t 2011-2020 median	4500	1.10	1.10	9	13722	9500	1.0-0.2*	+15%; -15%	20000t
CMPC5c	Slope- and target-based tunned to 7000t 2011-2020 median	4500	1.10	1.10	9	15204	9000	1.0-0.2*	+15%; -15%	20000t

*w_y changes linearly from the first value in 2010 to the second value in 2020 and then stays constant thereafter.

Table 2. Projections results (median and 95% PI) for a series of Performance Statistics for different CMPs under the RS. For each CMP tuning parameters were adjusted to meet the performance criterion shown in bold.

		C=6000t		CMPA10b		CMPB3b		CMPC4		CMPC5a		CMPC5b		CMPC5c	
$P_{2021}/P_{\text{target}}$	$B^{4\text{-}8}$	1.57	(0.23; 4.03)	1.50	(0.29; 4.04)	1.50	(0.29; 4.01)	1.50	(0.29; 3.98)	1.54	(0.36; 4.11)	1.50	(0.29; 3.98)	1.44	(0.24; 3.86)
	B^{sp}	4.66	(0.67; 9.64)	4.33	(1.28; 9.12)	4.60	(1.22; 9.17)	4.54	(1.14; 9.24)	4.85	(1.57; 9.62)	4.55	(1.14; 9.24)	4.23	(0.72; 8.86)
	B^{surv}	4.87	(0.29; 25.73)	4.83	(0.87; 26.80)	4.97	(0.76; 24.57)	4.94	(0.75; 26.04)	5.44	(1.10; 27.85)	4.94	(0.78; 26.09)	4.49	(0.50; 24.42)
P_{2016}/P_{2011}	$B^{4\text{-}8}$	3.77	(1.29; 13.39)	3.96	(1.38; 14.26)	4.12	(1.44; 14.30)	4.15	(1.45; 14.56)	4.35	(1.60; 14.88)	4.16	(1.45; 14.56)	3.99	(1.40; 14.20)
	B^{sp}	3.63	(1.57; 9.56)	3.74	(1.80; 10.18)	4.01	(2.10; 10.39)	4.06	(2.14; 10.74)	4.23	(2.30; 10.86)	4.06	(2.15; 10.75)	3.91	(1.97; 10.38)
	B^{surv}	4.08	(0.31; 35.72)	4.62	(0.29; 40.88)	4.92	(0.31; 40.87)	5.02	(0.31; 43.72)	5.27	(0.32; 45.12)	5.02	(0.31; 43.77)	4.72	(0.30; 40.79)
P_{2021}/P_{2011}	$B^{4\text{-}8}$	4.09	(0.82; 19.71)	3.92	(0.85; 19.65)	3.89	(0.84; 19.14)	3.87	(0.83; 19.39)	4.02	(0.89; 19.76)	3.87	(0.82; 19.40)	3.72	(0.70; 19.03)
	B^{sp}	9.53	(1.77; 37.01)	9.44	(2.89; 39.61)	9.55	(3.00; 38.18)	9.53	(2.92; 39.57)	10.45	(3.84; 41.25)	9.52	(2.95; 39.66)	8.76	(1.97; 37.61)
	B^{surv}	10.45	(1.14; 91.89)	10.72	(1.14; 98.94)	10.70	(1.23; 89.92)	10.56	(1.20; 93.73)	11.82	(1.36; 98.65)	10.57	(1.20; 93.81)	9.41	(1.01; 87.60)
P_{2031}/P_{2011}	$B^{4\text{-}8}$	3.81	(0.70; 17.91)	2.80	(0.42; 15.41)	2.70	(0.42; 15.37)	2.69	(0.42; 15.34)	2.95	(0.48; 15.89)	2.79	(0.42; 15.36)	2.71	(0.41; 14.86)
	B^{sp}	10.26	(1.02; 40.02)	5.40	(0.43; 27.59)	5.14	(0.44; 26.03)	5.05	(0.43; 26.09)	6.17	(0.51; 30.03)	5.29	(0.46; 27.58)	4.75	(0.42; 26.09)
	B^{surv}	12.94	(0.90; 57.14)	5.80	(0.44; 36.34)	5.63	(0.44; 33.40)	5.50	(0.44; 34.81)	6.74	(0.49; 40.68)	5.77	(0.44; 36.52)	5.17	(0.38; 34.43)
C_{2011}		6000	(6000; 6000)	4837	(4837; 4837)	4723	(4723; 4723)	4837	(4837; 4837)	4837	(4837; 4837)	4837	(4837; 4837)	4837	(4837; 4837)
C_{2012}		6000	(6000; 6000)	4654	(4112; 5363)	4633	(4492; 5431)	4657	(4112; 5358)	4496	(4112; 5211)	4654	(4112; 5363)	4807	(4225; 5509)
$C_{2011\text{-}2015}$		6000	(6000; 6000)	4707	(3755; 5922)	4762	(4205; 5826)	4711	(3767; 5917)	4255	(3588; 5650)	4707	(3755; 5922)	5138	(4115; 6227)
$C_{2015\text{-}2020}$		6000	(6000; 6000)	7347	(4656; 10966)	7234	(4703; 10634)	7356	(4712; 10937)	5775	(3362; 9607)	7347	(4656; 10966)	8802	(6018; 11917)
$C_{2011\text{-}2020}$		**6000**	(6000; 6000)	**6000**	(4234; 8344)	**6000**	(4509; 8087)	**6000**	(4259; 8328)	**5000**	(3531; 7510)	**6000**	(4234; 8344)	**7000**	(5031; 9007)
$C_{2011\text{-}2030}$		6000	(6000; 6000)	10075	(5837; 13166)	10267	(5432; 14856)	10238	(5717; 14720)	8809	(4567; 12499)	10148	(5712; 13153)	11190	(6845; 13745)
$AAV_{2011\text{-}2015}$		8.6	(8.6; 8.6)	9.5	(5.0; 13.5)	7.5	(4.4; 12.3)	9.5	(5.0; 13.4)	11.0	(5.4; 15.0)	9.5	(5.0; 13.5)	9.5	(5.4; 13.8)
$AAV_{2011\text{-}2030}$		2.1	(2.1; 2.1)	11.5	(11.5; 11.5)	10.8	(10.8; 10.8)	12.1	(12.1; 12.1)	12.2	(12.2; 12.2)	11.2	(11.3; 11.2)	10.5	(10.6; 10.5)

Table 3. Projections results (median and 95% PI) for a series of Performance Statistics for CMPC5b under the RS and three robustness tests: Rob1 (next 4 years have poor recruitment), Rob2 (future recruitment from average 2005-2009), and Rob3 (next 8 years have poor recruitment). Note that the CMPC5b tuning parameters remained unchanged for its application to the three robustness tests shown. Consequently there are changes to ability to meet the target value to which this CMP was tuned for the RS (see values shown in bold).

		RS		Rob1		Rob2		Rob3	
P_{2021}/P_{target}	$B^{4\text{-}8}$	1.50	(0.29; 3.98)	1.34	(0.12; 3.72)	0.77	(0.10; 2.26)	0.53	(0.11; 1.15)
	B^{sp}	4.55	(1.14; 9.24)	1.97	(0.14; 4.70)	1.80	(0.14; 5.35)	0.73	(0.10; 2.22)
	B^{surv}	4.94	(0.78; 26.09)	2.07	(0.11; 11.67)	1.90	(0.10; 12.17)	0.68	(0.05; 4.84)
P_{2016}/P_{2011}	$B^{4\text{-}8}$	4.16	(1.45; 14.56)	1.39	(0.44; 2.68)	2.17	(0.62; 5.44)	1.03	(0.34; 2.05)
	B^{sp}	4.06	(2.15; 10.75)	1.81	(0.67; 2.84)	2.47	(0.91; 4.38)	1.46	(0.48; 2.63)
	B^{surv}	5.02	(0.31; 43.77)	1.54	(0.13; 14.58)	2.42	(0.20; 22.51)	1.39	(0.11; 13.60)
P_{2021}/P_{2011}	$B^{4\text{-}8}$	3.87	(0.82; 19.40)	3.46	(0.61; 16.08)	2.16	(0.44; 8.15)	1.57	(0.35; 4.61)
	B^{sp}	9.52	(2.95; 39.66)	4.17	(0.67; 15.69)	4.37	(0.67; 13.39)	1.84	(0.43; 4.16)
	B^{surv}	10.57	(1.20; 93.81)	4.47	(0.29; 47.53)	4.16	(0.20; 46.86)	1.48	(0.13; 16.13)
P_{2031}/P_{2011}	$B^{4\text{-}8}$	2.79	(0.42; 15.36)	2.97	(0.41; 15.90)	1.88	(0.28; 8.77)	3.23	(0.41; 15.51)
	B^{sp}	5.29	(0.46; 27.58)	6.16	(0.43; 30.92)	2.88	(0.22; 12.28)	6.73	(0.40; 28.39)
	B^{surv}	5.77	(0.44; 36.52)	7.00	(0.44; 42.53)	3.25	(0.19; 15.78)	7.97	(0.38; 40.17)
C_{2011}		4837	(4837; 4837)	4837	(4837; 4837)	4837	(4837; 4837)	4837	(4837; 4837)
C_{2012}		4654	(4112; 5363)	4648	(4112; 5360)	4632	(4112; 5321)	4648	(4112; 5360)
$C_{2011\text{-}2015}$		4707	(3755; 5922)	4553	(3639; 5895)	4602	(3689; 5884)	4553	(3639; 5895)
$C_{2015\text{-}2020}$		7347	(4656; 10966)	5711	(3605; 10075)	6225	(3901; 10486)	5402	(3527; 9931)
$C_{2011\text{-}2020}$		**6000**	(4234; 8344)	**5153**	(3680; 7766)	**5443**	(3878; 8115)	**5017**	(3631; 7721)
$C_{2011\text{-}2030}$		10148	(5712; 13153)	8199	(4396; 12013)	7443	(4286; 12213)	6569	(4131; 10133)
$AAV_{2011\text{-}2015}$		9.5	(5.0; 13.5)	9.5	(5.5; 14.3)	9.5	(5.3; 14.0)	9.5	(5.5; 14.3)
$AAV_{2011\text{-}2030}$		11.2	(11.3; 11.2)	10.6	(10.6; 10.6)	10.6	(10.6; 10.6)	10.0	(10.0; 10.0)

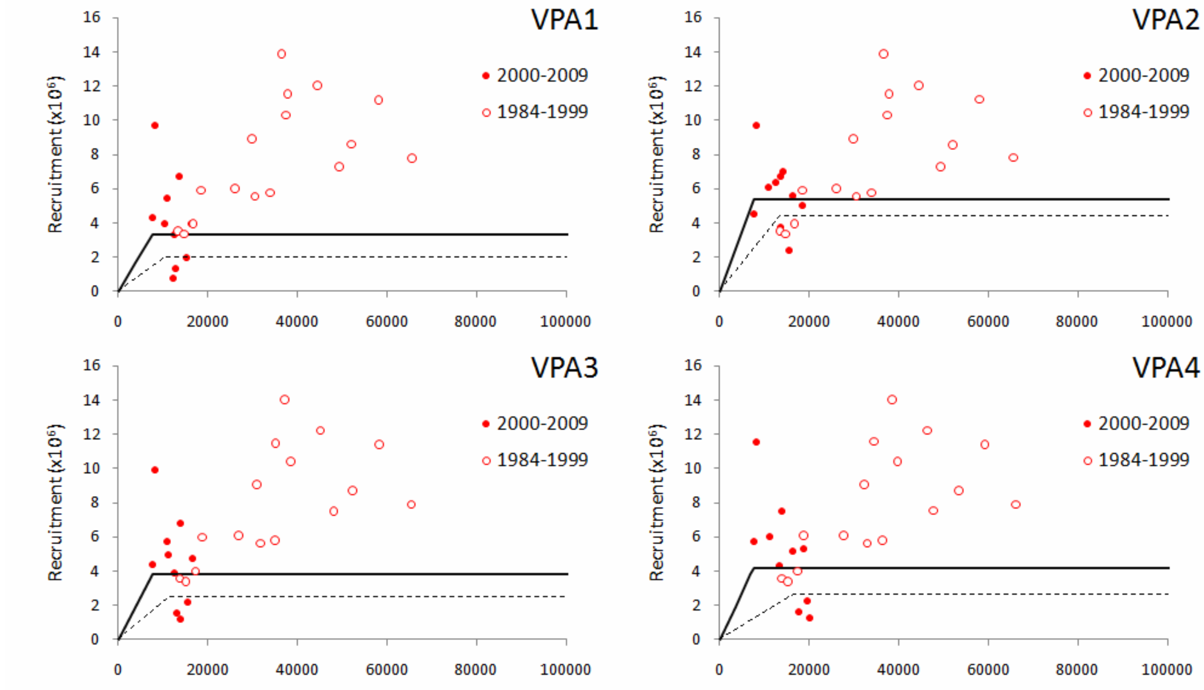

Fig. 1. Stock-recruitment relationships based on the 2000-2009 period and assumed for future projections for each of the four OMs in the RS. The past "data" are also shown. The stock-recruitment curve, based on the 2005-2009 recruitment geometric average, is shown by the dashed line. With reference to Rademeyer and Butterworth (2010), and Fig. 4 thereof, these plots correspond respectively to:

VPA1: St1_BC_withBias: Stone Base Case;
VPA2: St2_BC_withBias_no2010: Stone, excluding the 2010 survey biomass estimates;
VPA3: R1_sig001: Rademeyer Base Case;
VPA4: R3_sig03: Rademeyer, with more flexibility on age 9 fishing mortality.

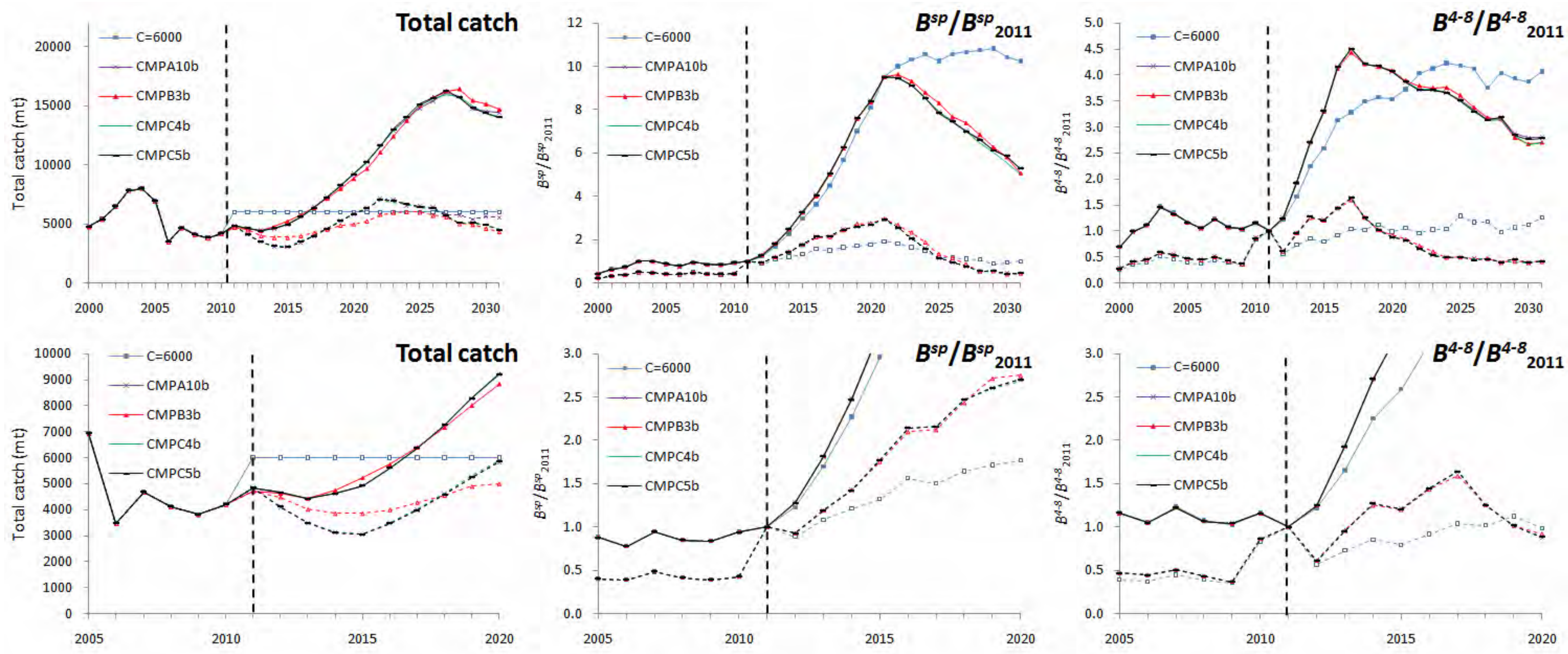

Fig. 2. Median (full lines) and lower 2.5%iles (dashed lines) TAC, spawning biomass, and exploitable (ages 4 to 8) biomass (both in terms of 2011 level) for a series of CMPs (all tuned to a median 2011-2020 catch of 6,000 t under the RS). The bottom row repeats the top row, but with different scales for improved discrimination.

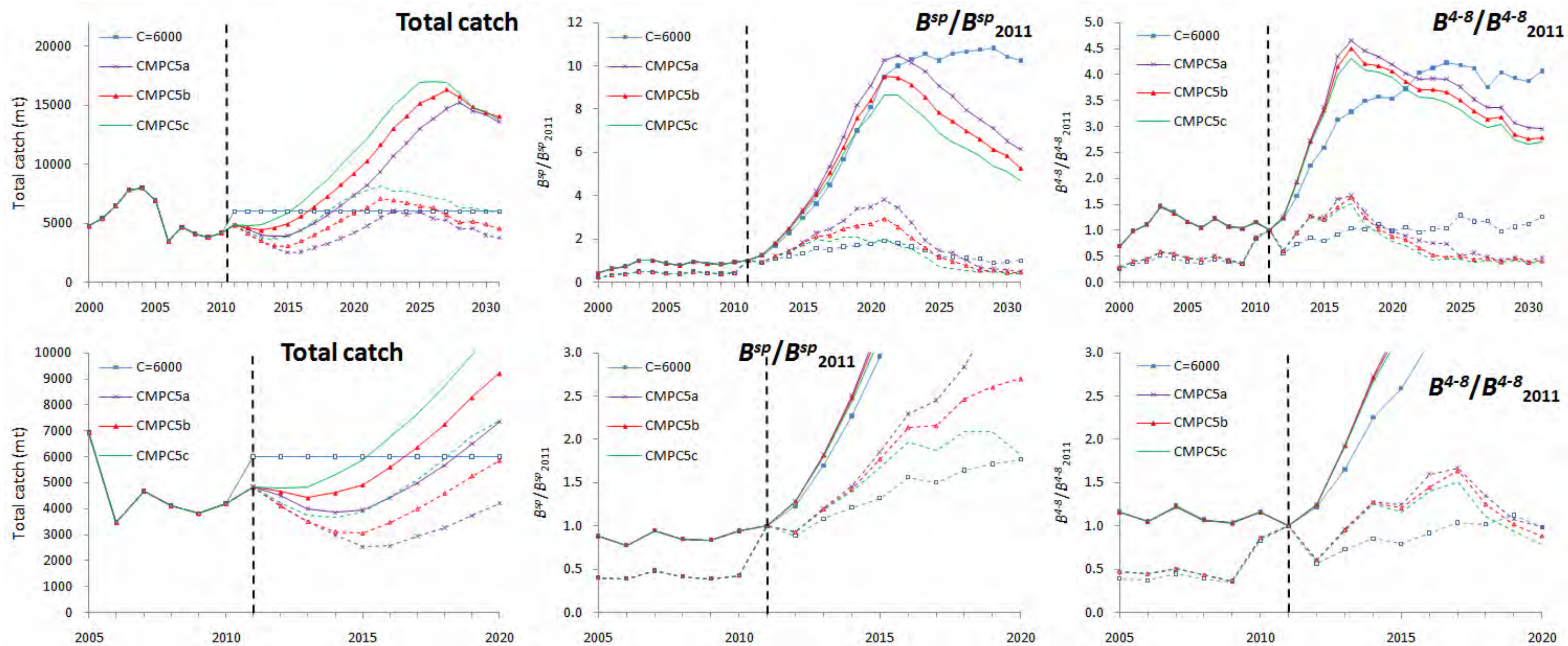

Fig. 3. Median (full lines) and lower 2.5%iles (dashed lines) TAC, spawning biomass, and exploitable (ages 4 to 8) biomass (both in terms of 2011 level) for a constant catch (6,000 t) and three variants of CMPC5, tuned to three different level of median 2011-2020 catch, under the RS. The bottom row repeats the top row but with different scales for improved discrimination.

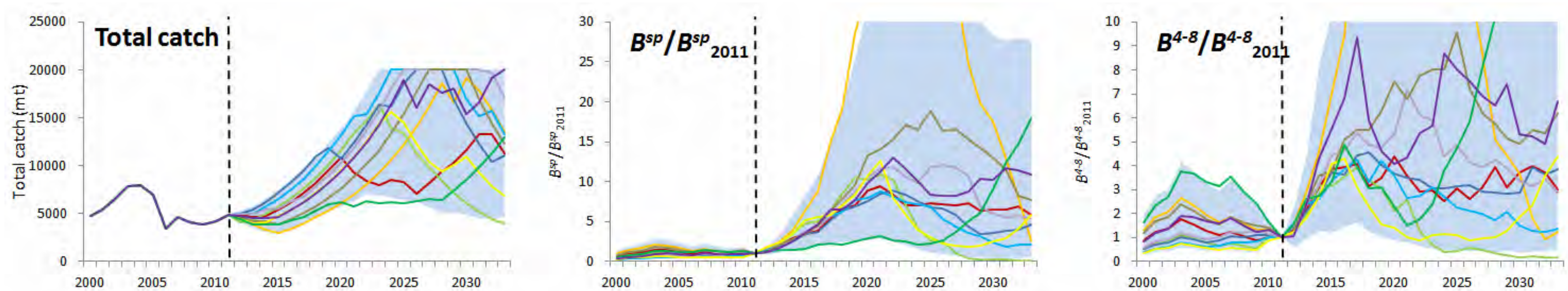

Fig. 4. Ten "worm" trajectories for TAC, spawning biomass and exploitable (ages 4 to 8) biomass (both in terms of 2011 level) for CMPC5b under the RS. The 95% PI are shown by the light shading.

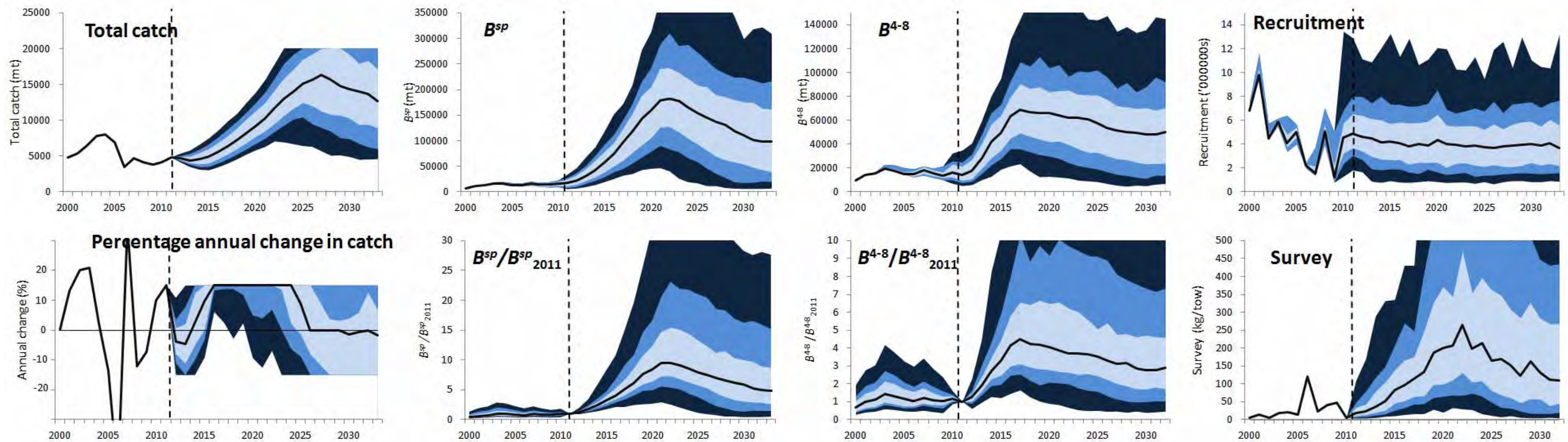

Fig. 5a. 95%, 75%, 50% PIs and median for a series of Performance Statistics for CMPC5b.

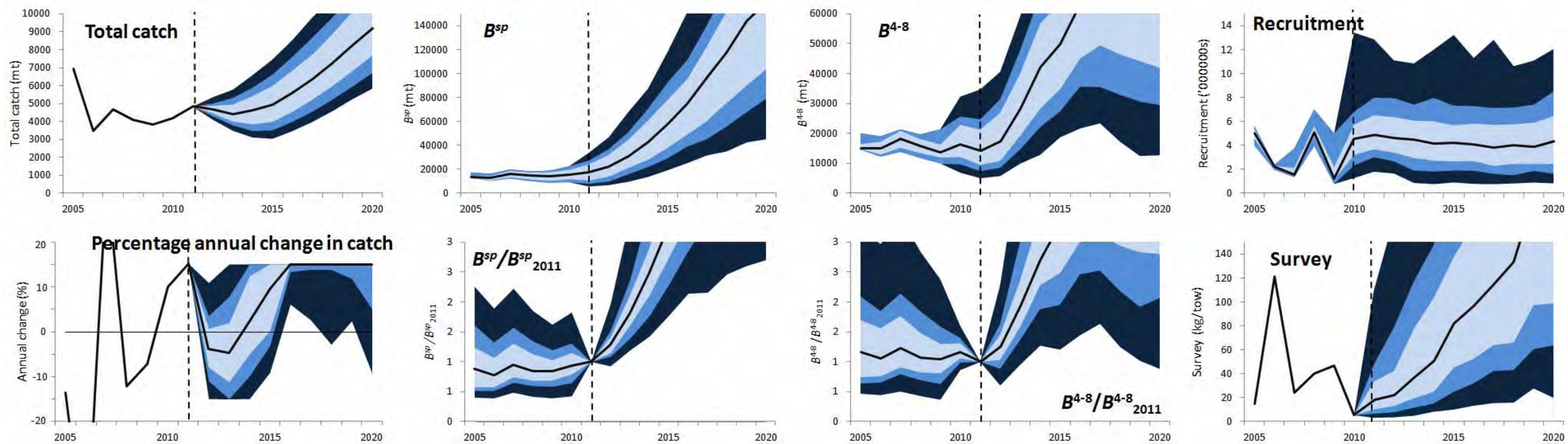

Fig. 5b. As Fig. 5a but with different scales for improved discrimination.

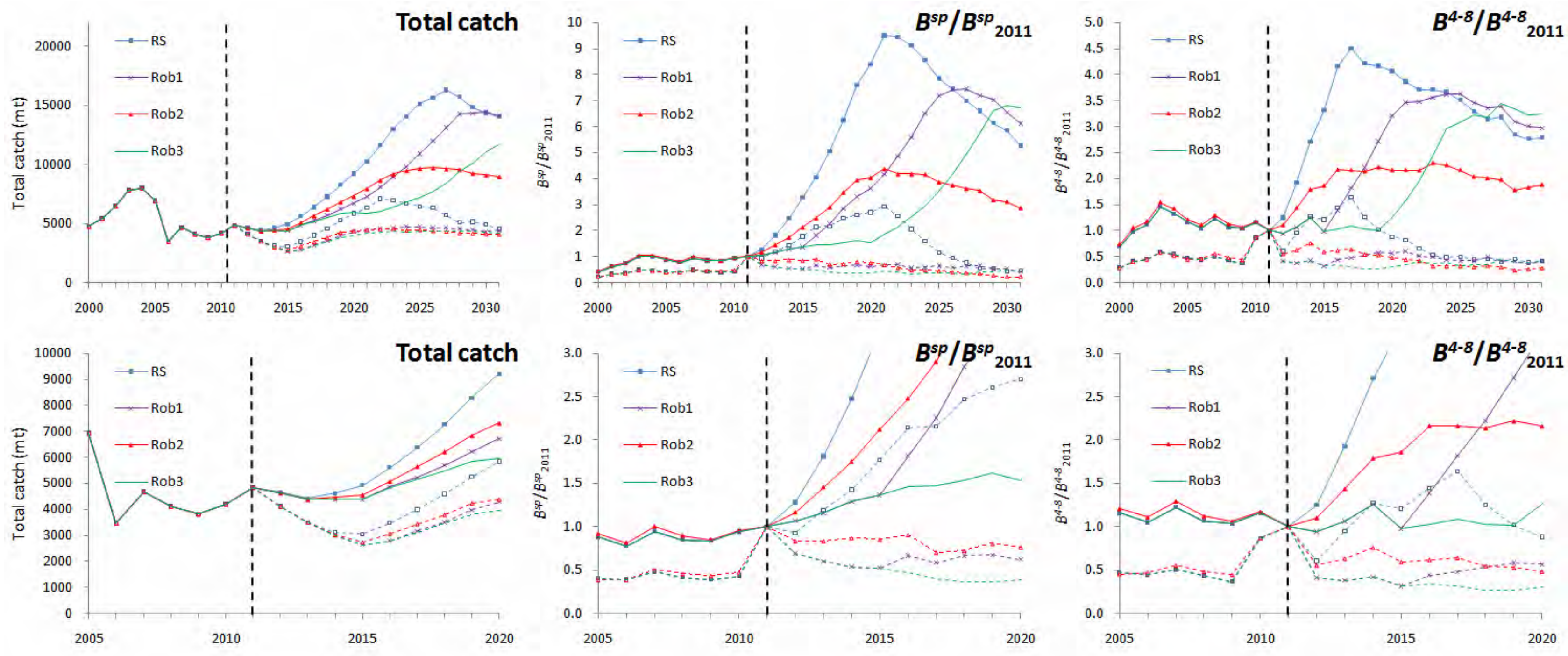

Fig. 6. Median (full lines) and lower 2.5%iles (dashed lines) TAC, spawning biomass, and exploitable (ages 4 to 8) biomass (both in terms of 2010 level) for CMPC5b under the RS and three robustness tests: Rob1 (4 years of poor recruitment), Rob2 (future recruitment from average 2005-2009), and Rob3 (8 years of poor recruitment). The bottom row repeats the top row but with different scales for improved discrimination.

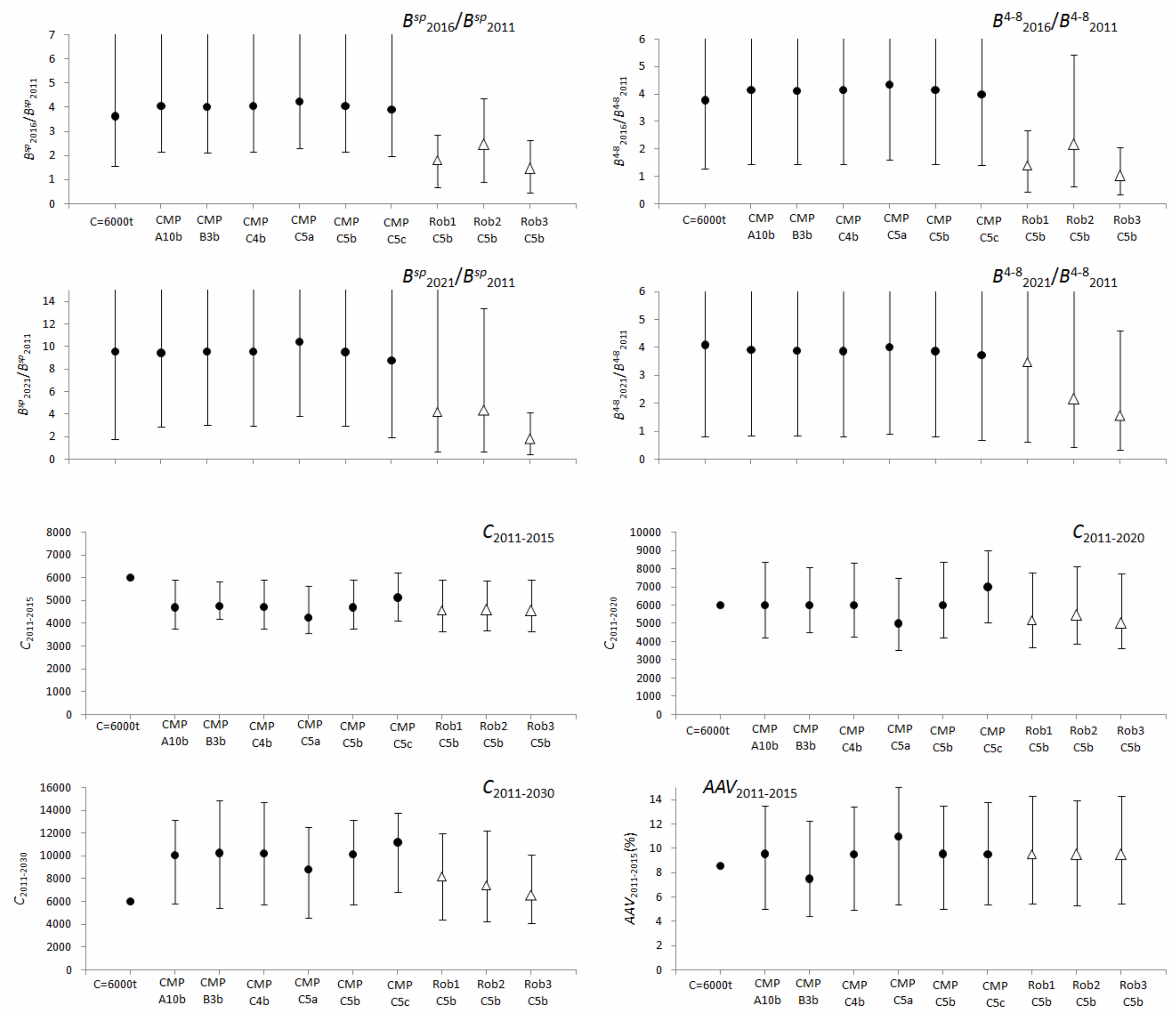

Fig. 7. Medians and 95% PI (probability intervals) for a series of Performance Statistics for different CMPs applied to the RS, followed by the application of CMPC5b to three robustness tests.

APPENDIX 4C-A. CANDIDATE MANAGEMENT PROCEDURES TESTING METHODOLOGY FOR CANADIAN POLLOCK IN THE WESTERN COMPONENT (4XOPQRS+5ZC)

PROJECTION METHODOLOGY

Projections into the future under a specific Candidate Management Procedure (CMP) are evaluated using the following steps.

Step 1: Begin-year numbers at age

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

$$N_{2010,a} \rightarrow N_{2010,a} e^{\varepsilon_a} \qquad \varepsilon_a \text{ from } N\left(0, \left(\sigma_R\right)^2\right) \tag{A1}$$

where σ_R is estimated in the process of fitting a stock-recruitment relationship to the outputs from that assessment as described below. Equation A1 is approximate in that it omits to adjust for past catches from the year-class concerned, but these are so small that the differential effect is negligible.

Step 2: Catch

These numbers-at-age are projected one year forward at a time given a catch for the year concerned.
For 2010:
A catch of 4,200 t is assumed.
From 2011 onwards:

C_y is as specified by the CMP.

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

Step 3: Catch-at-age

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

$$S_{y,a} = F_{y,a} / \max\left(F_{y,a}\right) \tag{A2}$$

where the maximum is taken across the ages for that year.
From this it follows that:

$$F_y = C_y / \sum_a w_{y,a}^{mid} N_{y,a}\, e^{-M_a/2} S_{y,a} \tag{A3}$$

where $w_{y,a}^{mid}$ is each year selected randomly from the weight-at-age vectors for the last 10 years (2000 to 2009) used in the assessment (Table A1), and hence that:

$$C_{y,a} = N_{y,a}\, e^{-M_a/2} S_{y,a} F_y \quad \text{(A4)}$$

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

$$N_{y+1,2} = R_{y+1} \quad \text{(A5)}$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - C_{y,a}\right) e^{-M_a/2} \qquad \text{for } 2 \le a \le m-1 \quad \text{(A6)}$$

These equations reflect Pope's approximation.
The maximum age *m* is 13 (not a plus-group).

<u>Step 4: Recruitment</u>

Future recruitments (age 2) are provided by a 'hockey-stick' stock-recruitment relationship with autocorrelation in the stock-recruitment residuals:

$$R_y = \begin{cases} \alpha e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } B_{y-2}^{sp} \ge B_{\min}^{sp} \\ \dfrac{\alpha}{B_{\min}^{sp}} B_{y-2}^{sp} e^{(\varepsilon_y^{SR} - \sigma_R^2/2)} & \text{if } B_{y-2}^{sp} < B_{\min}^{sp} \end{cases} \quad \text{(A7)}$$

where

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

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

$$\alpha = \exp\left(\sum_{y=2000}^{2009} \ln R_y \Big/ 10 \right) \text{ and} \quad \text{(A8)}$$

$B_{\min}^{sp} = \min\left(B_y^{sp}\right)$ for the 1998-2007 period.

ρ is obtained by minimising the following negative log-likelihood function:

$$-\ln L^{SR} = \sum_{2000}^{2009} \left[\ln \sigma_R + \left(\frac{\varepsilon_y^{SR} - \rho \varepsilon_{y-1}^{SR}}{\sqrt{1-\rho^2}} \right)^2 \Big/ 2\sigma_R^2 \right] \quad \text{(A9)}$$

with

$$\sigma_R = \sqrt{1/10 \sum_{y=2000}^{2009} \left(\varepsilon_y^{SR}\right)^2} \quad \text{(A10)}$$

$$B_y^{sp} = \sum_{a=1}^{m} f_a w_{y,a} N_{y,a} \quad \text{(A11)}$$

where $w_{y,a}$ is each year selected randomly from the weight-at-age vectors for the last 10 years (2000 to 2009) used in the assessment (Table A2), and

f_a is the maturity-at-age, taken to be 0 to age 3 and 1 from age 4 and above.

Step 5:

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

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \qquad \text{(A12)}$$

$$\varepsilon_y^i \quad \text{from } N\left(0, \left(\sigma^i\right)^2\right) \qquad \text{(A13)}$$

where

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

$$B_y^{summer} = \sum_{a=1}^{m} w_{y,a}^{mid} S_{y,a}^{surv} N_{y,a} e^{-M_a/2}\left(1 - S_{y,a} F_y / 2\right) \qquad \text{(A14)}$$

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

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

$$\ell n\, \hat{q}^i = 1/27 \sum_{y=1984}^{2010}\left(\ln I_y^i - \ln \hat{B}_y^i\right) \qquad \text{(A15)}$$

$$\hat{\sigma}^i = \sqrt{1/27 \sum_{y=1984}^{2010}\left(\varepsilon_y^i\right)^2} \qquad \text{(A16)}$$

$$\varepsilon_y^i = \ell n(I_y^i) - \ell n(q^i \widehat{B}_y^i) \qquad \text{(A17)}$$

where the survey index of biomass I_y^i is given in Table A3.

Step 6:

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

Step 7:

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

PERFORMANCE STATISTICS

A number of mathematical expressions (Performance Statistics) are used to measure achievement of the competing aims of avoiding undue depletion of the resource, maximising catch on average over time, and minimising the extent of inter-annual catch variation in the interests of Industry stability.

Resource depletion/recovery

(a) $\frac{P_{2021}}{P_{\text{target}}}$, where P_y is the population size in year *y*, and P_{target} is pre-defined recovery target population size, for which the 1984-1994 average is used

(b) $\frac{P_{2016}}{P_{2011}}$;

(c) $\frac{P_{2021}}{P_{2011}}$

(d) $\frac{P_{2031}}{P_{2011}}$;

For each of these, population can be measured as the exploitable biomass (B_y^{4-8}), spawning biomass (B_y^{sp}), or survey biomass (B_y^{surv}), where:

$$B_y^{4-8} = \sum_{a=4}^{8} w_{y,a}^{mid} N_{y,a} \tag{A18}$$

$$B_y^{sp} = \sum_{a=1}^{m} f_{y,a} w_{y,a}^{mid} N_{y,a} \tag{A19}$$

$$B_y^{surv} = \sum_{a=1}^{m} w_{y,a}^{mid} S_{y,a}^{surv} N_{y,a} e^{-M_a/2} \left(1 - S_{y,a} F_y / 2\right) \tag{A20}$$

Catches over time

(Average) annual catch over short, medium, and long terms:

$$C_{2011},\ C_{2012},\ \sum_{y=2011}^{2015} C_y \Big/ 5,\ \sum_{y=2016}^{2020} C_y \Big/ 5,\ \sum_{y=2011}^{2020} C_y \Big/ 5 \text{ and } \sum_{y=2011}^{2030} C_y \Big/ 20$$

Catch variation

Average annual variation in catch over short and long terms:

$$AAV_{2011-2015} = \frac{1}{5} \sum_{y=2011}^{2015} \left| C_y - C_{y-1} \right| / C_{y-1} \text{ and}$$

$$AAV_{2011-2030} = \frac{1}{20} \sum_{y=2011}^{2030} \left| C_y - C_{y-1} \right| / C_{y-1}$$

Table A1. Mid-year weights-at-age (kg) matrix for Canadian pollock in the Western Component (4Xopqrs+5Zc). Note: a missing value for age 12 in 2008 has been replaced by the average of the five previous years, while missing values for age 13 have been replaced by 11.

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

Table A2. Begin-year weights-at-age (kg) matrix for Canadian pollock in the Western Component (4Xopqrs+5Zc).

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

Table A3. Stratified mean catch per tow (kg) of pollock from the DFO summer research vessel survey in 4X strata corresponding to the Western Component.

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

APPENDIX 4C-B. TECHNICAL SPECIFICATIONS OF CANDIDATE MANAGEMENT PROCEDURES

The Candidate Management Procedures (CMPs) formula for computing the TAC each year is as follows:

$$C_{y+1} = w_y C_y \left[1 + \lambda_{up/down} s_y\right] + \left(1 - w_y\right)\left[a + b\left(J_y - 1\right)\right] \qquad \text{(B1)}$$

where

C_y is the total TAC recommended for year *y*,

w_y is a year-dependent tuning parameter,

$\lambda_{up/down}$ are tuning parameters; λ_{up} is used if $s_y \geq 0$ and λ_{down} is used if $s_y < 0$,

s_y is a measure of the immediate past trend in the survey abundance index (see details below) as available to use for calculations for year *y*,

a and b are tuning parameters, and

J_y is a measure of the immediate past level in the survey abundance index relative to a target level as available to use for calculations for year *y*:

$$J_y = \frac{\sum_{y-2}^{y} I_y \Big/ 3}{\sum_{1984}^{1994} I_y \Big/ 11}$$

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

The trend measure s_y is computed by linearly regressing $\ln I_y$ *vs*. year *y*' for $y' = y - p$ to $y' = y$.

where *p* is a tuning parameter.

Constraints on the interannual TAC change have also been introduced and in some cases a cap (upper bound) on the TAC has been imposed.