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Attachment 1
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REVISED ANALYSES RELATED TO PACIFIC SARDINE HARVEST PARAMETERS

Felipe Hurtado-Ferro and André E. Punt
School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020

EXCUTIVE SUMMARY
The analyses used to evaluate the performance of alternative candidate overfishing limit (OFL) and harvest guideline (HG) control rule variants are updated to reflect the recommendations of the Scientific and Statistical Committee (SSC), the Coastal Pelagic Species Advisory Subcommittee (CPSAS), the Coastal Pelagic Species Management Team (CPSMT), and the Pacific Fishery Management Council (Council) regarding performance measures, candidate control rules, and sensitivity tests.

INTRODUCTION

Amendment 8 to the Coastal Pelagic Species Fishery Management Plan (PFMC, 1998) established the following harvest control rule for Pacific sardine:

HG = (BIOMASS-CUTOFF) * FRACTION * DISTRIBUTION

where: HARVEST GUIDELINE is the target harvest level for each management year; BIOMASS is the annual population biomass estimate of sardine aged 1 and older; CUTOFF is 150,000 t, and is the threshold below which directed fishing is prohibited; FRACTION is a temperature-dependent exploitation fraction which ranges from 5% - 15%[1]; DISTRIBUTION is the average proportion of the coastwide biomass in U.S. waters, estimated at 0.87. MAXCAT is the maximum allowable catch regardless of biomass. MAXCAT is 200,000 t for Pacific sardine.

PFMC (2013) developed an initial risk assessment framework to evaluate the performance of alternative Overfishing Limit and Harvest Guideline control rules. This initial framework was based on representing the northern subpopulation of Pacific sardine using a population dynamics model that considers the entire population from northern Baja California (Mexico) to northern Vancouver Island (Canada) as a single fully-mixed population which is fished by a single fleet. Except for a small subset of sensitivity tests, and in common with the analyses on which Amendment 8 was based, the harvest by all fisheries is determined using a single harvest control rule (i.e., decision making in Mexico and Canada is not modelled explicitly).

Hurtado-Ferro and Punt (2013a) suggested changes to the specifications for the analyses developed during the harvest parameters workshop based on the results of initial analyses. They and Hurtado-Ferro and Punt (2013b) showed results for a set of candidate OFL and HG control rules. The results were presented to the Council at the April 2013 meeting, which led to recommendations for modifications to the management strategy evaluation framework. This document provides updated specifications for the analyses (Appendix A), shows the consequences of changing the metric used to define environmental forcing of recruitment on historical harvest guidelines, and provides results obtained by applying the harvest control rule variants to the trials.

[1] For ease of presentation, the document distinguished between the FRACTION in HG control rule (“HG FRACTION”) and the FRACTION in the OFL control rule (“OFL FRACTION”).

MANAGEMENT STRATEGY EVALUATION (MSE) FRAMEWORK

The MSE framework on which the analyses of this document are based is shown in Appendix A. The key differences between Appendix A and Appendix A of Hurtado-Ferro and Punt (2013a) is that the specifications for the sensitivity tests in Hurtado-Ferro and Punt (2013b) have been integrated, the performance statistics have been updated to reflect the recommendations of the SSC, the CPSMT and the CPSAS, and the table of specifications for the sensitivity tests has been updated.

CONTROL RULES

Figure 1a plots the current relationship between the OFL (the Acceptable Biological Catch [ABC] is 90.592% of the OFL) and 1+ biomass. Figure 1b shows the outcome of the HG control rule with HG FRACTION ranging between 0-15%, CUTOFF set to 150,000t and MAXCAT set to 200,000t when the ABC control rule is ignored, and Figure 1c show the HG when the constraint that the HG must be less than or equal to the ABC is applied based on the control rule from Amendment 13. Figure 2 shows the same information as Figure 1, except that the OFL and HG control rules are based on the CalCOFI-E_{MSY} relationship.

E_{MSY} ignoring the environmental effect

The "stochastic E_{MSY}" (SE_{MSY}) is here defined as the exploitation rate that maximizes the mean catch for the "All error" scenario[2,3] for a constant exploitation rate control rule when there is no observation error. SE_{MSY} (0.18) was calculated by projecting the operating model (OM) forward for 200,000 years (100 simulations × 2,000 years) for a range of values for FRACTION to guarantee equilibrium.

E_{MSY} accounting for an environmental effect

E_{MSY} is related to the environmental factor through the recruitment model; as temperature increases, E_{MSY} increases as well. Figure 3 illustrates this relationship. Figure 3 was calculated by projecting the operating model forward (with no process or observation error) for 5,000 years (sufficient to reach equilibrium) and a range of possible E_{MSY} values, while leaving temperature fixed to determine the relationship between E_{MSY} and temperature. This relationship was approximated using a polynomial equation (Figure 4).

Although the method used to estimate the relationship between temperature and E_{MSY} is similar to that used to estimate the current SIO-based temperature-E_{MSY} relationship in Amendment 8 (PFMC, 1998), the relationships differ for reasons other than the choice of environmental variable (CalCOFI vs. SIO). These reasons are: (a) the operating model for this analysis is age-structured and not a production model, and (b) the data used to estimate the relationship cover a different range of year (1984-2008 for CalCOFI vs. 1935-63 and 1986-90 for SIO). A unitless (i.e. in standard deviation space) comparison between the SIO- and CalCOFI-based relationships between SST and E_{MSY} is shown in Figure 5. Figure 5 also shows the relationship between E_{MSY} and temperature when the stock-recruitment relationship is fitted using CalCOFI data for 1984-2008 and the projections are based on the age-structured operating model to eliminate effects of these factors.

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[2] The value of E_{MSY} is 0.17 if expected yield is taken to be median rather than the mean of the distribution.

[3] With variation in the environment, and recruitment given the environment.

OFL, ABC and Harvest Guidelines

The OFLs, ABCs and the Harvest Guidelines are defined following the definitions in Amendment 13 (PFMC, 2010)[4]. Consistently with how OFLs have been calculated for the Pacific sardine, the OFL, defined as $OFL_y = E_{MSY}\left(I_y\right)\hat{B}_y^{1+}$ (eq. A5b), is bounded above by the E_{MSY} corresponding to the upper quartile of observed temperature. ABC is defined as OFL multiplied by an uncertainty buffer. The calculations of this report are based on the choice P*=0.4. The harvest guideline, HG, is defined as $HG_y = \text{DISTRIBUTION} \times \text{HG FRACTION}_y(B_y^{1+} - \text{CUTOFF})$, where the HG FRACTION is given by the polynomial approximation of the relationship between E_{MSY} and temperature. DISTRIBUTION is set equal to 1 (Figure 4). The HG is bounded below by an E_{MIN} and above by MAXCATCH.

Table 1 lists the full set of harvest control rule variants considered in this report. Taking harvest control rule variant "J" as a base-case (OFL FRACTION ranging between 0-26%; HG FRACTION ranging between 0-15%; CUTOFF set to 150,000t; MAXCAT set to 200,000t), the remaining variants differ from this base-case follows:

- Variant 4: No CUTOFF or MAXCAT, HG FRACTION is always set to 0.19.
- Variant 9: No MAXCAT, CUTOFF set to 20% of average unfished biomass ($0.2\overline{B_0}$)[5], HG FRACTION ranges from 5 to 18%.
- Variant 13: CUTOFF of 50,000t, HG FRACTION ranges between 11 and 18%.
- Variant 14: No MAXCAT, HG FRACTION set to 0.18, and a CUTOFF of 50,000t.
- Variant 15: HG FRACTION equal to 18%.
- Variant 16: HG FRACTION equal to 18% and no MAXCAT.
- Variant 17: As for harvest control rule variant 9, but with MAXCATCH set to 200,000t.
- Variant 18: OFL computed with a OFL FRACTION of 18% and the HG with a HG FRACTION of 15%.
- Variant 19: HG FRACTION is 15% and depends on the most recent year of V instead of a 3-year average.
- Variant 20: HG FRACTION depends on the most recent year of V instead of a 3-year average.
- Variant 21: No fishing
- Variant 22: HG FRACTION is 15%.

IMPACT OF CHANGING FROM SIO TO CalCOFI

Table 2 lists the estimates of 1+ biomass from the assessments for the last 10 years, the values for CalCOFI temperatures (SST_CC_ann), the values for the SIO temperatures and the resulting OFLs and harvest guidelines. The differences in HG are explained by the difference between the various time series (Figure 6), where the CalCOFI and SIO series have diverged since around 2000, with CalCOFI getting increasingly colder, while SIO has remained warm.

HGs and OFLs are calculated from the temperature and biomass for a given management year. Using management year 2000 as an example, first calculate the reference points using SIO. From the relationship shown in the right panel of Figure 4, the E_{MSY} for an SIO SST of 18.08^{0}C is 66%, and the HG FRACTION is consequently 15% (HG FRACTION = max(E_{MSY}, HG

[4] The OFL as defined in Amendment 13 includes the DISTRIBUTION parameter, but DISTRIBUTION is assumed to be 1 for the bulk of the calculations reported here.

[5] $\overline{B_0}$ is here defined as the mean unfished biomass. Note that this definition of $\overline{B_0}$ is not the 'true B_0' of the stock, and is only used to define the CUTOFF parameter of the HG. The 'true' B_0 of the stock is not a static value and is related to the environment. Thus, the definition of B_0 being used here is not appropriate for defining an overfished threshold.

$FRACTION_{max}$)). The OFL for 2000 using SIO temperature is equal to the biomass (1'581,346t) times OFL FRACTION (44%, not shown in table; OFL FRACTION = max(E_{MSY}, OFL $FRACTION_{max}$), where OFL $FRACTION_{max}$ is the value of E_{MSY} at the upper quartile of observed SST, 17.76°C), times DISTRIBUTION (0.87). The HG is equal to the biomass minus CUTOFF (150,000t), times HG FRACTION, times DISTRIBUTION. The reference points using CalCOFI are calculated in a similar way, but the HG FRACTION and OFL FRACTION (OFL $FRACTION_{max}$ is 24% for CalCOFI, occurring at 16.11°C) are calculated using the relationship shown in the left panel of Figure 4.

RESULTS FOR A BASE-CASE OPERATING MODEL

The base-case operating model is defined in Table A4. Figure 7 shows the cumulative 1+ biomass and cumulative catch for the harvest control rule variant which most closely resembles the current HG control rule (harvest control rule variant "J" in Table 1), as well as those for the least (setting the harvest rate to DE_{MSY} with no CUTOFF or MAXCATCH; harvest control rule variant "M" in Table 1) and most (setting CUTOFF to $0.20\overline{B_0}$; harvest control rule variant 9 in Table 1) conservative harvest control rule variants. The catch for the OFL control rule is unbounded, whereas the catch for harvest control rule variants J and V4 do not allow the catch to exceed 200,000t (MAXCAT). Figure 8 shows 150-year time-trajectories of biomass for these three harvest control rule variants.

Table 4 lists the values for the performance measures for the harvest control rule variants in Table 1 (see Section 4 of Appendix A for definitions of the performance measures), highlighting those harvest control rule variants which perform best (green highlighted) and poorest (red highlighted) for each performance measure. No harvest control rule variant is always in the "best" group, indicating that there are trade-offs amongst the management objectives which underlie the performance measures. Some of the key trade-offs are illustrated in Figure 9. Best performance occurs in the top right corner of the left panel of Figure 9 (high average catches and 1+ biomasses) and in the top right corner of the right panel of Figure 9 (high probability that the catch is larger than 50,000t and the 1+ biomass exceeds 400,000t). Some of the harvest control rule variants (e.g. 4, "DE_{MSY}") are "dominated" in Figure 9 (they achieve the same [or lower] average catch as another variant, but at lower average biomass). Harvest control rule variant 4 leads to a high proportion of years with no catch (Figure 9, right panel) and 1+ biomass values below 400,000t (Figure 9, right panel).

The current harvest control rule variant ("J" in Table 1, "6" in Figure 9), achieves amongst the lowest average catches, but performs best in terms of low catch variation and a low probability of the HG being zero (Table 3). This harvest control rule variant also leads to fairly high variation in 1+ biomass, but not as high as harvest control rule variant 18. However, 1+ biomass remains about 400,000t with high probability (~95% of years) under harvest control rule variant J. Harvest control rule variants 14 and 16, which both have no relationship between HG FRACTION and the environmental variable, lead to the highest average catches, but also to quite considerable between-year variation in catches and amongst the lowest probabilities of 1+ biomass dropping below 400,000t.

SENSTIVITY TO ALTERNATIVE SCENARIOS

Tables 5, 6 and 7 show the values for the performance measures for harvest control rule variant J, while the results of the sensitivity tests in the trade-off space are shown in Figure 10. Perhaps not surprisingly, variation in catch and biomass, as well as the probability of low (or zero) catches, is higher when the extent of recruitment variation is higher (case S2), and is lower when recruitment variation is lower (case S1). The same effect occurs when the extent of uncertainty in biomass estimates is changed (cases S3 and S4), although the size of the effect is less for cases S3 and S4 than for cases S1 and S2. The probability of low (or zero) catches is markedly higher when the number of years of poor environmental conditions is increased (case S6). In contrast, longer periods of good and poor environmental conditions (case S9), or a smoother (i.e. sine) underlying environmental signal (case S8) are relatively inconsequential. Overall, a slower decline in the environment (case S7) leads to better overall performance (higher average catches and higher average biomasses).

Less variation in the environment (case S10) leads to higher average catches and less between-year variation in catches, to a higher probability of biomass exceeding 400,000t and to a markedly lower probability of a zero catch. More variation in the environment leads to the opposite effects. The results are not very sensitive to time-varying selectivity and weight-at-age (cases S12, S13, S16 and S17) nor to hyper-stability in biomass estimates (Table 7). However, the results are sensitive to Mexico and Canada not following the US control rule (case S14 in Table 6). This is the only case in which the resource is rendered extinct. The results are more optimistic if only Canada does not follow the US control rule even though risks remain higher (case S15[6]). Risk is also much higher, and average catches lower and more variable, if natural mortality increases when the environment is declining (case S5).

The results are insensitive to basing the uncertainty between *I* and *V* on the variance between CC_SST_ann and ERSST_ann when the population dynamics are assumed to be driven by CC_SST_ann.

The results are generally more optimistic when the simulations are based on the ERSST series (higher average catches, lower probabilities of catches less than 50,000t and higher average biomasses), but the trade-offs achieved by the harvest control rule variants are similar to those from the simulations for the base case analysis (Table 8). This is because the ERSST series implies higher average biomasses given the fit of the environmental-recruitment model. Table 9 lists the estimates of 1+ biomass from the assessments for the last 10 years, the values for ERSST_ann, the values for the SIO temperatures and the resulting OFLs and harvest guidelines. It is important to keep in mind that the environmental-recruitment model based on CalCOFI (CC_SST_ann) fits the data better than the model based on ERSST_ann (Table 10). The relationship between ERSST and E_{MSY} is shown in Figure 11.

The results when simulations are based on the SIO_SST_ann time series show similar trade-offs as the base case, except for variant 4, which shows relatively higher catches than in the ERSST and base cases (Table 11). The recalculated relationship between SIO and E_{MSY} is shown in Figure 12. Table 12 lists the estimates of 1+ biomass from the assessments for the last 10 years, the values for the SIO temperatures and the resulting OFLs and harvest guidelines from changing the relationship between SST and E_{MSY}.

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[6] This sensitivity tests also captures some of the effects of there being two stocks with catches off Mexico coming from a southern subpopulation.

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Table 1. Harvest control rule variants. The numbers associated with each control rule variants are used in the figures. PFMC (2013) included a 15th variant, but this was equivalent to "HG Variant-1".

	Variants from Hurtado-Ferro and Punt (2013a)				
Variant	**M (4)**	**HG (J) (6)**	**HG Variant-3 (9)**	**Alt-3 (13)**	**Alt-4 (14)**
HG FRACTION (%)	DE_{MSY}	5-15	5- SE_{MSY}	11- SE_{MSY}	SE_{MSY}
CUTOFF	0	150	$0.20\overline{B_0}$	50	50
MAXCAT		200		200	-
	Additional analyses				
Variant	**New-1 (15)**	**New-2 (16)**	**New-3 (17)**	**New-4 (18)**	**New-5 (19)**
HG FRACTION (%)	Best fit	Best fit	5- SE_{MSY}	15*	15**
CUTOFF	150	150	$0.20\overline{B_0}$	150	150
MAXCAT	200	-	200	200	200
	Additional analyses				
Variant	**New-6 (20)**	**New-7 (21)**	**New-8 (22)**		
HG FRACTION (%)	5-15**	0	15		
CUTOFF	150	-	150		
MAXCAT	200	-	200		

* OFL/ABC = 0.18

** OFL/ABC based on E_{MSY} (0-0.26), linked to CC_SST_ann

Table 2. Impact of changing the environmental variable from SIO to CalCOFI, using both annual and 3-year averages.

Mgmt	Biomass	SIO				CalCOFI ann					CalCOFI 3-year average				
year	**(July)**	**SST**	**Fraction**	**HG**	**OFL**	**ann SST**	**Fraction**	**HG**	**Difference**	**OFL**	**3-y SST**	**Fraction**	**HG**	**Difference**	**OFL**
2000	1581346	18.08	0.15	186791	605339	15.19	0.09	113150	-73641	125008	16.18	0.15	186791	0	331561
2001	1182465	17.75	0.15	134737	433005	15.73	0.15	134737	0	185281	15.82	0.15	134737	0	202183
2002	1057599	17.24	0.15	118442	149081	15.50	0.14	110000	-8442	128179	15.47	0.14	106625	-11817	124247
2003	999871	17.31	0.15	110908	165969	14.91	0.05	38097	-72811	44821	15.38	0.12	88639	-22270	104283
2004	1090587	17.46	0.15	122747	246185	15.98	0.15	122747	0	214618	15.46	0.13	109008	-13738	126392
2005	1193515	17.60	0.15	136179	346672	15.78	0.15	136179	0	196454	15.56	0.15	135381	-797	154842
2006	1061391	18.03	0.15	118937	406300	15.36	0.12	93036	-25900	108349	15.71	0.15	118937	0	162261
2007	1319072	18.11	0.15	152564	504941	15.72	0.15	152564	0	203690	15.62	0.15	152564	0	184025
2008	832706	18.12	0.15	89093	318760	15.06	0.07	42989	-46104	52435	15.38	0.12	71394	-17699	87081
2009	662886	17.83	0.15	66932	253753	15.13	0.08	36621	-30311	47331	15.30	0.11	48181	-18750	62272
2010	702024	17.84	0.15	72039	268735	15.15	0.08	40617	-31422	51654	15.11	0.08	38243	-33796	48634
2011	537173	17.90	0.15	50526	205630	15.49	0.14	46600	-3926	64654	15.26	0.10	33950	-16576	47103
2012	988385	17.64	0.15	109409	307746	14.82	0.05	36470	-72939	42995	15.15	0.09	62453	-46956	73627
2013	659539	17.35	0.15	66495	118854	-	-	-	-	-	-	-	-	-	-

Table 3. Values of biomass used in the harvest control rule variants (in ‘000 t).

Quantity	Value
$\overline{B_0}$	1655
0.33 $\overline{B_0}$	551.9
0.20 $\overline{B_0}$	331.1
0.10 $\overline{B_0}$	165.6

Table 4. Results of applying each of harvest control rule variants to a base-case scenario (see Table A4 for specifications). The variants where the performance measure is within 5% of the best value are shaded in green and those for which the performance measure is within 5% of the poorest value are shaded in red (Variant 21 [no catch] not included in this calculation).

Scenario	**M**	**HG J**	**HG Var3**	**Alt3**	**Alt4**	**New1**	**New2**	**New3**	**New4**	**New5**	**New6**	**New7**	**New8**
Code	**4**	**6**	**9**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
OFL FRACTION (%)	0-26	0-26	0-26	0-26	0-26	0-26	0-26	0-26	18	0-26	0-26	-	0-26
HG FRACTION (%)	19	5-15	5-18	11-18	18	18	18	5-18	15	15	5-15	0.0	15
CUTOFF	0	150	$0.20\overline{B_0}$	50	50	150	150	$0.20\overline{B_0}$	150	150	150	-	150
MAXCAT	-	200	-	200	-	200	-	200	200	200	200	-	200
Performance Measure													
Mean catch all	128.3	107.1	134.9	114.3	151.2	112.1	147.8	101.5	114.2	103.3	102.5	0.0	108.0
SD catch all	164.8	71.8	164.6	72.4	164.3	72.3	163.4	75.7	68.5	72.0	72.7	0.0	70.7
Mean catch CO	151.8	110.0	145.1	116.9	154.7	115.3	152.0	109.0	116.3	111.0	110.2	0.0	111.0
SD catch CO	169.0	70.6	166.5	71.1	164.6	70.8	163.8	73.2	67.4	68.8	69.7	0.0	69.3
Mean B1+	675.4	1259.6	1215.3	1201.0	1087.3	1222.1	1118.4	1304.7	1176.6	1268.3	1276.9	1598.5	1247.0
SD B1+	768.5	879.5	750.1	880.3	744.4	881.8	751.8	868.3	911.0	881.2	877.9	895.9	884.1
Mean SSB	477.1	978.8	922.5	925.3	804.9	944.3	833.3	1019.8	905.5	988.7	996.4	1326.3	967.8
SD SSB	573.0	752.4	587.0	752.8	576.7	754.0	584.5	743.4	775.8	756.1	753.5	797.3	756.0
%B1+>400	52.7	94.7	96.9	91.9	91.2	92.9	92.5	97.1	86.8	94.3	95.0	99.1	93.6
%No catch	15.5	2.8	7.2	2.3	2.3	2.8	2.8	6.9	1.8	7.1	7.1	100.0	2.7
%Catch<50	39.8	30.4	37.2	27.5	28.3	28.3	29.3	35.9	24.0	31.5	32.6	100.0	29.0
Median catch	77.0	98.8	82.2	110.6	102.6	106.2	98.8	88.9	109.3	93.8	93.0	0.0	99.3
Median B1+	445.7	1037.7	1037.7	972.2	907.2	995.8	937.7	1086.7	948.0	1055.6	1063.7	1430.2	1026.0
Median SSB	304.6	779.2	781.1	719.6	664.6	740.3	691.2	823.5	697.2	795.5	802.9	1163.8	768.4
Mean pop age	2.03	2.84	2.77	2.78	2.64	2.80	2.67	2.88	2.75	2.85	2.86	3.29	2.82
Mean Catch Age	1.30	1.83	1.79	1.79	1.70	1.81	1.72	1.87	1.78	1.84	1.85	NA	1.83
%HCR min	NA	11.88	11.88	33.33	NA	NA	NA	11.88	NA	NA	17.64	NA	NA
%HCR max	NA	52.23	42.10	42.10	NA	NA	NA	42.10	NA	NA	52.01	NA	NA
Mean Yrs HCRmin	NA	2.63	2.63	4.81	NA	NA	NA	2.63	NA	NA	1.59	NA	NA
Mean Yrs HCRmax	NA	7.40	6.01	6.01	NA	NA	NA	6.01	NA	NA	3.14	NA	NA
Mean Yrs NoCatch	139.22	1.66	1.63	1.74	1.75	1.64	1.64	1.64	1.37	1.27	1.27	NA	1.65
% Collapses	28	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Results of applying harvest control rule variant J to a base-case scenario and nine of the sensitivity tests. Scenarios "σ_R=0.5" and "σ_R=0.9" refer to changing the assumed extent of recruitment variability; scenarios "σ_B=0.268" and "σ_B=0.5" refer to changing the assumed extent of uncertainty associated with biomass estimation; scenario "M&G" refers to time-varying natural mortality as a function of G; scenarios "G=a2","G=b", "G=c", and "G=d" refer to the shape of the underlying environmental signal, G, as described in Figure A1.

Scenario	**HG J**	**σ_R=0.5**	**σ_R=0.9**	**σ_B=0.268**	**σ_B=0.5**	**M&G**	**G=a2**	**G=b**	**G=c**	**G=d**
Code	**6**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Performance Measure										
Mean catch all	107.1	113.1	102.4	109.2	103.0	97.5	89.8	116.9	108.7	106.6
SD catch all	71.8	70.8	72.5	71.1	73.0	75.5	69.9	70.4	68.2	72.4
Mean catch CO	110.0	115.7	106.0	111.9	106.9	104.9	93.2	119.3	110.4	109.8
SD catch CO	70.6	69.5	71.2	69.9	71.6	73.3	69.0	69.2	67.3	71.1
Mean B1+	1259.6	1279.7	1244.4	1253.4	1271.9	1138.2	1095.7	1339.2	1216.6	1254.2
SD B1+	879.5	702.2	1035.2	877.7	883.2	921.5	783.0	897.4	783.6	866.6
Mean SSB	978.8	991.2	969.5	972.2	991.9	873.4	853.4	1038.8	941.9	974.7
SD SSB	752.4	586.7	895.9	750.5	756.5	775.4	663.5	772.4	671.2	738.4
%B1+>400	94.7	98.6	91.1	94.8	94.6	82.4	92.5	96.0	96.1	94.0
%No catch	2.8	2.3	3.5	2.4	3.7	7.2	3.8	2.0	1.6	2.9
%Catch<50	30.4	26.9	33.3	28.9	33.4	38.0	39.9	24.5	26.5	31.2
Median catch	98.8	110.2	90.4	102.9	91.3	84.1	70.2	116.9	100.7	98.3
Median B1+	1037.7	1112.3	975.9	1029.8	1054.0	912.1	883.3	1128.7	1028.9	1036.7
Median SSB	779.2	839.2	730.3	770.9	794.5	672.0	673.2	841.1	770.7	778.1
Mean pop age	2.84	2.74	2.91	2.83	2.85	2.69	2.85	2.81	2.79	2.83
Mean Catch Age	1.83	1.77	1.88	1.83	1.84	1.74	1.84	1.82	1.80	1.83
%HCR min	11.88	11.88	11.88	11.88	11.88	11.88	16.00	8.96	8.32	12.23
%HCR max	52.23	52.24	52.24	52.24	52.24	52.24	40.14	59.00	52.88	52.00
Mean Yrs HCRmin	2.63	2.64	2.64	2.64	2.64	2.64	2.68	2.55	2.33	2.72
Mean Yrs HCRmax	7.40	7.40	7.40	7.40	7.40	7.40	5.55	8.22	6.02	7.81
Mean Yrs NoCatch	1.66	1.71	1.69	1.72	1.54	2.16	1.69	1.65	1.56	1.69
% Collapses	0	0	0	0	0	0	0	0	0	0

Table 6. Results of applying harvest control rule variant J to a base-case scenario and ten of the sensitivity tests. Scenarios “Amp=0.5” and “Amp=2” refer to changing the amplitude of the environmental signal; scenarios “Sel=Mex” and “Sel=PNW” refer to changing the selectivity of the fishery; scenarios “MF” and “MF=NoMex” refer to only the US following the US control rule; scenario “TV Selex” refers to time-varying selectivity; scenario “TV WaA” refers to time-varying weight-at-age; scenario “ERSST error” refers to variance in *I* equal to the variance between CC_SST_ann and ERSST_ann.

Scenario	**HG J**	**Amp = 0.5**	**Amp = 2**	**Sel=Mex**	**Sel=PNW**	**MF**	**MF=NoMex**	**TV Selex**	**TV WaA**	**ERSST error**
Code	**6**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**
Performance Measure										
Mean catch all	107.1	110.1	99.8	108.7	114.7	60.5	89.0	112.9	108.2	107.5
SD catch all	71.8	65.5	85.7	71.9	71.8	60.5	63.2	71.3	72.2	71.6
Mean catch CO	110.0	111.0	117.9	111.7	117.5	72.8	92.4	115.7	111.2	109.9
SD catch CO	70.6	65.0	81.3	70.6	70.4	59.6	61.9	70.0	70.9	70.6
Mean B1+	1259.6	1195.9	1459.2	1285.4	1373.7	768.4	1193.9	1339.4	1287.6	1258.0
SD B1+	879.5	717.8	1335.3	888.7	904.0	726.4	890.8	881.2	917.6	879.3
Mean SSB	978.8	923.7	1149.9	999.5	1084.5	530.4	911.1	1050.3	980.5	977.2
SD SSB	752.4	617.2	1138.7	761.9	783.0	537.4	750.2	758.9	757.7	752.2
%B1+>400	94.7	97.3	82.5	95.2	96.9	64.3	90.6	96.8	94.8	94.8
%No catch	2.8	0.9	15.6	2.7	2.5	17.2	3.8	2.5	2.7	2.2
%Catch<50	30.4	23.7	44.1	29.7	26.8	56.4	36.9	27.2	30.2	30.2
Median catch	98.8	101.9	84.6	101.8	113.0	37.8	79.4	109.6	100.6	99.3
Median B1+	1037.7	1027.3	1065.1	1063.6	1158.9	570.5	970.9	1129.1	1051.9	1034.9
Median SSB	779.2	770.0	803.9	798.2	884.3	386.0	714.9	857.1	778.4	776.2
Mean pop age	2.84	2.77	3.06	2.85	2.69	2.23	2.61	2.72	2.84	2.83
Mean Catch Age	1.83	1.79	1.99	1.97	3.80	1.44	1.71	3.24	1.84	1.83
%HCR min	11.88	6.03	30.48	11.88	11.88	11.80	11.80	11.88	11.88	11.12
%HCR max	52.23	53.21	50.66	52.24	52.24	52.82	52.82	52.23	52.23	52.25
Mean Yrs HCRmin	2.63	2.00	5.33	2.64	2.64	2.67	2.67	2.63	2.63	2.62
Mean Yrs HCRmax	7.40	5.31	19.65	7.40	7.40	7.60	7.60	7.40	7.40	8.08
Mean Yrs NoCatch	1.66	1.40	2.91	1.67	1.69	3.45	1.75	1.69	1.66	1.62
% Collapses	0	0	0	0	0	8	0	0	0	0

Table 7. Results of applying harvest control rule variant J to five scenarios of the sensitivity test for hyper-stability in biomass estimates.

	***g*=210**	***g*=320**	***g*=400**	***g*=500**	***g*=620**
Performance Measure					
Mean catch all	107.1	107.1	107.1	107.1	107.1
SD catch all	71.8	71.8	71.8	71.8	71.7
Mean catch CO	110.0	110.0	110.0	110.0	109.8
SD catch CO	70.6	70.6	70.6	70.6	70.6
Mean B1+	1259.6	1259.6	1259.6	1259.5	1258.1
SD B1+	879.5	879.5	879.5	879.5	879.9
Mean SSB	978.8	978.8	978.8	978.7	977.6
SD SSB	752.4	752.4	752.4	752.4	752.7
%B1+>400	94.7	94.7	94.7	94.7	94.6
%No catch	2.8	2.8	2.8	2.7	2.5
%Catch<50	30.4	30.4	30.4	30.4	30.5
Median catch	98.8	98.8	98.8	98.8	98.6
Median B1+	1037.7	1037.7	1037.7	1037.7	1036.8
Median SSB	779.2	779.2	779.2	779.2	778.5
Mean pop age	2.84	2.84	2.84	2.84	2.83
Mean Catch Age	1.83	1.83	1.83	1.83	1.83
%HCR min	11.88	11.88	11.88	11.88	11.88
%HCR max	52.23	52.23	52.23	52.23	52.23
Mean Yrs HCRmin	2.63	2.63	2.63	2.63	2.63
Mean Yrs HCRmax	7.40	7.40	7.40	7.40	7.40
Mean Yrs NoCatch	1.66	1.66	1.66	1.65	1.65
% Collapses	0	0	0	0	0

Table 8. Results of applying each of harvest control rule variants to a model based on the ERSST time-series. The variants where the performance measure is within 5% of the best value are shaded in green and those for which the performance measure is within 5% of the poorest value are shaded in red (Variant 21 [no catch] not included in this calculation).

Scenario	**M**	**HG J**	**HG Var3**	**Alt3**	**Alt4**	**New1**	**New2**	**New3**	**New4**	**New5**	**New6**	**New7**	**New8**
Code	**4**	**6**	**9**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
FRACTION (%)	19	5-15	5-18	11-18	18	18	18	5-18	15	15	5-15	0	15
CUTOFF	0	150	$0.20\overline{B}_0$	50	50	150	150	$0.20\overline{B}_0$	150	150	150	-	150
MAXCAT	-	200	-	200	-	200	-	-	200	200	200	-	200
Performance Measure													
Mean catch all	183.6	138.3	172.5	142.7	182.9	141.8	181.7	132.6	146.3	133.7	133.0	0.0	139.2
SD catch all	161.3	61.2	160.4	59.7	153.2	60.0	153.4	65.8	58.1	63.7	64.6	0.0	59.8
Mean catch CO	184.4	138.5	174.1	142.8	183.0	141.9	181.9	133.6	146.5	135.7	135.0	0.0	139.3
SD catch CO	161.2	61.1	160.3	59.6	153.2	59.8	153.4	65.0	58.0	62.0	63.0	0.0	59.7
Mean B1+	965.8	1637.3	1537.2	1580.7	1389.2	1596.4	1415.6	1695.3	1540.8	1660.3	1669.4	2204.6	1624.3
SD B1+	711.1	875.2	733.3	880.1	731.6	879.2	735.1	864.0	898.2	875.8	873.1	892.6	879.0
Mean SSB	681.6	1272.8	1165.8	1222.8	1035.5	1236.5	1058.4	1324.6	1187.4	1295.1	1303.1	1829.6	1261.4
SD SSB	534.8	756.1	585.7	759.5	581.2	759.0	584.6	747.5	772.2	759.2	757.1	803.9	759.0
%B1+>400	80.5	99.6	99.8	98.9	98.6	99.2	99.0	99.9	98.3	99.5	99.7	100.0	99.4
%No catch	0.5	0.1	1.0	0.1	0.1	0.1	0.1	0.8	0.1	1.5	1.5	100.0	0.11
%Catch<50	12.8	11.0	17.6	9.1	10.3	9.3	10.7	15.5	7.8	13.3	14.4	100.0	9.63
Median catch	140.7	150.3	127.9	158.9	141.6	156.9	140.2	143.5	165.8	143.0	143.1	0.0	149.76
Median B1+	805.4	1450.4	1387.3	1393.2	1242.4	1409.2	1266.9	1508.4	1348.0	1479.4	1487.8	2048.7	1438.28
Median SSB	553.3	1093.6	1039.4	1043.4	912.0	1056.5	932.8	1146.9	1000.8	1120.9	1128.5	1676.7	1082.71
Mean pop age	2.31	2.75	2.66	2.71	2.56	2.72	2.58	2.78	2.68	2.76	2.77	3.21	2.74
Mean Catch Age	1.48	1.77	1.71	1.75	1.65	1.75	1.66	1.80	1.73	1.78	1.79	NA	1.77
%HCR min	NA	2.90	2.90	26.50	NA	NA	NA	2.90	NA	NA	9.30	NA	NA
%HCR max	NA	46.12	27.23	27.23	NA	NA	NA	27.23	NA	NA	47.33	NA	NA
Mean Yrs HCRmin	NA	1.74	1.74	3.19	NA	NA	NA	1.74	NA	NA	1.23	NA	NA
Mean Yrs HCRmax	NA	4.61	3.23	3.23	NA	NA	NA	3.23	NA	NA	2.30	NA	NA
Mean Yrs NoCatch	63.00	1.16	1.13	1.23	1.24	1.16	1.15	1.13	1.07	1.07	1.07	NA	1.16
% Collapses	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 9. Impact of changing the environmental variable from SIO to ERSST_ann.

Mgmt	Biomass	SIO				ERSST ann					ERSST 3-year average				
year	(July)	SST	Fraction	HG	OFL	ann SST	Fraction	HG	Difference	OFL	3-y SST	Fraction	HG	Difference	OFL
2000	1581346	18.08	0.15	186791	605339	17.96	0.05	62264	-124527	39506	18.87	0.14	178836	-7955	197577
2001	1182465	17.75	0.15	134737	433005	18.76	0.13	114844	-19893	131529	18.57	0.10	91337	-43399	104607
2002	1057599	17.24	0.15	118442	149081	18.57	0.10	80636	-37806	93962	18.43	0.08	66319	-52123	77279
2003	999871	17.31	0.15	110908	165969	18.49	0.09	67125	-43784	78972	18.61	0.11	78843	-32066	92758
2004	1090587	17.46	0.15	122747	246185	19.08	0.15	122747	0	165874	18.71	0.12	99086	-23661	114888
2005	1193515	17.60	0.15	136179	346672	19.06	0.15	136179	0	178857	18.87	0.14	131001	-5178	149831
2006	1061391	18.03	0.15	118937	406300	18.89	0.15	116732	-2205	135944	19.01	0.15	118937	0	152007
2007	1319072	18.11	0.15	152564	504941	18.94	0.15	152564	0	176705	18.97	0.15	152564	0	180985
2008	832706	18.12	0.15	89093	318760	18.54	0.10	57766	-31327	70458	18.79	0.13	78462	-10631	95701
2009	662886	17.83	0.15	66932	253753	18.32	0.07	30881	-36051	39912	18.60	0.11	47004	-19927	60751
2010	702024	17.84	0.15	72039	268735	-	-	-	-	-	-	-	-	-	-
2011	537173	17.90	0.15	50526	205630	-	-	-	-	-	-	-	-	-	-
2012	988385	17.64	0.15	109409	307746	-	-	-	-	-	-	-	-	-	-
2013	659539	17.35	0.15	66495	118854	-	-	-	-	-	-	-	-	-	-

Table 10. Summary statistics for ln(R/S) models when fitting data from 1984-2008 only. Taken from PFMC 2013, Table App.E.6.

Series	AIC	R^2
SST_CC_ann	44.49	0.76
SIO_SST_ann	56.81	0.61
ERSST_ann	55.3	0.63

Table 11. Results of applying each of harvest control rule variants to a model based on the SIO time-series. The variants where the performance measure is within 5% of the best value are shaded in green and those for which the performance measure is within 5% of the poorest value are shaded in red (Variant 21 [no catch] not included in this calculation).

Scenario	**M**	**HG J**	**HG Var3**	**Alt3**	**Alt4**	**New1**	**New2**	**New3**	**New4**	**New5**	**New6**	**New7**	**New8**
Code	**4**	**6**	**9**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
FRACTION (%)	19	5-15*	5-18*	11-18*	18	18	18	5-18*	15*	15**	5-15**	0	15
CUTOFF	0	150	$0.20\overline{B_0}$	50	50	150	150	$0.20\overline{B_0}$	150	150	150	-	150
MAXCAT	-	200	-	200	-	200	-	-	200	200	200	-	200
Performance Measure													
Mean catch all	132.8	87.7	93.8	91.4	105.5	90.8	104.5	80.9	115.6	85.5	84.4	0.0	89.2
SD catch all	118.8	66.8	110.4	67.5	110.7	67.2	109.8	67.4	61.7	68.1	68.7	0.0	66.1
Mean catch CO	134.5	94.0	101.7	97.9	113.0	97.2	111.9	87.6	116.1	98.0	96.7	0.0	95.5
SD catch CO	118.7	64.9	111.6	65.3	110.9	65.1	110.1	66.0	61.4	64.3	65.2	0.0	64.0
Mean B1+	698.9	1277.3	1274.4	1252.8	1202.8	1257.8	1210.5	1315.1	1076.7	1277.0	1284.9	1570.4	1267.5
SD B1+	525.9	594.4	541.7	593.9	538.5	594.5	540.3	592.0	623.7	600.7	599.0	647.9	596.1
Mean SSB	493.3	1005.5	998.4	982.6	931.2	987.2	938.4	1041.2	820.9	1007.0	1014.3	1302.9	996.4
SD SSB	395.3	511.3	446.6	511.4	443.9	511.7	445.3	509.3	527.1	521.7	520.3	582.8	512.9
%B1+>400	67.9	99.6	99.8	99.4	99.3	99.4	99.4	99.8	94.3	99.5	99.6	99.9	99.5
%No catch	1.2	6.8	8.0	6.7	6.7	6.8	6.8	7.9	0.4	13.0	13.0	100.0	6.8
%Catch<50	21.7	38.0	44.9	35.5	36.1	35.7	36.3	44.0	17.7	38.9	40.6	100.0	35.9
Median catch	101.3	71.9	58.7	76.8	74.7	76.0	74.1	60.6	109.2	71.8	69.0	0.0	74.9
Median B1+	580.9	1156.6	1170.6	1132.7	1100.2	1137.6	1107.2	1196.1	937.7	1157.2	1164.6	1456.9	1147.2
Median SSB	399.6	894.0	908.2	871.5	842.2	875.7	848.4	930.4	693.0	893.8	901.1	1191.4	885.0
Mean pop age	2.30	2.85	2.84	2.83	2.77	2.83	2.78	2.89	2.65	2.85	2.86	3.22	2.84
Mean Catch Age	1.47	1.84	1.83	1.82	1.78	1.83	1.79	1.87	1.71	1.84	1.85	NA	1.83
%HCR min	NA	2.19	1.99	2.20	NA	NA	NA	2.00	NA	NA	1.44	NA	NA
%HCR max	NA	28.68	28.68	63.46	NA	NA	NA	28.68	NA	NA	33.24	NA	NA
Mean Yrs HCRmin	NA	19.12	10.65	10.65	NA	NA	NA	10.65	NA	NA	25.32	NA	NA
Mean Yrs HCRmax	NA	3.79	3.79	7.65	NA	NA	NA	3.79	NA	NA	2.03	NA	NA
Mean Yrs NoCatch	NA	3.10	2.53	2.53	NA	NA	NA	2.53	NA	NA	1.77	NA	NA
% Collapses	3	0	0	0	0	0	0	0	0	0	0	0	0

Table 12. Impact of continuing to use SIO as temperature index, but changing the relationship between SIO and E_{MSY}.

Mgmt year	Biomass (July)	SIO - current				SIO - recalculated relationship			
		SST	Fraction	HG	OFL	Fraction	HG	Difference	OFL
2000	1581346	18.08	0.15	186791	605339	0.15	186791	0	229754
2001	1182465	17.75	0.15	134737	433005	0.15	134737	0	164481
2002	1057599	17.24	0.15	118442	149081	0.09	74955	-43487	87343
2003	999871	17.31	0.15	110908	165969	0.10	76481	-34428	89979
2004	1090587	17.46	0.15	122747	246185	0.12	99833	-22914	115754
2005	1193515	17.60	0.15	136179	346672	0.14	127299	-8880	145597
2006	1061391	18.03	0.15	118937	406300	0.15	118937	0	154209
2007	1319072	18.11	0.15	152564	504941	0.15	152564	0	191648
2008	832706	18.12	0.15	89093	318760	0.15	89093	0	120984
2009	662886	17.83	0.15	66932	253753	0.15	66932	0	96311
2010	702024	17.84	0.15	72039	268735	0.15	72039	0	101997
2011	537173	17.90	0.15	50526	205630	0.15	50526	0	78046
2012	988385	17.64	0.15	109409	307746	0.15	106344	-3065	125371
2013	659539	17.35	0.15	66495	118854	-	-	-	-

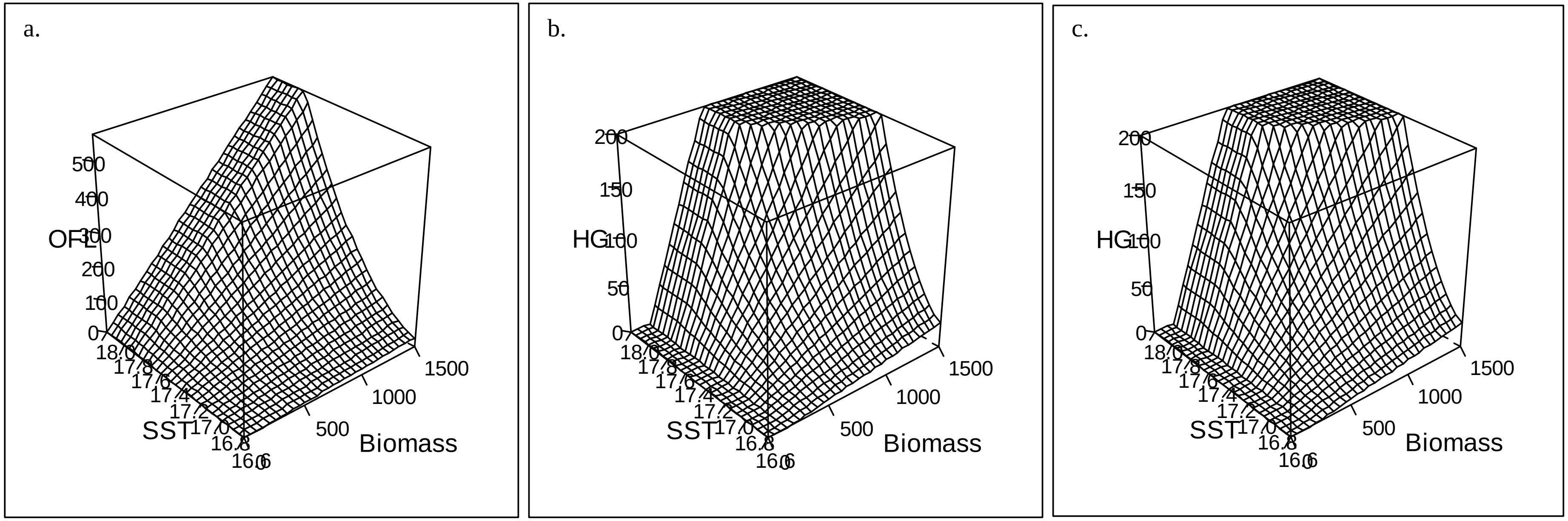

Figure 1. Current OFL control rule (a), HG control rule (b), and HG control rule when the constraint that the HG must be less than the ABC is imposed (c), across a range of 1+ biomass and temperature.

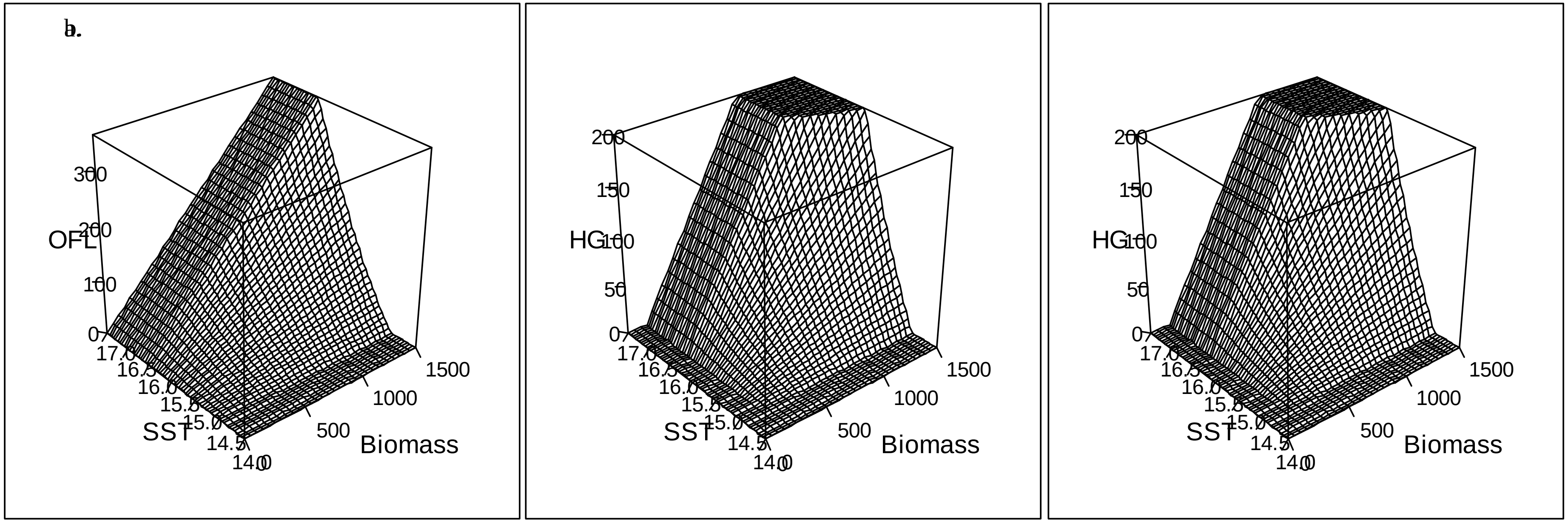

Figure 2. OFL control rule (a), HG control rule (b), and HG control rule when the constraint that the HG must be less than the ABC is imposed (c), across a range of 1+ biomass and temperature when temperature is based on the CalCOFI data.

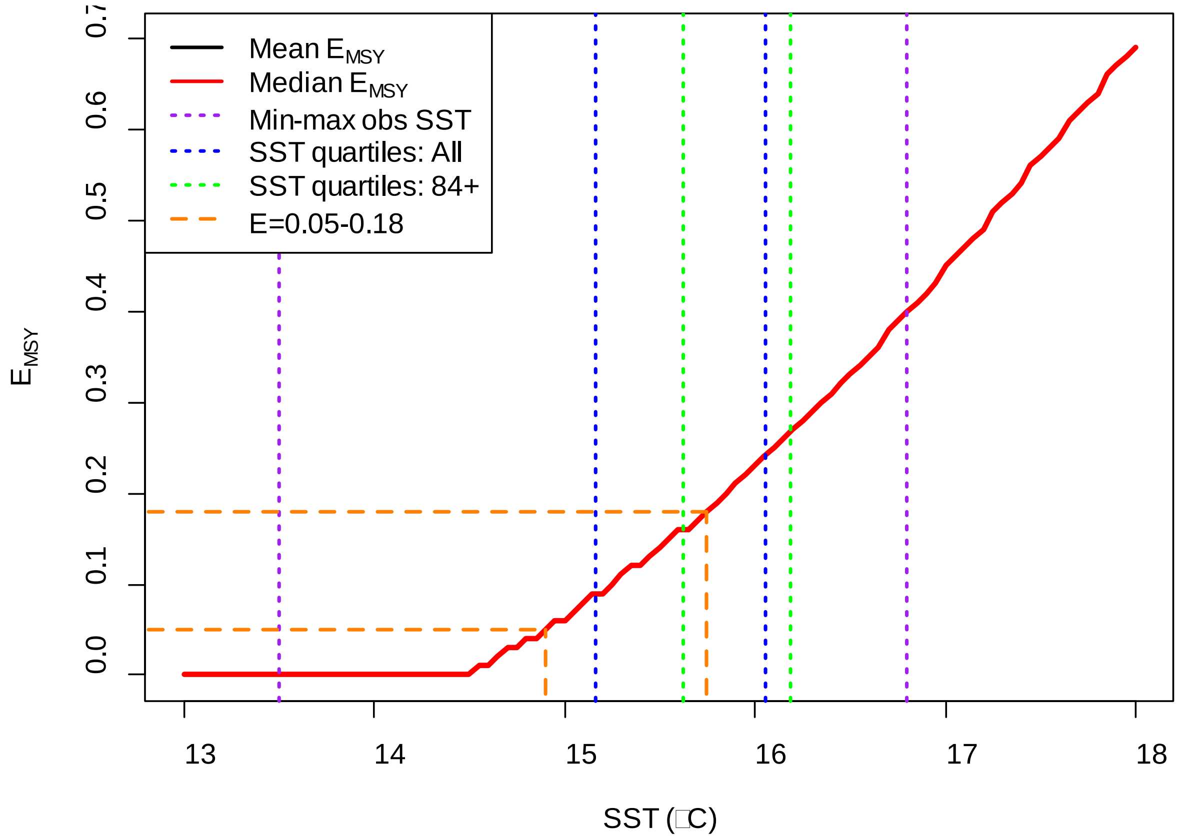

Figure 3. Relationship between CalCOFI SST and E_{MSY}, showing quartiles of observed SST in the SST_CC_ann time series.

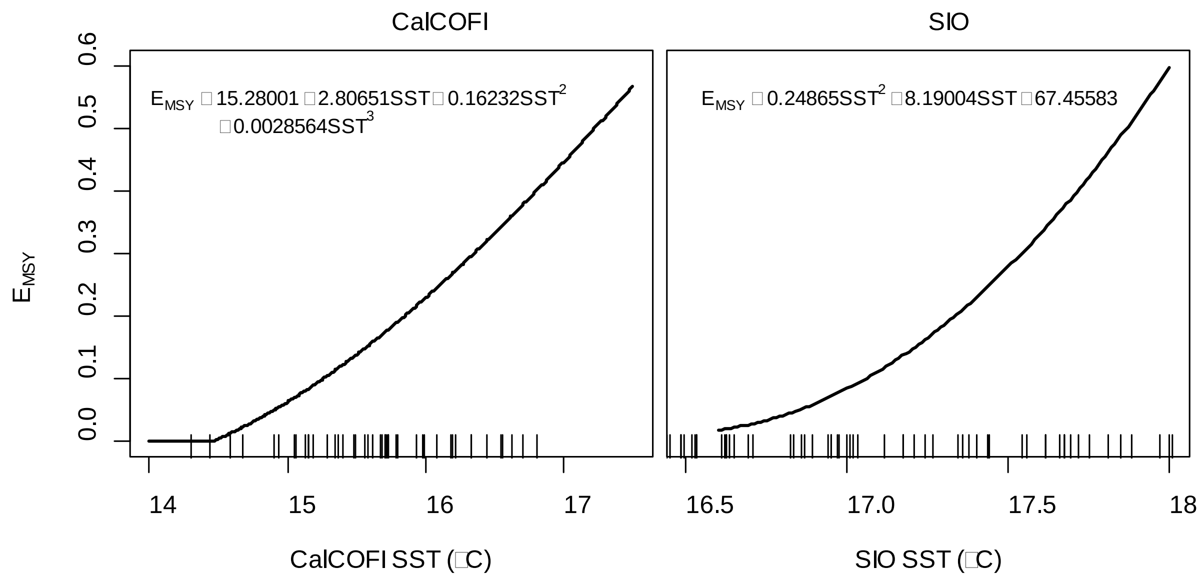

Figure 4. Polynomial approximation to the relationship between CalCOFI SST and E_{MSY} (left), and SIO SST and E_{MSY} (right). Marks at the bottom of each plot represent the spread of each series' SST data. Note that the scale in both plots is different.

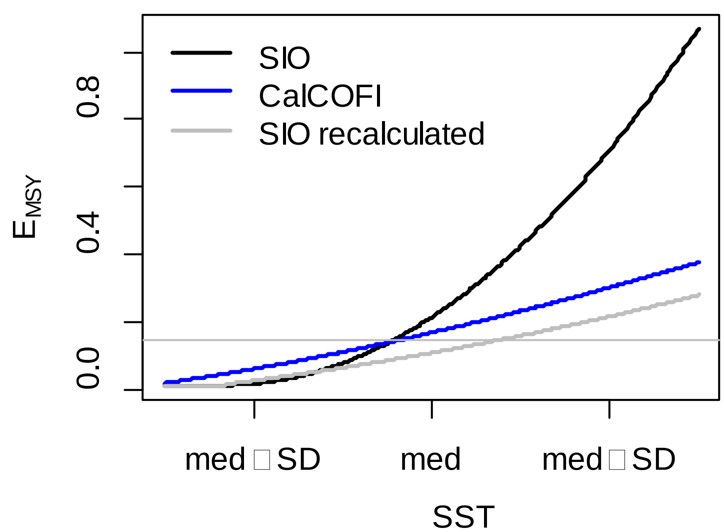

Figure 5. Unitless comparison between the SIO- and CalCOFI-based relationship between SST and E_{MSY}, centered around the median of the observed SST for each time series during the period 1984-2008. The gray horizontal line indicates 0.15.

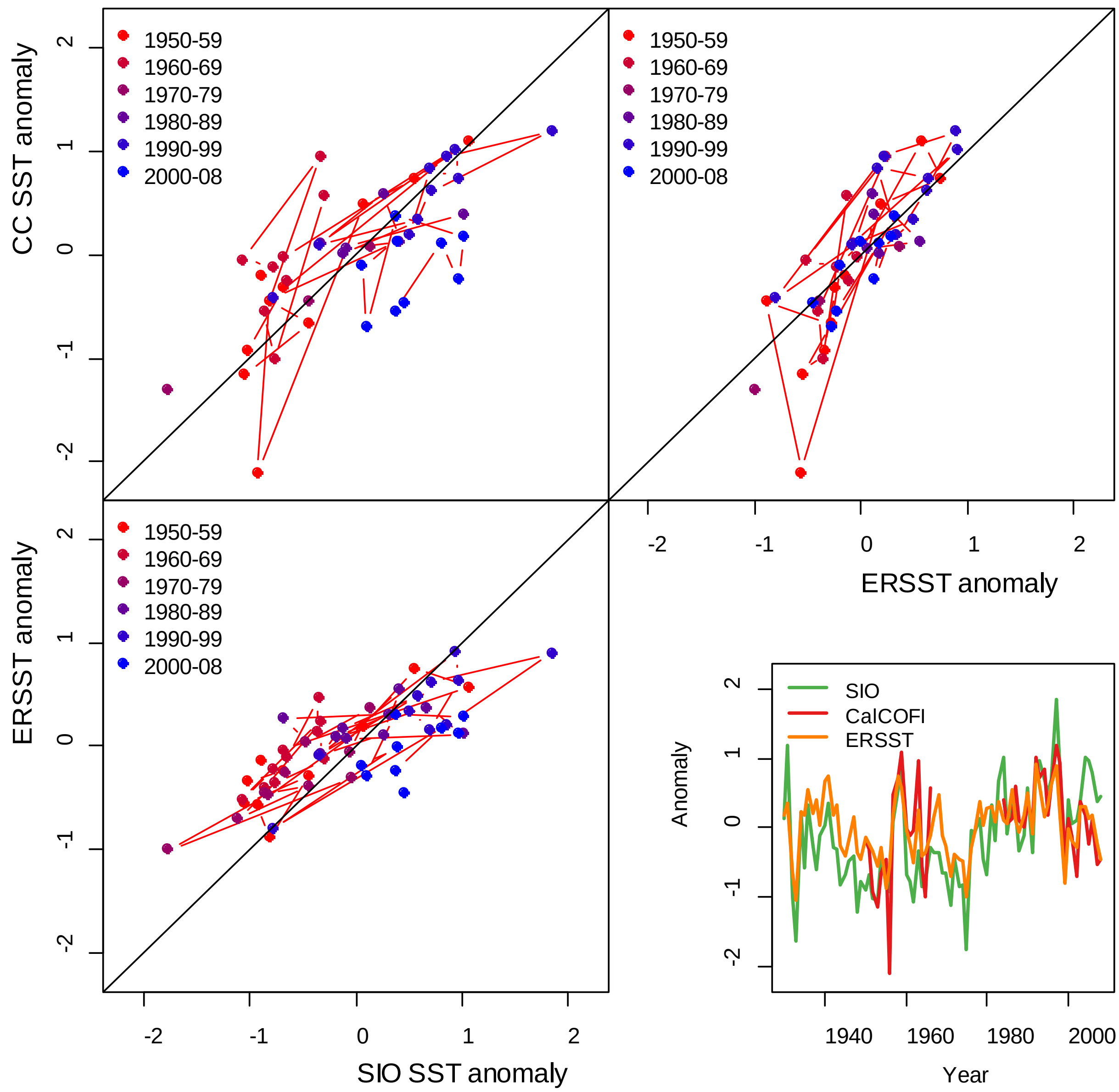

Figure 6. Comparison of the SIO_SST_ann, SST_CC_ann and ERSST_ann time series.

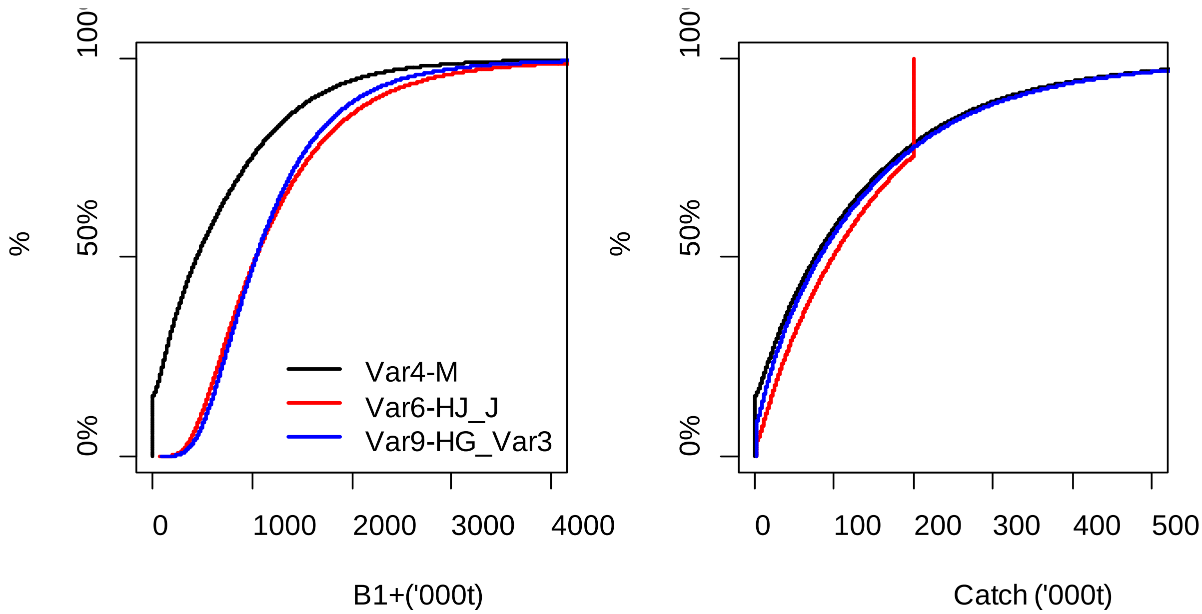

Figure 7. Cumulative distributions for biomass (1+) and catch for three harvest control rule variants.

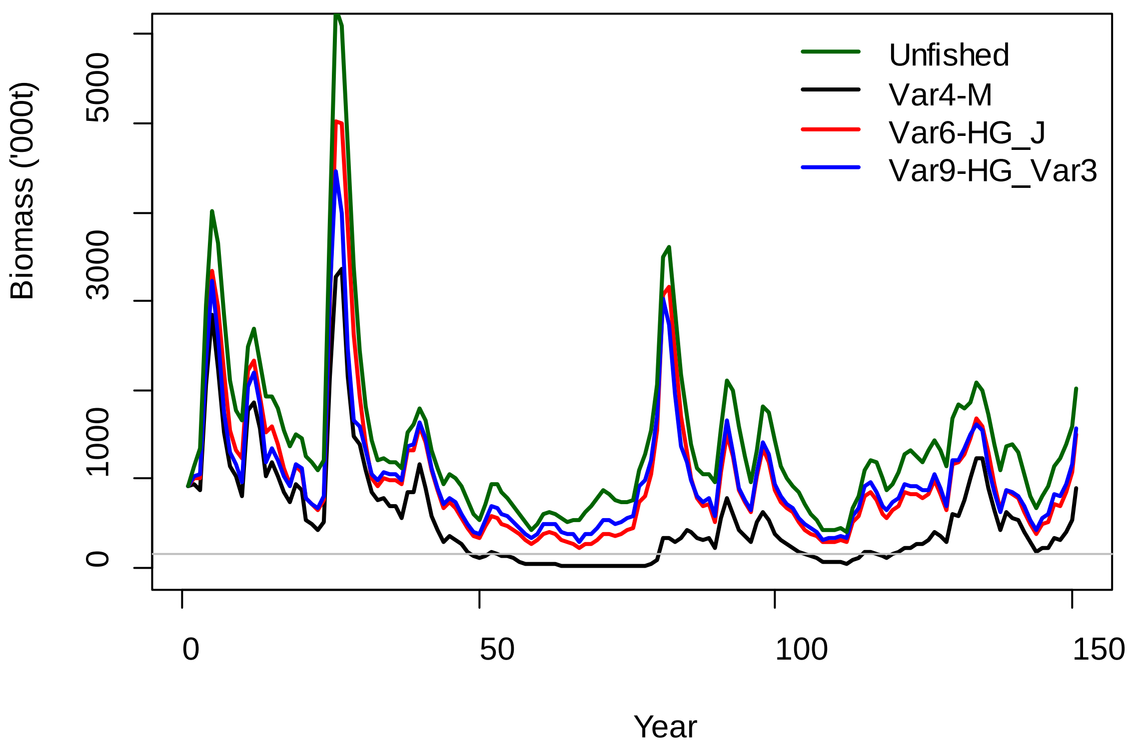

Figure 8. Example 150-year time-trajectories of 1+ biomass for three harvest control rule variants. The horizontal gray line indicates 150,000t.

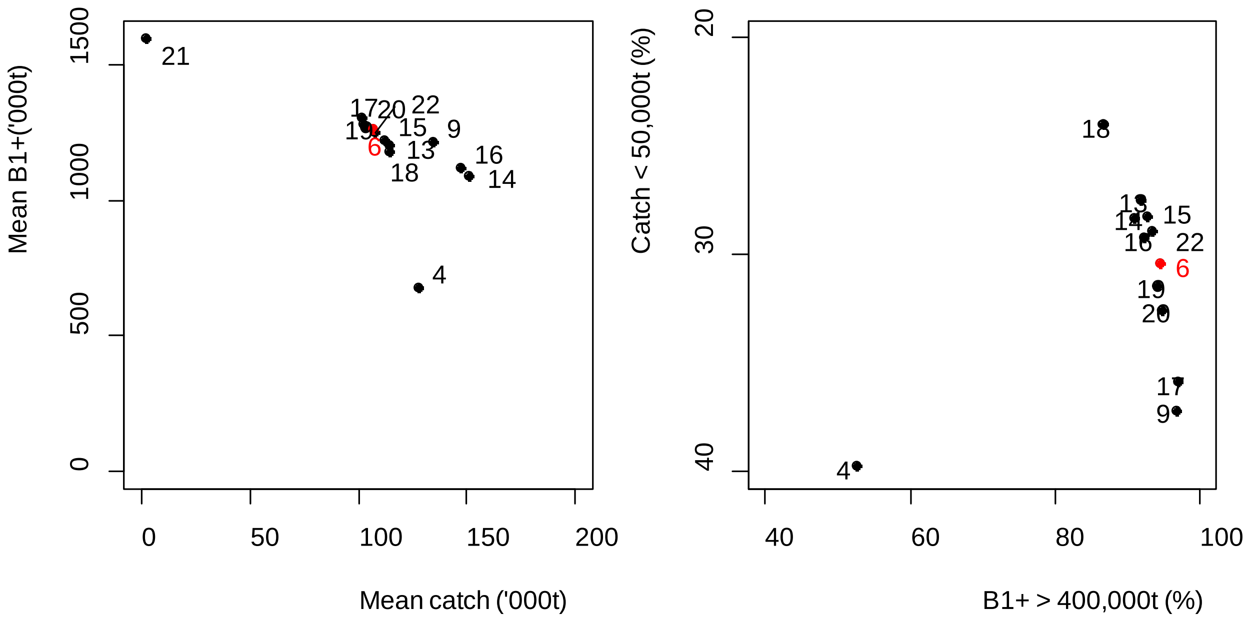

Figure 9. Trade-offs plots (mean annual catch when the catch is non-zero vs 1+ biomass [left]; and the probability of a catch < 50,000t vs. the probability of 1+ biomass exceeding 400,000t [right]) for the base-case scenario. The numbers denote the values used to refer to the harvest control rule variants in Table 1.

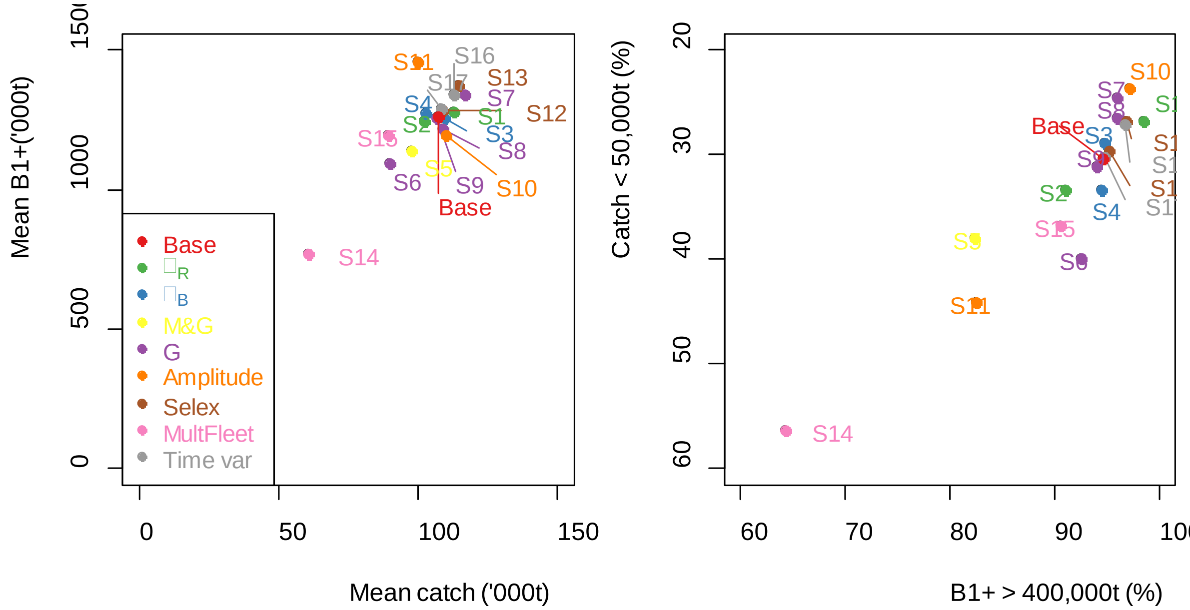

Figure 10. Trade-offs plots (mean annual catch when the catch is non-zero vs 1+ biomass [left]; and the probability of a catch < 50,000t vs. the probability of 1+ biomass exceeding 400,000t [right]) for the various selectivity scenarios. The numbers denote the values used to refer to the sensitivity scenarios in Tables 5 and 6.

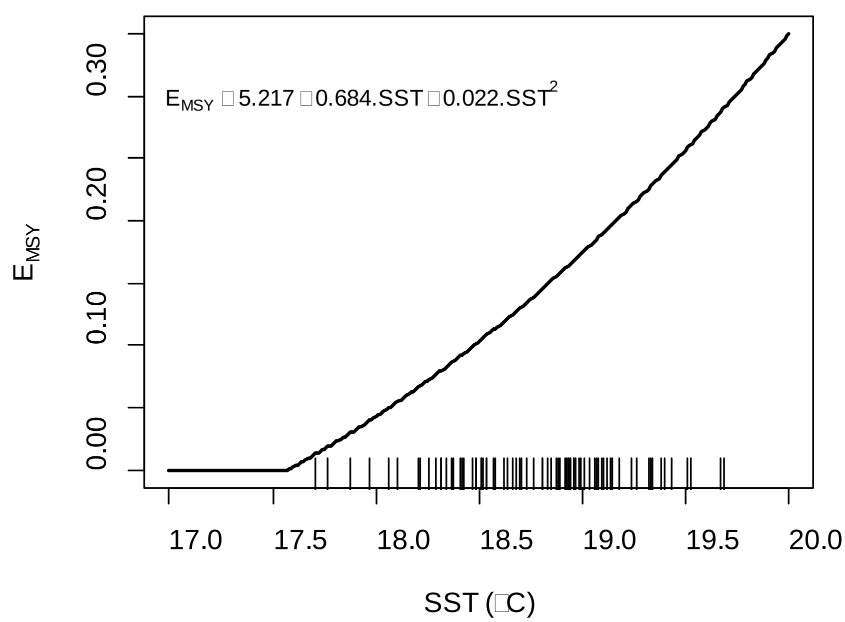

Figure 11. Polynomial approximation to the relationship between ERSST and E_{MSY}. Marks at the bottom of the plot represent the spread of ERSST data.

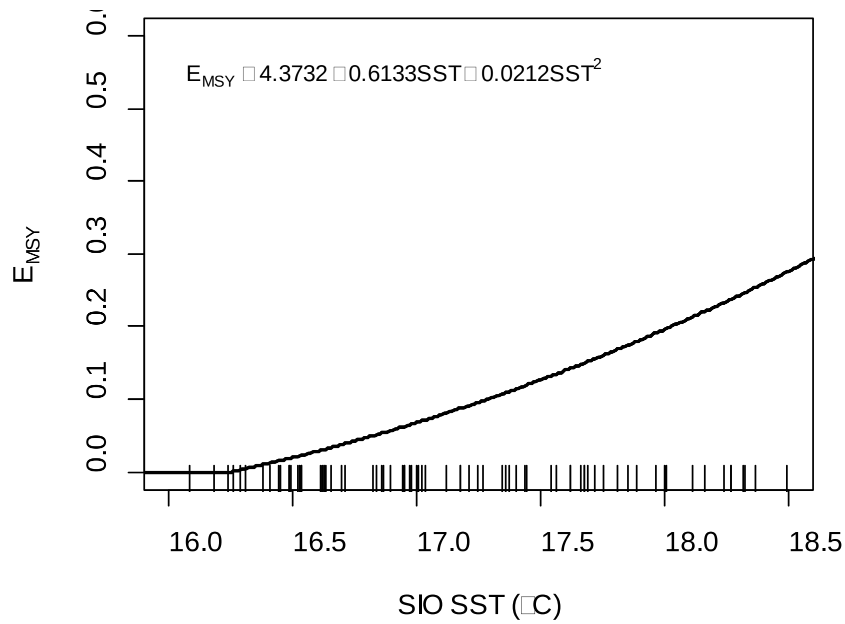

Figure 12. Polynomial approximation to the recalculated relationship between SIO and E_{MSY}. Marks at the bottom of the plot represent the spread of SIO data.

Appendix A. Specifications for Calculations to Evaluate Control Rules for Pacific Sardine

1. Basic dynamics

The operating model is age-structured, and recruitment is related to an environmental covariate (or driven on the assumption that recruitment is cyclic). The basic population dynamics are governed by the equation:

$$N_{y+1,a} = \begin{cases} R_{y+1} & \text{if } a = 0 \\ N_{y,a-1} e^{-M - S_{y,a-1} F_y} & \text{if } 1 \le a < x \\ N_{y,x-1} e^{-M - S_{y,x-1} F_y} + N_{y,x} e^{-M - S_{y,x} F_y} & \text{if } a = x \end{cases} \tag{A.1}$$

where $N_{y,a}$ is the number of animals of age a at the start of year y, M is the rate of natural mortality (assumed to be 0.4yr^{-1} for consistency with the stock assessment[7]), $S_{y,a}$ is the selectivity of the fishery on animals of age a during year y, F_y is the fully-selected fishing mortality during year y, and x is the maximum (plus-group) age.

Several fisheries (e.g. Ensenada, Southern California, Central California, Oregon, Washington, and Canada) operate on Pacific sardine. Rather than trying to model how the catch limit for the Pacific sardine fishery is allocated amongst those fisheries, selectivity-at-age is computed as a fishing mortality-weighted average selectivity from the most recent assessment (Table A.1, row "2011").

Recruitment is governed by a stock-recruitment relationship with deviations which are autocorrelated and subject to a cyclic pattern.

$$R_y = f\left(SSB_y\right) e^{\varepsilon_y - \sigma_R^2/2} \tag{A.2a}$$

$$f\left(SSB_y\right) = SSB_y \exp\left(\alpha + \beta SSB_y + \phi V_y\right) \tag{A.2b}$$

$$\varepsilon_y = \rho_R \varepsilon_{y-1} + \sqrt{1-\rho_R^2}\,\eta_y \tag{A.2c}$$

$$\eta_y \sim N(0;\sigma_R^2); \tag{A.2d}$$

where $f(SSB_y)$ is the stock-recruitment relationship, α and β are the parameters of the stock-recruitment relationship (see Table A.2 for the base-case values for these parameters when the environmental is modelled based on the CalCOFI SST), SSB_y is spawning stock biomass in year y (age 2+ biomass), σ_R^2 is the extent of variation about the stock-recruitment relationship due to unmodelled white-noise processes, ρ_R determines the extent of auto-correlation in the deviations about the stock-recruitment due to white noise processes, ϕ determines the extent of the link to

[7] Sensitivity could be conducted to this assumption in future work, but this requires rerunning the stock assessment and repeating the stock-recruitment analyses.

the environmental variable, and V_y is the value of the environmental variable in future year *y*. V_y is assumed to be cyclic and temporally auto-correlated, i.e.:

$$V_y = \rho_V V_{y-1} + (1-\rho_V)G_y + \sqrt{1-\rho_V^2}\,\nu_y \tag{A.3a}$$

$$G_y = -\psi \frac{\sin(2\pi(y-\bar{y})/p)}{\left|\sin(2\pi(y-\bar{y})/p)\right|} \tag{A.3b}$$

$$\nu_y \sim N\left(0;\sigma_\nu^2\right) \tag{A.3c}$$

where ρ_V is the extent of auto-correlation in the environmental variable, ν_y is the deviation in the environmental variable about its expected value, G_y is the underlying signal in the environmental variable (Figure A.1), ψ is the amplitude of the underlying signal, $\bar{y}$ is a reference year, and *p* is the period of the wave.

The catch during (future) year *y* is determined using the equation:

$$C_y = \sum_{a=0}^{x} \tfrac{w_{y,a+1/2}\, S_{y,a} F_y}{M+S_{y,a}F_y} N_{y,a}(1-e^{-M-S_{y,a}F_y}) \tag{A.4}$$

where $w_{y,a+1/2}$ is weight-at-age in the middle of year *y*. The catch includes age-0 fish even through the HCRs are based on estimates of the biomass of fish of age 1 and older (see below).

The initial numbers-at-age are taken from the 2012 stock assessment (Hill *et al*., 2012; Model X6e), along with the values of the parameters determining fecundity-at-age and weight-at-age (Table A.3, row "1991-2010").

2. Potential control rules

2.1 OFL control rule

One possible OFL control rule is:

$$OFL_y = E_{MSY}\, \hat{B}_y^{1+} \tag{A.5a}$$

where B_y^{1+} is the estimate of 1+ biomass at the start of fishing season, and E_{MSY} is the proxy for F_{MSY}. Given the structure of Equation A.5a, here F_{MSY} is an exploitation rate, E_{MSY}, rather than a fishing mortality. This structure is consistent with the way the current OFL and HG control rules were developed (PFMC 1998), and also avoids the need to generate estimates of the population age-structure at the start of year *y* (the error structure for which could be complicated).

Selection of a value for E_{MSY} in equation A.5a is based on projecting the operating model forward for 20 replicates of 1,000 years for a range of values for E_{MSY} assuming that B_y^{1+} is log-normally distributed about the true 1+ biomass. E_{MSY} is computed for various choices for V_y to allow a relationship between F_{MSY} and V_y to be determined, i.e. :

$$OFL_y = E_{MSY}(I_y)\, \hat{B}_y^{1+} \tag{A.5b}$$

where I_y allows for error in the measuring the "true" value of the environmental variable[8], i.e. E_{MSY} would not be based on V_y but rather an estimate of V_y which is subject to error, i.e.:

$$I_y = V_y + \varsigma_y\,;\ \varsigma_y \sim N(0, \sigma_\varsigma^2) \tag{A.6}$$

where σ_ς determines the extent of measurement error.

2.2 Potential Harvest Guideline control rules

The general form of the harvest guideline (HG) control rule is:

$$HG_y = \text{DISTRIBUTION}\, x\, \text{FRACTION}_y (B_y^{1+} - \text{CUTOFF}) \tag{A.8}$$

where HG_y is the harvest guideline for year *y*, DISTRIBUTION is the proportion of the stock in US waters, FRACTION_y is the proportion of the stock above the cutoff which is taken in all fisheries during year *y*, and CUTOFF is the biomass level below which no directed fishing is permitted. Given that the purpose of this analysis is to analyse stockwide harvest, DISTRIBUTION is set to 1 (except for a small subset of the sensitivity runs). The value of the harvest guideline is constrained to be less than the ABC (the OFL multiplied by a buffer based on a P* of 0.4, which consistent with the way the Council have selected the ABC for the 2012 and 2013 fisheries) and the maximum catch (MAXCAT). FRACTION depends on the environmental variable for some of the harvest control rule variants.

The catch is always assumed to be at least 2,000t to cover catches in the live bait fishery.

3. Performance measures

The performance measures are:

- Average catch (abbreviation "Mean catch") [all years]
- Standard deviation of catch (abbreviation "SD catch") [all years]
- Average catch (abbreviation "Mean catch") [all years for which the catch is non-zero]
- Standard deviation of catch (abbreviation "SD catch") [all years for which the catch is non-zero]
- Mean biomass (SSB and 1+ biomass) (abbreviations "Mean B1+" and "Mean SSB")
- Standard deviation (SSB and 1+ biomass) (abbreviations "SD B1+" and "SD SSB")
- Percentage (1+) biomass > 400,000t (abbreviation "%B1+>400,000t")
- Percentage of years with no catch (or catch below a threshold value) (abbreviations "% No catch" and "%Catch < 50,000t")
- Median catch (abbreviation "Median catch") [all years]
- Median biomass (SSB and 1+ biomass) (abbreviations "Median B1+" and "Median SSB")
- Cumulative distribution for catch
- Cumulative distribution for biomass
- Average number of consecutive years with zero catch (abbreviation "Mean Yrs No Catch")

[8] It is best not to think of SST or any other real-world measurement as being *V*. The real *V* is probably unmeasurable (it may be most related to some property of the flow of the California Current), and the best we can do is to use a proxy for it, such as SST. For that reason there is error associated with the connection between *V* and *I*.

- How often the HCR sets FRACTION to its minimum value (abbreviation "%HCR min")
- How often the HCR sets FRACTION to its maximum value (abbreviation "%HCR max")
- Average number of consecutive years FRACTION equals its minimum value (abbreviation "Mean Yrs HCR min")
- Average number of consecutive years FRACTION equals its maximum value (abbreviation "Mean Yrs HCR max")
- Mean age of the population (abbreviation "Mean Pop Age")
- Mean age of the catch (abbreviation "Mean Catch Age")
- Mean and maximum number of consecutive years in which catch < 50,000t
- Mean and maximum number of consecutive years in which 1+ Biomass < 400,000t.

4. Sensitivity analyses

There are many factors (apart from the parameters of the OFL and HG control rules; Table 1) which could be varied to explore the robustness of candidate control rule variants. Table A.4 lists the factors which define the operating model, along with base-case values for the parameters of the operating model. Table A.5 lists the sensitivity runs which are used to explore the robustness of the results to changes to the specifications of the operating model.

Multiple fleets

For this sensitivity test, the OFL and HG were computed based on a value for DISTRIBUTION of 0.87, the catch by Canada was computed using the Pacific Northwest selectivity pattern and a fully-selected fishing mortality of 0.1y^{-1}, and the catch by Mexico was computed using the MexCal selectivity pattern and a fully-selected fishing mortality of 0.2yr^{-1}, i.e. the fully-selected fishing mortality for the whole fishery was computed as:

$$C_y = \sum_{a=0}^{x} \frac{w_{y,a+1/2} S_{y,a} F_y}{Z_{y,a}} N_{y,a} (1 - e^{-Z_{y,a}}) \qquad \text{(A.9)}$$

where $Z_{y,a} = M + S_{y,a} F_y + S_a^{\text{MexCal}} 0.2 + S_a^{\text{PNW}} 0.1$ and C_y was set to the US harvest guideline.

Time varying selectivity

For this sensitivity test, the age-specific selectivity pattern is:

$$S_{y,a} = J_y S_{y,a}^{\text{MexCal}} + (1 - J_y) S_a^{\text{PNW}} \qquad \text{(A.10a)}$$

where $J_y = \max(0, \min(1, a + bV_y))$ and a and b are selected so that $J_{1985} = 0$ and $J_{2011} / (1 - J_{2011})$ matches the ratio of the fully-selected *F*s for the MexCal area to the PNW. The selectivity-at-age for the MexCal fleet is:

$$S_{y,a}^{\text{MexCal}} = L_y S_a^{\text{MexCal-1}} + (1 - L_y) S_a^{\text{MexCal-2}} \qquad \text{(A.10b)}$$

where $L_y = \max(0, \min(1, c + dV_y))$ and c and d are selected so that $L_{1996} = 1$ and $L_{2006} = 0$. $S_a^{\text{MexCal-1}}$ is the *F*-weighted selectivity-at-age (between seasons) for the MexCal area for 1993-

1999 and $S_a^{\text{MexCal-2}}$ is the *F*-weighted selectivity-at-age (between seasons) for the MexCal area for 2000-2011 (Table A.6).

Time-varying weight-at-age

The weight-at-age for year *y* is:

$$w_{y,a} = Q_y w_a^{1981-1993} + (1-Q_y) w_a^{2000-2011} \tag{A.11}$$

where $Q_y = \max(0, \min(1, e + fV_y))$ and *e* and *f* are selected so that $Q_{1987} = 1$ and $Q_{2006} = 0$. The weight-at-age used when computing 1+ biomass for use in the HCR was set to the average weight-at-age.

Hyper-stability in biomass estimates

Hyper-stability in biomass estimates is modelled by modifying the way $\hat{B}_y^{1+}$ is set in the operating model. In the base-case model, $\hat{B}_y^{1+} = B_y^{1+} e^{\psi}; \psi \sim N(0, \sigma_B)$, which was modified to:

$$\hat{B}_y^{1+} = q_y B_y^{1+} e^{\psi}; \psi \sim N(0, \sigma_B) \tag{A.12a}$$

$$q_y = \max\left(g\left(B_y^{1+}\right)^{-0.5}, 1\right), \tag{A.12b}$$

where *g* is a scaling parameter set at 620, 500, 400, 320 and 210, so that biomass is overestimated when the true 1+ biomass is below 400 000t, 250 000t, 150 000t, 100 000t and 50 000t respectively.

Table App.A.1. Fleet-average selectivity (computed using the output of model X6e of Hill *et al*. [2012]). Results are shown for 2011, 2007-2011, and 2002-2011.

Year Range	Age (yr)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2011	0.263	1.000	1.000	0.669	0.471	0.390	0.358	0.345	0.339	0.335	0.333	0.332	0.332	0.331	0.331	0.331
2007-11	0.245	0.962	1.000	0.713	0.539	0.468	0.440	0.428	0.423	0.420	0.418	0.417	0.417	0.417	0.416	0.416
2002-11	0.218	0.918	1.000	0.741	0.578	0.511	0.485	0.475	0.470	0.467	0.466	0.465	0.464	0.464	0.464	0.464

Table App.A.2. Parameter values for the recruitment model

Parameter	Value
α	-13.788
β	-0.001198
ϕ	1.076

Table App.A.3. Vector of weights-at-age

Year Range	Age (yr)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1981-90	0.014	0.081	0.134	0.160	0.172	0.177	0.179	0.179	0.180	0.180	0.180	0.180	0.180	0.180	0.180	0.180
1991-2010	0.015	0.067	0.130	0.163	0.178	0.184	0.187	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188

Table App.A.4. Values for the specifications on the base-case analyses.

Factor	Base-Case Value	Notes
Recruitment variation, σ_R	0.752	Hill *et al.* (2012)
Auto-correlation in recruitment deviations, ρ_R	0.091	
Assessment SE(log), σ_B	0.36	Ralston *et al.* (2011)
Auto-correlation in assessment error, ρ_B	0.707	
Future correlation between M and V_y	None	
Variance of the measurement error associated with the environmental index, σ_ς	0.374	
Nature of the environmental variable	Square Wave with period of 60 years (equal periods of high and low values)	See Figure App.1a1
Auto-correlation in the environmental variable, ρ_v	0.337	
Variance of the environmental variable about its expectation, σ_v	0.477	
Amplitude of the underlying environmental signal, ψ	0.434	
Scaling parameter, ϕ	1.076	
Center of wave	1975	
Selectivity	Set to average values	
Hyper-stability of biomass estimates	None	

Table App.A.5. Specifications for the sensitivity tests.

Factor (abbreviation)	Specification	Justification / reference
Lower variation in recruitment (**σ_R=0.5**)	$\sigma_R = 0.5$	
Higher variation in recruitment (**σ_R=0.9**)	$\sigma_R = 0.9$	
Lower variation in estimated biomass (**σ_B=0.268**)	$\sigma_B = 0.268$	0.268 is the CV of ending biomass from the 2012 assessment
Higher variation in estimated biomass (**σ_B=0.5**)	$\sigma_B = 0.5$	
Lower auto-correlation in assessment error (**ρ_B=0.5**)	$\rho_B = 0.5$	
Natural mortality increases when the environment is trending downwards **(M&G)**	[M=0.4 yr^{-1} when ΔG>0; M=0.8 yr^{-1} when ΔG<0]	Murphy (1966) suggested that *M* increase while the population as declining
Nature of the environmental variable		
Square wave, with unequal periods of good and poor recruitment **(G=a2)**	Figure App.A.1a2	
Square wave, with equal periods of good and poor recruitment but the environment declines more gradually than for the base case **(G=b)**	Figure App.A.1b	
Sine wave with period of 60 years (equal periods of high and low values **(G=c)**	Figure App.A.1c	
Square wave with period of 100 years (equal periods of high and low values) **(G=d)**	Figure App.A.1d	
The environment fluctuates less than for the base-case **(Amp=0.5)**	ψ =0.217	
The environment fluctuates more than for the base-case **(Amp=2)**	ψ =0.868	
Future selectivity matches that for PNW **(Sel=PNW)**	Table App.A.6	
Future selectivity matches that for Mexico **(Sel=Mex)**	Table App.A.6	
Only the US follows the US control rule **(MF)**	Equation A.9	
Only the US follows the US control rule (catch by Mexico is zero) **(MF=NoMex)**	Equation A.9 but the *F* for Mexico is 0	
Time-varying selectivity **(TV Selex)**	Equation A.10	
Time-varying weight-at-age **(TV WaA)**	Equation A.11	
Hyper-stability in biomass estimates **(HS)**	Equation A.12; *g*=210,320,400,500,620	Five versions of the test depending on the value of *g*
ERSST drives recruitment, but the CalCOFI index is used in the HCR **(ERSST error)**		
Analysis is based on the ERSST time-series **(ERSST)**		

Table App.A.6. Selectivities-at-age for sensitivity analyses (computed using the output of model X6e of Hill *et al*. [2012]).

	Age (yr)															
Pattern	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$S^{MexCal-1}$	0.118	0.793	1	0.749	0.496	0.339	0.254	0.207	0.182	0.166	0.158	0.152	0.149	0.148	0.146	0.145
$S^{MexCal-2}$	0.212	1	0.864	0.444	0.221	0.132	0.097	0.082	0.075	0.07	0.069	0.067	0.066	0.066	0.066	0.064
S^{PNW} (2011)	0.001	0.077	0.377	0.695	0.867	0.94	0.97	0.984	0.991	0.994	0.997	0.998	0.999	0.999	0.999	1
S^{PNW} (2007-11)	0.001	0.077	0.377	0.695	0.867	0.94	0.97	0.984	0.991	0.994	0.997	0.998	0.999	0.999	0.999	1

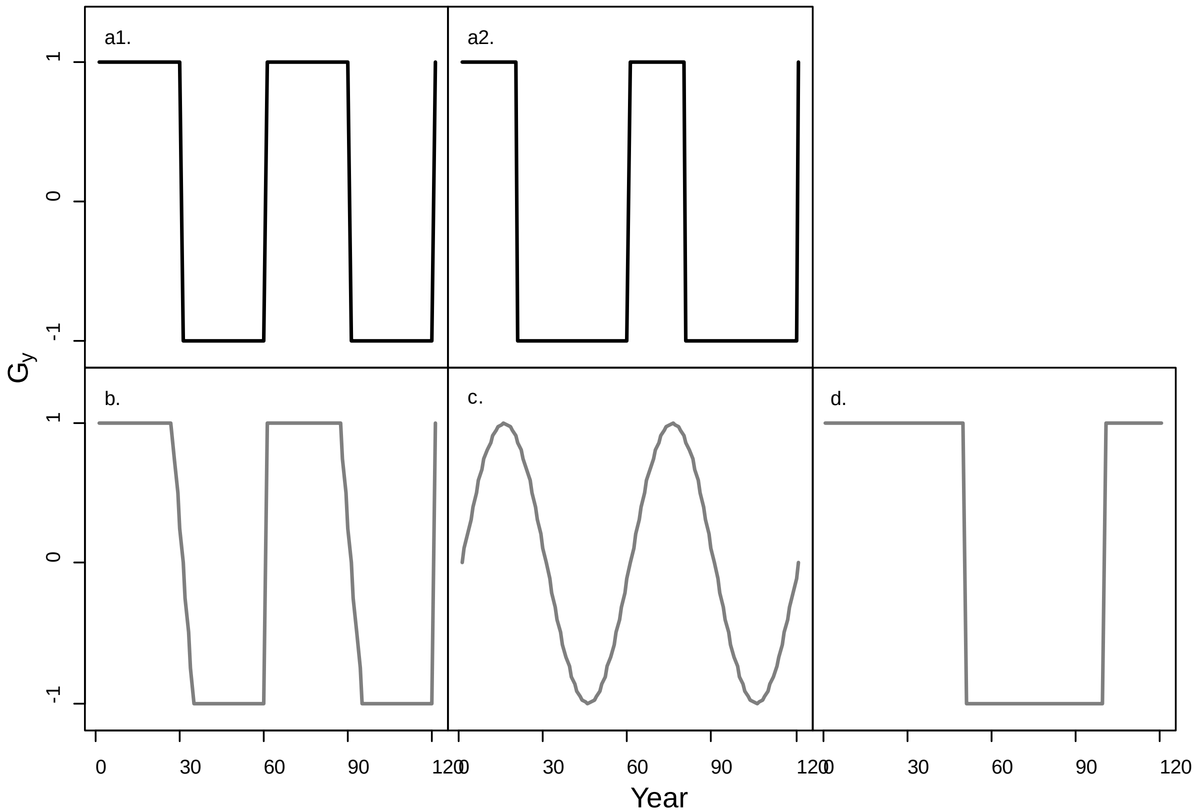

Figure App.A.1. Defined shapes for the environmental signal G_y. a1) is the base case; a2), b), c) and d) are sensitivity tests.

Appendix B. Update to fitting environmental data to the chosen model

The Pacific sardine harvest control rule parameters workshop decided that the values for the parameters of the environmental model in the sardine OM would be estimated by fitting it to the ERSST_ann data, since the ERSST_ann time-series is long and likely more reliable than the SST_CC_ann time series (which was used to fit the stock-recruitment relationship). The methods and parameter estimates are described in Adjunct B of Appendix J of PFMC (2013) for the analyses based on the ERSST_ann time series. However, ERSST_ann was not an ideal choice to model the environmental variable because (1) the biomass cycles observed in projections were not of the desired amplitude, with the lowest simulated biomasses being around 1,000,000 t in the absence of harvest; and (2) the OM unable to reproduce the observed SST data.

The parameters for the environmental variable were re-estimated by applying the methods described in Adjunct B of Appendix J of PFMC (2013) to the SST_CC_ann time series. The estimates of amplitude and σ_V based on the SST_CC_ann data are larger than those based on the ERSST_ann data, while the estimate of ρ_V is smaller. The revised parameter estimates are shown in Table App.B.1, while Table App.B.2 shows the results from the fit to the ERSST_ann data (repeated from Adjunct B for convenience). Figures App.A.1 and App.A.2 show the fits and residuals for the SST_CC_an data.

Using the parameter values in Table App.B.1 improves model performance in terms of the problems described above, but also introduces a new problem: the high value of σ_V. The SST_CC_an temperatures during 1957, 1958, 1959, 1963, and 1995 were high even though these years correspond to the ‘cold period’ (i.e. pre-1975). Three of these years (1957, 1965, and 1966) coincided with El Nino events, and removing these years could lead to an improved OM. The results removing the 3 El Nino outliers are shown in Table App.B.3, and Figures App.B.3 and App.B.4. The results removing all five unusual years are given in Table App.B.4, and Figures App.B.5 and App.B.6.

Table App.B.1. Estimated parameters and AIC for each model fit for SST_CC_ann data.

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.288	0.613	-	5.0
SQ with AC	0.293	0.601	0.214	5.1
Sin	0.340	0.626	-	6.9

Table App.B.2. Estimated parameters and AIC for each model fit for ERSST_ann data.

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.181	0.393	-	-64.4
SQ with AC	0.193	0.364	0.372	-74.6
Sin	0.222	0.404	-	-60

Table App.B.3. Parameters removing the thee El Nino years

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.353	0.582	-	0.500
SQ with AC	0.362	0.564	0.302	-0.312
Sin	0.449	0.592	-	1.959

Table App.B.4. Parameters removing all five unusual years

Model	Amplitude	σ_V	ρ_V	AIC
SQ	0.428	0.494	-	-12.832
SQ with AC	0.434	0.477	0.337	-13.744
Sin	0.592	0.488	-	-13.811

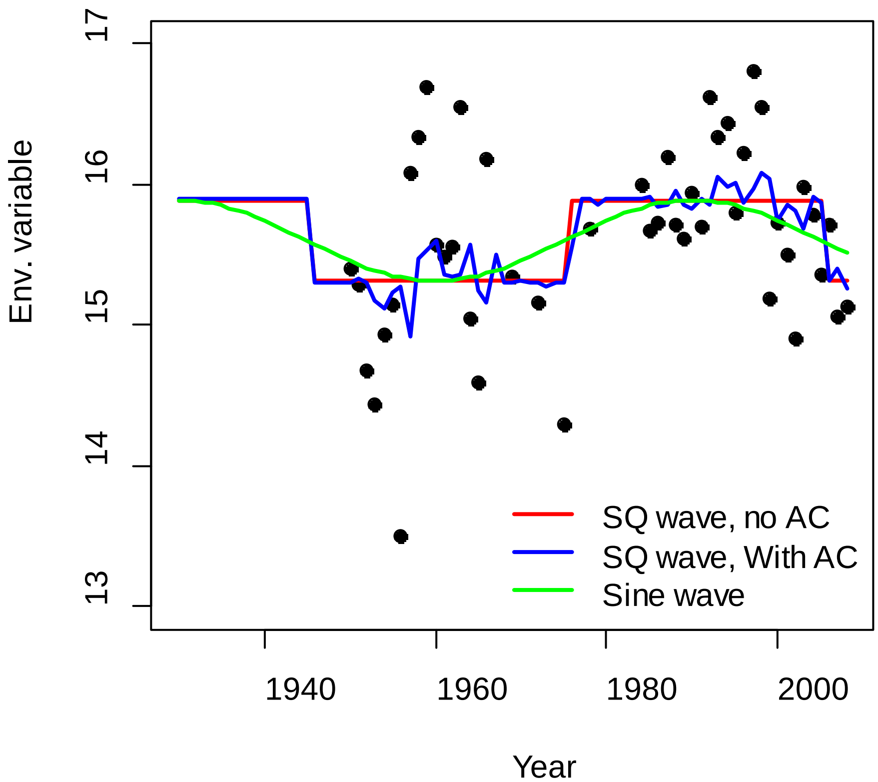

Figure App.B.1. Fits of each model to the SST_CC_ann data

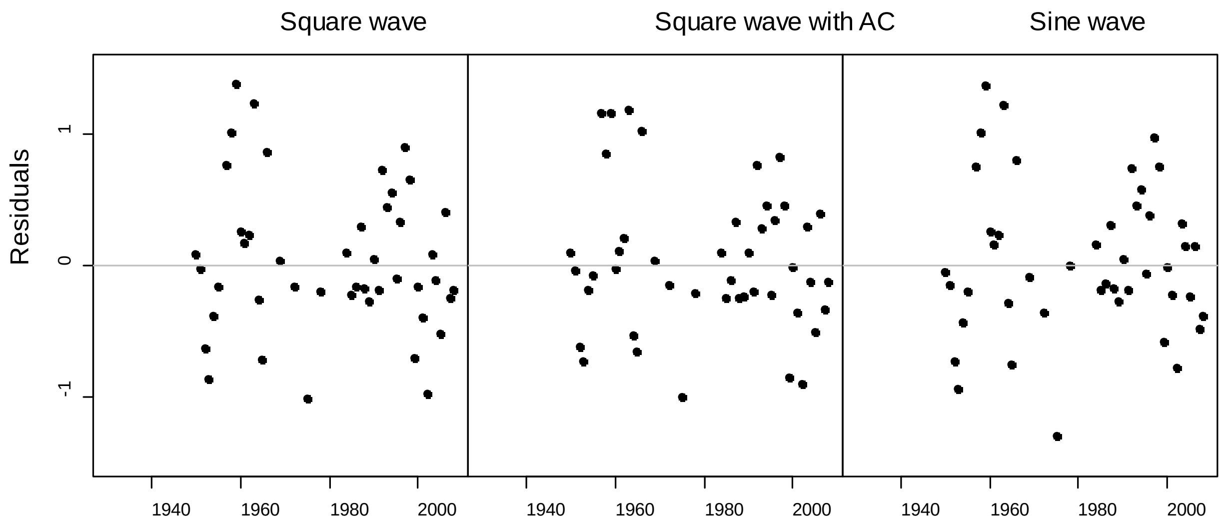

Figure App.B.2. Residual plot for the three models

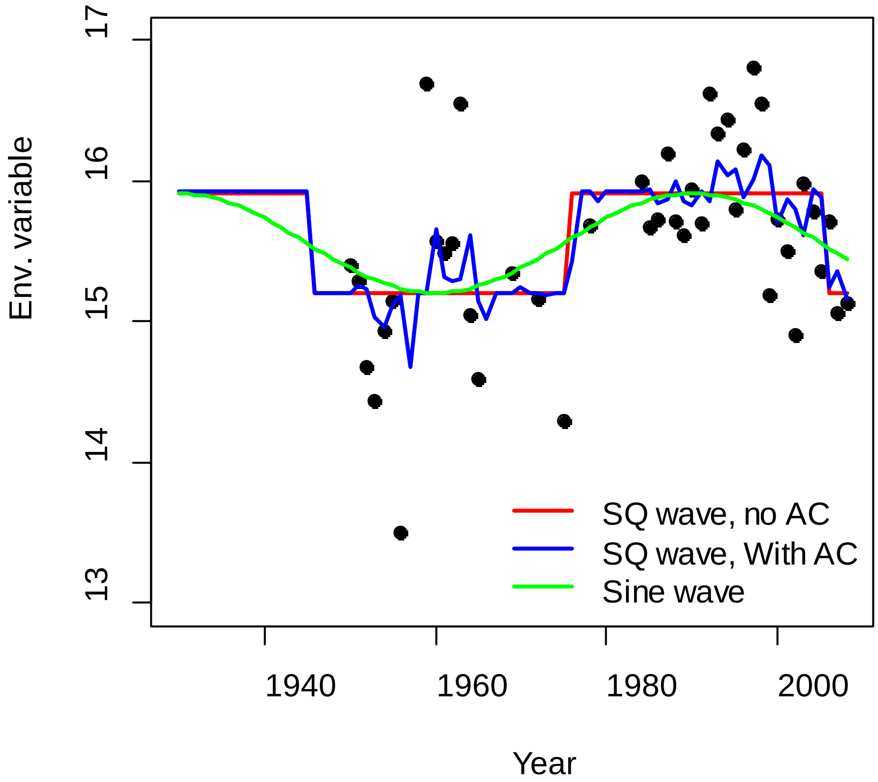

Figure App.B.3. Fits of each model to the SST_CC_ann data removing the three El Nino years

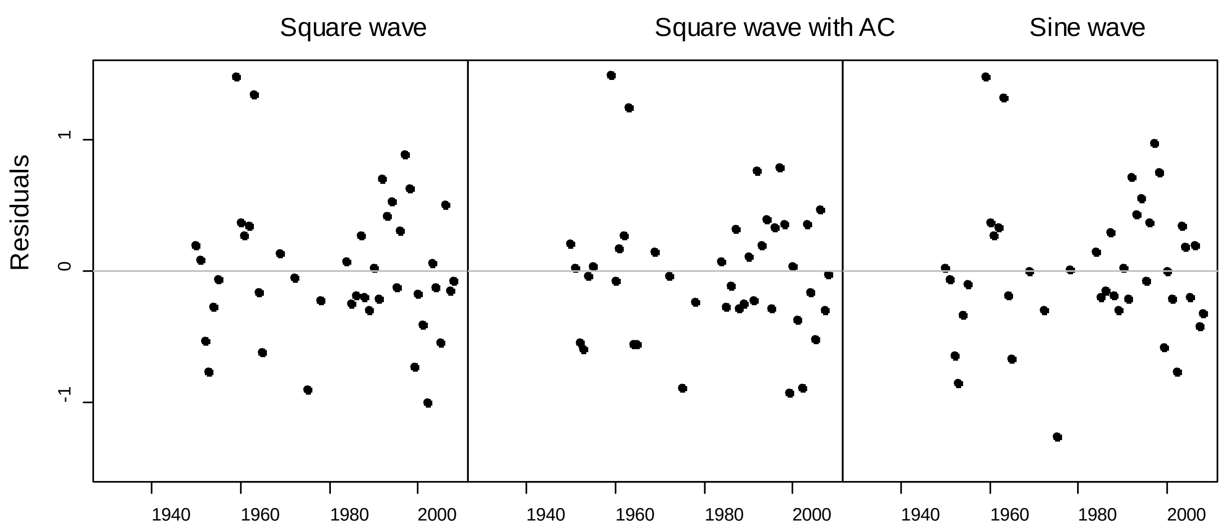

Figure App.B.4. Residual plot for the three models removing the three El Nino years

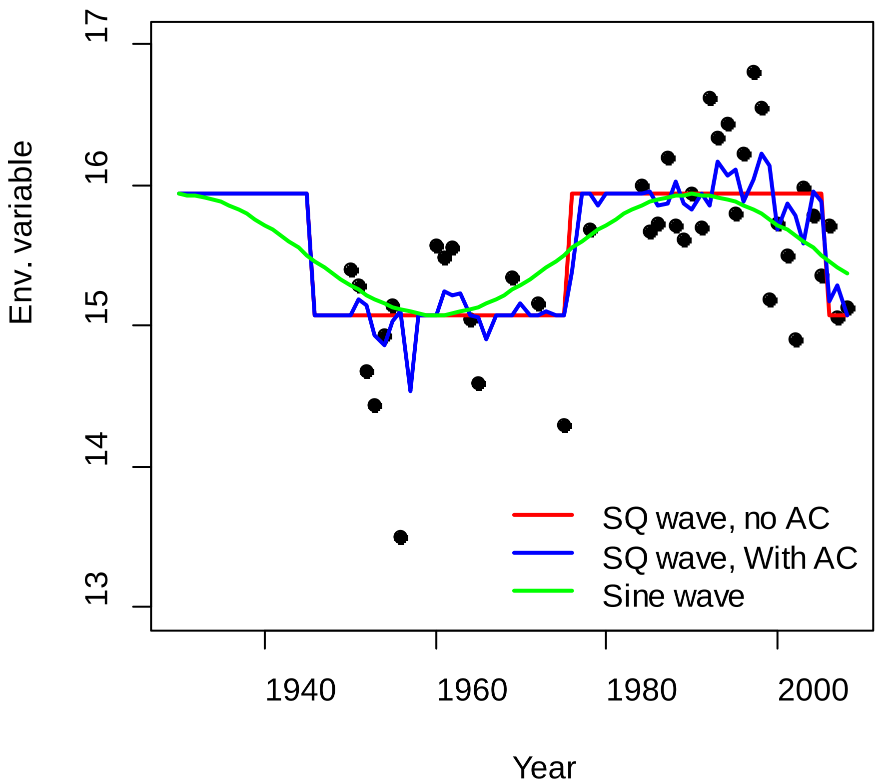

Figure App.B.5. Fits of each model to the SST_CC_ann data removing all five unusual years

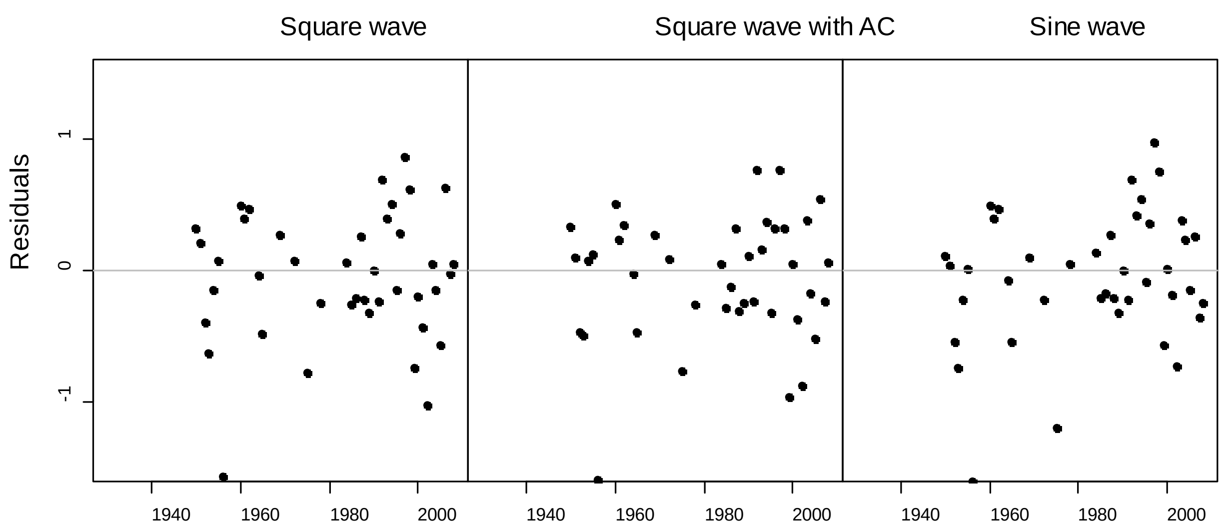

Figure App.B.6. Residual plot for the three models removing all five unusual years