

Cowcod Rebuilding Analysis

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Introduction and background

The status of cowcod (*Sebastes levis*) in the Southern California Bight was first assessed by Butler et al. (1999), who concluded that spawning biomass in 1998 was approximately 7% of the unfished biomass. The stock was declared overfished in 2000 and the first rebuilding plan was adopted under Amendment 16-3 (PFMC, 2004). The stock was assessed again in 2005 (Piner et al., 2006) and the original rebuilding plan parameters were supplanted by the rebuilding analysis of Piner (2006). Subsequent assessments and rebuilding analyses were completed by Dick et al. (2007), Dick and Ralston (2008), Dick et al. (2009) and Dick and Ralston (2009). Rebuilding reference points from previous analyses are provided in Table 1.

Overview of the most recent stock assessment

This rebuilding analysis is based on the assessment by Dick and MacCall (2013). Results are derived from outputs of a Bayesian production model (Extended Depletion-Based Stock Reduction Analysis, XDB-SRA). Estimated parameters in the population dynamics equation include the natural mortality rate (M), the fishing mortality rate achieving long-term MSY relative to M (F_{MSY}/M), biomass associated with MSY in units of unfished biomass (B_{MSY}/B_0), and biomass in year t relative to unfished biomass (B_t/B_0). Major assumptions in the model include stationary population dynamics, a deterministic production function, knife-edged selectivity and maturity (both at 11 years), and spawning output proportional to mature biomass.

Management quantities derived from the 2013 cowcod assessment integrate uncertainty in parameters governing the dynamics of population biomass (listed above), as well as ‘nuisance’ parameters for the abundance indices such as catchability coefficients and additive variance parameters. Alternative states of nature used in the decision table are therefore based on percentiles (12.5%, 50%, and 87.5%) of the marginal posterior distribution for biomass in 2013.

The median estimate of spawning biomass (SB) in 2013, as a percentage of unfished SB (“depletion”), was 34%, with 5th and 95th percentiles of 15% and 66%, respectively. Medians and 95% credible intervals for depletion and other management quantities are provided in Table 2.

Management performance under rebuilding

Estimates of total cowcod mortality have not exceeded the ACL (or OY) in any year since 2003 (Table 3). Estimated annual catch of cowcod south of Point Conception has been <1 metric ton since 2003 (Dick and MacCall, 2013), however, mortality estimates for this species are highly uncertain due to infrequent encounters. $T_{REBUILD}$ is 2020 under the current SPR harvest rate ($F_{82.7\%}$, based on the 2009 assessment). This SPR harvest rate is equivalent to an exploitation rate (catch over age 11+ biomass) of 0.007 based on the 2009 assessment. The estimate of $T_{REBUILD}$ under the current harvest rate is 48 years earlier than the current estimate of T_{TARGET} (2068). Reasons for the change in rebuilding times are described in detail by Dick and MacCall (2013).

Simulation model and rebuilding calculations

The XDB-SRA model tracks biomass dynamics, and therefore does not explicitly track age-specific quantities. Fishing mortality is modeled as a single fleet in the assessment and in rebuilding projections.

Mean generation time

Mean generation time for cowcod is estimated from the net maternity function (external to the model) and is 38 years. This is the same estimate for mean generation time as in the 2009 rebuilding analyses (see Table 4 for relevant age-specific quantities).

Estimation of virgin biomass (B_0)

The base model for the 2013 cowcod stock assessment uses a generalized production function (details in Dick and MacCall, 2011), parameterized in terms of the annual rate of natural mortality (M), the ratios F_{MSY}/M and B_{MSY}/B_0 , and stock depletion (Δ) in the year 2000. Given a draw from the joint prior distribution, and a time series of removals since the beginning of the fishery, an estimate of total (male + female) unfished vulnerable biomass is obtained by numerical solution. Draws from the joint posterior distribution are simulated by resampling from the prior distributions with weights proportional to the likelihood for the abundance indices (i.e. sampling importance resampling, SIR). Nominal unfished female spawning biomass (B_0) is reported as half the total vulnerable biomass, assuming a 1:1 sex ratio, knife-edge selectivity at age of maturity (11 years), and similar growth for males and females. The posterior median of unfished female spawning biomass is 1549 mt. A summary of rebuilding reference points for this analysis is provided in Table 5.

Simulation of future recruitments and treatment of uncertainty

In each rebuilding model run, simulated future trajectories were generated using 15000 SIR draws from the joint posterior distribution. Similar to the previous cowcod rebuilding analysis, variability in future recruitment is expressed as a weighted set of different states of nature (parameter values), rather than random deviations from an average stock-recruitment relationship. While the previous rebuilding analysis accounted only for uncertainty in the steepness parameter of the Beverton-Holt stock-recruitment relationship, the current analysis accounts for uncertainty in all estimated model parameters.

Description of model runs

Model runs presented in this document follow the PFMC's Terms of Reference for the Groundfish Rebuilding Analysis (TOR) (PFMC, September 2012). All runs are based on output produced by the 2013 base model (Dick and MacCall, 2013). Rebuilding run numbers correspond to the list of requested runs in the TOR (PFMC, September 2012, pg. 8). In all models, the catches for 2013 and 2014 were set to the ACL for cowcod in the assessed area (1.5 mt for the region south of Point Conception).

This report includes the following set of requested harvest policies for analysis:

- 1) eliminate all harvest beginning in the next management cycle (i.e., estimate $T_{F=0}$),
- 2) apply the harvest rate that would generate the ACL specified for the current year (i.e., the latest year specified in regulations),
- 3) apply the spawning potential ratio or relevant harvest control rule in the current rebuilding plan,

- 4) apply the harvest rate that is estimated to lead to a 50% probability of recovery by the current T_{TARGET} ,
- 5) apply the harvest rate that is estimated to lead to a 50% probability of recovery by the T_{MAX} from the current cycle,
- 6) apply the harvest rate that is estimated to lead to a 50% probability of recovery by the T_{MAX} from the previous cycle,
- 7) apply the default (e.g. 40-10 or 25-5) harvest policy, and
- 8) apply the ABC harvest rate (i.e., F_{MSY} less the uncertainty buffer).
- 9) apply the OFL harvest rate (F_{MSY} proxy).
- 10-23) apply harvest rates generating 0.5 mt increments of catch in 2015, ranging from 1.5 mt to 8 mt, for the Southern California assessment. Following the past convention of doubling the Southern CA ACL, this becomes a range of ACLs from 3 mt to 16 mt for the combined Monterey/Conception areas.
- 24-27) apply the harvest rates that are estimated to lead to a 50% probability of recovery by 2022, 2025, 2030, and 2035

Methods

Rebuilding projections are based on 15000 posterior draws from the Bayesian production model (XDB-SRA). In this way, parameter uncertainty is accounted for but recruitment is deterministic for each individual trajectory. When projecting forward using fixed catches, if biomass fell below zero for any trajectory all subsequent biomass values for that trajectory were set equal to zero. Removals in 2013 and 2014 were set to 1.5 mt for all runs. ABC estimates for 2016 were calculated only for the PFMC's preliminary preferred alternative (run 3) and an assumed ABC catch in 2015 (run 8).

Run 1

Catches from 2015-2100 were set equal to zero and all trajectories projected through 2100.

Run 2

A catch of 1.5 mt in 2015 was applied to all posterior trajectories (parameter vectors). The resulting distribution of harvest rates in 2015 was held constant and projected forward. Median catches from the projection were then treated as fixed catches in a follow-up projection to produce the final results from this run.

Run 3

Results from the 2009 rebuilding analysis were used to determine the harvest rate (0.007; catch divided by age 11+ biomass) associated with the SPR target specified in the previous rebuilding analysis (82.7%). All trajectories were projected forward using a constant 0.007 harvest rate, followed by a 'fixed catch' run using median catches from the initial projection.

Run 4

A numerical search routine was used to identify a median harvest rate which lead to a 50% probability of recovery in 2068. Each iteration of the search required two projections. The first applied a trial catch value in 2015 to each trajectory and projected forward using the distribution of implied harvest rates. A second run was conducted based on fixed catches set equal to the median catch from the first run. The trial value of catch from the first projection was adjusted until the probability of rebuilding in 2068 was 50% based on the fixed-catch projection.

Run 5

A new T_{MIN} was calculated by setting catch to zero beginning in 2000 (the first year the ACL could have been set to zero) and projecting the model forward until 50% of the posterior trajectories equaled or exceeded $0.4 \cdot B_0$ (determined for each trajectory separately). T_{MIN} is 2019. A new T_{MAX} was then calculated by adding 38 years to the new T_{MIN} , giving 2057.

A numerical search routine was used to identify a median harvest rate which lead to a 50% probability of recovery in 2057. Each iteration of the search required two projections. The first applied a trial catch value in 2015 to each trajectory and projected forward using the distribution of implied harvest rates. A second run was conducted based on fixed catches set equal to the median catch from the first run. The trial value of catch from the first projection was adjusted until the probability of rebuilding in 2057 was 50% based on the fixed-catch projection.

Run 6

A numerical search routine was used to identify a median harvest rate which lead to a 50% probability of recovery in 2097. Each iteration of the search required two projections. The first applied a trial catch value in 2015 to each trajectory and projected forward using the distribution of implied harvest rates. A second run was conducted based on fixed catches set equal to the median catch from the first run. The trial value of catch from the first projection was adjusted until the probability of rebuilding in 2097 was 50% for the fixed-catch projection.

Run 7

Projections using the PFMC ACL control rule (40-10) were calculated starting from ABC catches (proxy $B_{40\%} F_{\text{MSY}}$, with a 16.7% buffer based on $\sigma=0.72$ and $P^*=0.4$). Catch for each trajectory was proportionally reduced from 100% of the ABC for biomasses between 40% and 10% of unfished biomass. Catch from biomasses above 40% of B_0 equaled the ABC, and catch below 10% was set equal to zero. Median catches from this first set of projections were then applied as fixed catches to each trajectory in a second projection. The results of the second (fixed catch) run are reported here.

Run 8

Projections based on the ABC were calculated for each parameter vector, based on proxy ($B_{40\%}$) F_{MSY} and a 16.7% reduction (buffer based on $\sigma=0.72$ and $P^*=0.4$). The median catches from this first set of projections were then applied as fixed catches to each trajectory in a second run. The results of the second (fixed catch) run are reported in Table 5.

Run 9

Projections based on the OFL were calculated for each parameter vector, based on proxy ($B_{40\%}$) F_{MSY} . The median catches from this first set of projections were then applied as fixed catches to each trajectory in a second run. The results of the second (fixed catch) run are reported in Table 5.

Runs 10-23

An approach similar to Run 2 (which is repeated as Run 10 for convenience) was used to estimate catches based on 2015 catches between 1.5 mt to 8 mt. Each run required two projections, the first of which estimated a stream of median catches, followed by a projection treating the median catches as fixed.

Runs 24-27

Similar to Run 4, a numerical search routine was used to identify the median harvest rates which led to a 50% probability of recovery in 2022, 2025, 2030 and 2035.

Results

Management quantities associated with the runs described above are provided in tabular form, as follows:

Run Number(s)	Table Numbers
1 – 9	6, 7
10 – 16	8, 9
17 – 23	10, 11
24 – 27	12, 13

Literature cited

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Table 1. Parameters from previous cowcod rebuilding analyses. A decision on T_{TARGET} has been deferred until the PFMC's June 2014 meeting.

Rebuilding Parameter	Date of Analysis				
	2004	2006	2008	2009	2013
B_0 [female spawning biomass, mt]	1684	1523	2488	2183	1549
B_{MSY} [mt]	675	609	995	873	620
T_{MIN}	2062	2035	2060	2059	2019
T_{MAX}	2099	2074	2098	2097	2057
$T_{F=0}$	2062	2035	2061	2060	2019
P_{MAX}	60%	90.6%	66.2%	66.2%	88.4%
T_{TARGET}	2090	2039	2072	2068	TBD
Harvest Control Rule ($F_{\%SPR}$)	$F_{78\%}$	$F_{90\%}$	$F_{79\%}$	$F_{82.7\%}$	--
Harvest Control Rule (catch / 11+ biomass)	*	*	*	0.007	0.007

* not reported

Table 2. Percentiles of posterior distributions for management quantities from the 2013 cowcod assessment (Dick and MacCall, 2013). Quantities related to MSY are based on a proxy ($B_{40\%}$) harvest rate. OFL and ABC distributions for 2015 assume an annual total mortality of 1.5 mt in 2013-14. ABC is OFL reduced by 16.7%. The OFL and ABC in 2016 are not reported, as these depend on actual catch in 2015.

Quantity	Percentile		
	2.5%	50%	97.5%
Depletion ($B_{2013} / B_{unfished}$)	0.150	0.339	0.656
Vulnerable biomass (mt) in 2013	546	1049	1848
Spawning biomass (mt) in 2013	273	524	924
2013 spawning biomass / B_{MSY} proxy ($B_{40\%}$)	0.376	0.849	1.640
Overfishing Limit (OFL) in 2015 (mt)	10.5	55.0	169.5
Acceptable Biological Catch (ABC) in 2015 (mt)	8.8	45.8	141.2
40-10 Control Rule Catch in 2015 (mt)	8.5	44.1	136.0
Proxy ($B_{40\%}$) MSY exploitation rate	0.012	0.050	0.113

Table 3. Total mortality (mt) of cowcod by year and area. Commercial mortality estimates (retained + discarded catch) are from the West Coast Groundfish Observer Program and recreational estimates are from RecFIN (weight of catch types A and B1).

YEAR	COMMERCIAL		RECREATIONAL		TOTAL	OFL	ABC	OY (ACL)
	North of 34° 27'	South of 34° 27'	North of 34° 27'	South of 34° 27'				
2003	0.22	0.00	--	0.48	0.70	--	24	4.8
2004	0.54	0.41	--	0.45	1.40	--	24	4.8
2005	1.15	0.00	--	0.15	1.30	--	24	4.2
2006	2.20	0.00	--	0.07	2.27	--	24	4.2
2007	1.93	0.10	0.19	0.11	2.33	--	36	4
2008	0.48	0.00	--	0.25	0.73	--	36	4
2009	1.45	0.00	--	0.21	1.66	--	13	4
2010	1.00	0.00	0.02	0.17	1.20	--	14	4
2011	0.02	0.00	--	0.83	0.85	13.00	8	(3)
2012	0.00	0.00	0.02	0.82	0.84	13.00	8	(3)
Grand Total	9.00	0.51	0.23	3.53	13.28			

Table 4. Age-specific quantities from the 2009 rebuilding analysis (natural mortality and age-specific fecundity used in calculation of mean generation time).

Age	Fecundity	Females		Fleet 1		Fleet 2		
		M	Init N	Init N Tmin	Weight	Selectivity	Weight	Selectivity
0	0	0.055	21.14480	12.12700	0	0	0	0
1	0	0.055	19.08350	10.92020	0	0	0.00021	0.002
2	0	0.055	17.17440	9.50210	0	0.00005	0.00227	0.009
3	0.00009	0.055	15.40280	8.50067	0.000	0.00059	0.01471	0.038
4	0.00126	0.055	13.75680	8.75935	0.004	0.00427	0.05404	0.105
5	0.00874	0.055	12.22690	8.39472	0.019	0.01840	0.13398	0.214
6	0.03501	0.055	10.80600	8.51984	0.060	0.05302	0.25695	0.349
7	0.09615	0.055	9.48871	7.57525	0.144	0.11464	0.41630	0.489
8	0.20397	0.055	8.27006	7.03875	0.277	0.20253	0.60222	0.618
9	0.36160	0.055	7.37078	5.94612	0.458	0.30968	0.80567	0.726
10	0.56415	0.055	6.62725	4.93306	0.679	0.42609	1.01990	0.812
11	0.80184	0.055	5.75479	4.06880	0.930	0.54175	1.24047	0.876
12	1.06323	0.055	5.13225	4.77038	1.199	0.64862	1.46472	0.921
13	1.33757	0.055	5.26342	5.01929	1.477	0.74137	1.69123	0.952
14	1.61611	0.055	5.01240	6.10020	1.755	0.81741	1.91931	0.972
15	1.89259	0.055	5.04995	6.46118	2.029	0.87650	2.14856	0.984
16	2.16318	0.055	4.45653	5.85213	2.296	0.92006	2.37873	0.991
17	2.42614	0.055	4.11206	4.50618	2.555	0.95053	2.60949	0.995
18	2.68117	0.055	3.45271	3.70317	2.806	0.97075	2.84044	0.997
19	2.92888	0.055	2.85021	2.68034	3.050	0.98348	3.07109	0.999
20	3.17027	0.055	2.34170	1.83116	3.289	0.99107	3.30088	0.999
21	3.40632	0.055	2.73746	1.18960	3.523	0.99537	3.52922	1
22	3.63780	0.055	2.87422	0.71499	3.752	0.99768	3.75554	1
23	3.86519	0.055	3.48807	0.40520	3.977	0.99887	3.97926	1
24	4.08867	0.055	3.69086	0.21926	4.199	0.99946	4.19989	1
25	4.30823	0.055	3.34083	0.11517	4.416	0.99974	4.41697	1
26	4.52370	0.055	2.57145	0.06016	4.63	0.99988	4.63008	1
27	4.73487	0.055	2.11272	0.03201	4.839	0.99994	4.83888	1
28	4.94148	0.055	1.52897	0.01774	5.043	0.99997	5.04307	1
29	5.14331	0.055	1.04448	0.01039	5.242	0.99999	5.24241	1
30	5.34016	0.055	0.67851	0.00651	5.437	0.99999	5.43668	1
31	5.53186	0.055	0.40780	0.00439	5.626	1	5.62574	1
32	5.71826	0.055	0.23111	0.00314	5.809	1	5.80945	1
33	5.89927	0.055	0.12506	0.00238	5.988	1	5.98774	1
34	6.07482	0.055	0.06569	0.00187	6.161	1	6.16054	1
35	6.24488	0.055	0.03431	0.00153	6.328	1	6.32784	1
36	6.40942	0.055	0.01826	0.00128	6.49	1	6.48963	1
37	6.56846	0.055	0.01012	0.00110	6.648	1	6.64799	1
38	6.72610	0.055	0.00592	0.00095	6.803	1	6.8028	1
39	6.87810	0.055	0.00371	0.00084	6.952	1	6.95201	1
40	7.02454	0.055	0.00250	0.00075	7.096	1	7.09569	1
41	7.16549	0.055	0.00179	0.00067	7.234	1	7.23394	1
42	7.30106	0.055	0.00136	0.00061	7.367	1	7.36686	1
43	7.43136	0.055	0.00107	0.00055	7.495	1	7.49457	1
44	7.55650	0.055	0.00087	0.00051	7.617	1	7.61718	1
45	7.67661	0.055	0.00073	0.00047	7.735	1	7.73483	1
46	7.79183	0.055	0.00063	0.00043	7.848	1	7.84764	1
47	7.90229	0.055	0.00054	0.00040	7.956	1	7.95577	1
48	8.00812	0.055	0.00048	0.00037	8.059	1	8.05935	1
49	8.10948	0.055	0.00043	0.00034	8.159	1	8.15852	1
50	8.20650	0.055	0.00038	0.00031	8.253	1	8.25342	1
51	8.29932	0.055	0.00035	0.00029	8.344	1	8.34421	1
52	8.38810	0.055	0.00032	0.00027	8.431	1	8.43102	1
53	8.47297	0.055	0.00029	0.00025	8.514	1	8.51399	1
54	8.55408	0.055	0.00027	0.00023	8.593	1	8.59327	1
55	8.63157	0.055	0.00025	0.00021	8.669	1	8.66899	1
56	8.70556	0.055	0.00023	0.00020	8.741	1	8.74129	1
57	8.77620	0.055	0.00021	0.00018	8.81	1	8.81031	1
58	8.84362	0.055	0.00019	0.00017	8.876	1	8.87617	1
59	8.90795	0.055	0.00018	0.00016	8.939	1	8.93899	1
60	8.96931	0.055	0.00016	0.00015	8.999	1	8.99892	1
61	9.02782	0.055	0.00015	0.00014	9.056	1	9.05605	1
62	9.08361	0.055	0.00014	0.00013	9.111	1	9.11052	1
63	9.13679	0.055	0.00013	0.00012	9.162	1	9.16243	1
64	9.18747	0.055	0.00012	0.00011	9.212	1	9.2119	1
65	9.23575	0.055	0.00011	0.00011	9.259	1	9.25903	1
66	9.28175	0.055	0.00010	0.00010	9.304	1	9.30392	1
67	9.32556	0.055	0.00010	0.00009	9.347	1	9.34667	1
68	9.36728	0.055	0.00009	0.00009	9.387	1	9.38738	1
69	9.40700	0.055	0.00008	0.00008	9.426	1	9.42614	1
70	9.44481	0.055	0.00008	0.00008	9.463	1	9.46303	1
71	9.48080	0.055	0.00007	0.00008	9.498	1	9.49814	1
72	9.51506	0.055	0.00007	0.00007	9.532	1	9.53156	1
73	9.54765	0.055	0.00006	0.00007	9.563	1	9.56335	1
74	9.57867	0.055	0.00006	0.00006	9.594	1	9.5936	1
75	9.60817	0.055	0.00006	0.00006	9.622	1	9.62238	1
76	9.63624	0.055	0.00005	0.00006	9.65	1	9.64975	1
77	9.66293	0.055	0.00005	0.00005	9.676	1	9.67579	1
78	9.68832	0.055	0.00005	0.00005	9.701	1	9.70055	1
79	9.71247	0.055	0.00005	0.00004	9.724	1	9.72409	1
80	9.73543	0.055	0.00059	0.00051	9.746	1	9.74648	1

Table 5. Summary of rebuilding reference points for cowcod

Parameter	Values
Year declared overfished	2000
Current year	2013
First ACL year	2015
T_{MIN} (re-estimated)	2019
Mean generation time (years)	38
T_{MAX} (re-estimated)	2057
$T_{\text{F=0}}$ (beginning in 2015)	2019
B_0 (median female spawning biomass, mt)	1549
Median rebuilding target ($B_{40\%}$) (mt)	620
Current SPR target (2013-2014 cycle)	82.7%
Current exploitation target (catch / 11+ biomass; 2013-2014 cycle)	0.007
Median MSY proxy exploitation rate ($B_{40\%}$)	0.050
Current T_{TARGET} (2013-2014 cycle)	2068
Median SB_{2013} (mt)	524

Table 6. Rebuilding reference points for model runs 1-9 (see text for run descriptions). Values in bold italic font exceed the ABC harvest rate. Catch estimates (ACLs and ABCs) in 2016 are based on 2015 ACL removals shown for each run. * At the time of writing, median ABC and OFL estimates for 2016 were available for runs 3 (Council preliminary preferred alternative) and 8 (ABC catch based on proxy B_{40%} harvest rate). Individual rebuilding years are reported as integer values, and are therefore associated with a range of harvest rates and probabilities of recovery.

	Run								
	1	2	3	4	5	6	7	8	9
	T(F=0)	current ACL	current rate	Ttarget	Tmax 2057	Tmax 2097	40-10	ABC	OFL
Exploitation Rate in 2015	0	0.0013	0.007	<i>0.0474</i>	<i>0.0458</i>	<i>0.0490</i>	0.0352	0.0409	<i>0.0491</i>
50% prob. recovery by:	2019	2019	2020	2068	2057	2097	2034	2039	>2100
2015 ACL (mt)	0.0	1.5	7.8	<i>53.0</i>	<i>51.3</i>	<i>54.9</i>	39.3	45.8	<i>55.0</i>
2015 ABC (mt)	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8
2015 OFL (mt)	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
2016 ACL (mt)	0.0	1.5	8.0	<i>52.3</i>	<i>50.6</i>	<i>54.0</i>	39.1	45.4	<i>54.1</i>
2016 ABC (mt)	*	*	47.0	*	*	*	*	45.4	*
2016 OFL (mt)	*	*	56.4	*	*	*	*	54.6	*
Probability of recovery by									
2019 (new Tmin)	52.2%	51.8%	49.8%	37.4%	37.8%	37.1%	40.7%	39.3%	37.1%
2057 (new Tmax)	93.8%	93.0%	88.4%	48.8%	50.0%	47.4%	52.8%	53.4%	47.3%
2059 (old Tmin)	94.3%	93.5%	88.9%	49.1%	50.2%	47.6%	52.9%	53.7%	47.5%
2068 (current Ttarget)	95.9%	95.2%	90.9%	50.0%	51.4%	48.5%	52.8%	55.0%	48.2%
2097 (old Tmax)	98.4%	97.6%	94.2%	51.7%	53.3%	50.0%	52.2%	55.0%	49.5%

Table 7. Median depletion, female spawning biomass, probabilities of recovery, and catch for model runs 1-9 (see text for descriptions of individual runs). Bold values indicate $\Pr\{\text{recovery}\} \geq 0.5$.

	Run								
	1	2	3	4	5	6	7	8	9
	T(F=0)	current ACL	current rate	Ttarget	Tmax 2057	Tmax 2097	40-10	ABC	OFL
Median depletion									
2013	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%
2014	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%
2015	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%
2016	37.2%	37.2%	37.0%	35.5%	35.5%	35.4%	35.9%	35.7%	35.4%
2017	38.4%	38.3%	38.0%	35.1%	35.2%	35.0%	36.0%	35.5%	35.0%
2018	39.6%	39.5%	38.9%	34.9%	35.0%	34.7%	36.1%	35.5%	34.7%
2019	40.8%	40.7%	39.9%	34.6%	34.8%	34.5%	36.2%	35.5%	34.5%
2020	42.0%	41.8%	40.9%	34.6%	34.9%	34.4%	36.4%	35.6%	34.4%
2021	43.2%	42.9%	41.9%	34.6%	34.9%	34.4%	36.6%	35.7%	34.4%
2022	44.5%	44.2%	42.9%	34.7%	35.0%	34.4%	36.9%	35.9%	34.4%
2023	45.7%	45.3%	43.9%	34.9%	35.2%	34.6%	37.2%	36.2%	34.6%
2024	46.9%	46.5%	44.9%	35.1%	35.4%	34.8%	37.6%	36.5%	34.8%
Median female SSB (mt)									
2013	524.5	524.5	524.5	524.5	524.5	524.5	524.5	524.5	524.5
2014	541.9	541.9	541.9	541.9	541.9	541.9	541.9	541.9	541.9
2015	559.4	559.4	559.4	559.4	559.4	559.4	559.4	559.4	559.4
2016	577.3	576.6	573.4	550.8	551.7	549.9	557.6	554.4	549.8
2017	598.0	596.5	590.3	548.0	549.6	546.3	560.6	554.6	546.2
2018	619.1	617.0	607.8	545.2	547.6	542.7	563.8	555.1	542.7
2019	638.3	635.4	623.5	543.7	546.5	540.5	567.0	555.9	540.5
2020	658.4	655.0	640.3	544.9	548.2	541.1	572.0	559.0	541.0
2021	679.0	674.7	657.4	545.9	549.9	541.6	577.2	562.6	541.5
2022	700.1	695.1	674.4	548.1	552.2	543.6	582.2	565.9	543.6
2023	721.3	715.8	692.7	551.7	556.3	546.9	589.2	571.9	546.8
2024	741.2	735.1	709.8	556.6	561.4	551.2	595.4	578.2	551.1
Probability of rebuilding									
2013	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336
2014	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363
2015	0.392	0.392	0.392	0.392	0.392	0.392	0.392	0.392	0.392
2016	0.424	0.423	0.418	0.383	0.385	0.383	0.393	0.388	0.383
2017	0.454	0.452	0.444	0.378	0.381	0.375	0.396	0.386	0.375
2018	0.490	0.486	0.469	0.374	0.378	0.371	0.400	0.390	0.371
2019	0.522	0.518	0.498	0.374	0.378	0.371	0.407	0.393	0.371
2020	0.548	0.543	0.524	0.375	0.381	0.371	0.414	0.396	0.371
2021	0.575	0.566	0.542	0.379	0.387	0.374	0.423	0.402	0.374
2022	0.600	0.592	0.563	0.387	0.391	0.377	0.429	0.410	0.377
2023	0.629	0.621	0.583	0.392	0.396	0.384	0.441	0.416	0.384
2024	0.651	0.645	0.604	0.396	0.402	0.392	0.454	0.424	0.392
Catch (fixed at median)									
2013	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2014	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2015	0	1.5	7.8	53.0	51.3	54.9	39.3	45.8	55.0
2016	0	1.5	8.0	52.3	50.6	54.0	39.1	45.4	54.1
2017	0	1.6	8.3	51.7	50.2	53.4	39.2	45.1	53.4
2018	0	1.6	8.5	51.4	50.0	53.0	39.6	45.1	53.0
2019	0	1.7	8.7	51.3	49.9	52.8	40.1	45.2	52.8
2020	0	1.7	9.0	51.3	49.9	52.7	40.6	45.3	52.8
2021	0	1.8	9.2	51.3	50.0	52.7	41.2	45.6	52.8
2022	0	1.8	9.4	51.5	50.2	52.9	42.1	45.9	52.9
2023	0	1.9	9.7	51.7	50.4	53.1	43.2	46.2	53.0
2024	0	1.9	9.9	52.0	50.8	53.3	44.4	46.6	53.3

Table 8. Rebuilding reference points for model runs 10-16 (see text for run descriptions).

	Run						
	10	11	12	13	14	15	16
	ACL=1.5	ACL=2.0	ACL=2.5	ACL=3.0	ACL=3.5	ACL=4.0	ACL=4.5
Exploitation Rate in 2015	0.0013	0.0018	0.0022	0.0027	0.0031	0.0036	0.0040
50% prob. recovery by:	2019	2019	2019	2019	2019	2019	2019
2015 ACL (mt)	1.5	2.0	2.5	3.0	3.5	4.0	4.5
2015 ABC (mt)	45.8	45.8	45.8	45.8	45.8	45.8	45.8
2016 ACL (mt)	1.5	2.1	2.6	3.1	3.6	4.1	4.6
2016 ABC (mt)	*	*	*	*	*	*	*
Probability of recovery by							
2019 (new Tmin)	51.8%	51.5%	51.3%	51.1%	51.0%	50.8%	50.6%
2057 (new Tmax)	93.0%	92.7%	92.4%	91.9%	91.5%	91.3%	91.0%
2059 (old Tmin)	93.5%	93.2%	92.9%	92.5%	92.3%	91.7%	91.5%
2068 (current Ttarget)	95.2%	95.0%	94.7%	94.4%	94.0%	93.7%	93.4%
2097 (old Tmax)	97.6%	97.5%	97.3%	97.1%	96.9%	96.5%	96.3%

Table 9. Median depletion, female spawning biomass, probabilities of recovery, and catch for model runs 10-16 (see text for descriptions of individual runs). Bold values indicate $\Pr\{\text{recovery}\} \geq 0.5$.

	Run						
	10 ACL=1.5	11 ACL=2.0	12 ACL=2.5	13 ACL=3.0	14 ACL=3.5	15 ACL=4.0	16 ACL=4.5
Median depletion							
2013	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%
2014	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%
2015	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%
2016	37.2%	37.2%	37.1%	37.1%	37.1%	37.1%	37.1%
2017	38.3%	38.3%	38.3%	38.2%	38.2%	38.2%	38.2%
2018	39.5%	39.5%	39.4%	39.4%	39.3%	39.3%	39.3%
2019	40.7%	40.6%	40.6%	40.5%	40.4%	40.4%	40.3%
2020	41.8%	41.7%	41.7%	41.6%	41.5%	41.5%	41.4%
2021	42.9%	42.8%	42.8%	42.7%	42.6%	42.5%	42.4%
2022	44.2%	44.0%	43.9%	43.8%	43.7%	43.6%	43.5%
2023	45.3%	45.2%	45.1%	45.0%	44.9%	44.8%	44.7%
2024	46.5%	46.4%	46.3%	46.1%	46.0%	45.9%	45.7%
Median female SSB (mt)							
2013	524.5	524.5	524.5	524.5	524.5	524.5	524.5
2014	541.9	541.9	541.9	541.9	541.9	541.9	541.9
2015	559.4	559.4	559.4	559.4	559.4	559.4	559.4
2016	576.6	576.3	576.1	575.8	575.6	575.3	575.1
2017	596.5	596.0	595.5	595.0	594.5	594.0	593.5
2018	617.0	616.3	615.6	614.9	614.1	613.4	612.7
2019	635.4	634.5	633.5	632.6	631.6	630.7	629.8
2020	655.0	653.9	652.7	651.5	650.4	649.2	647.9
2021	674.7	673.3	671.8	670.4	669.0	667.6	666.2
2022	695.1	693.4	691.8	690.1	688.5	686.9	685.3
2023	715.8	714.0	712.1	710.3	708.4	706.6	704.8
2024	735.1	733.3	731.1	729.2	727.2	725.3	723.2
Probability of rebuilding							
2013	0.336	0.336	0.336	0.336	0.336	0.336	0.336
2014	0.363	0.363	0.363	0.363	0.363	0.363	0.363
2015	0.392	0.392	0.392	0.392	0.392	0.392	0.392
2016	0.423	0.423	0.422	0.422	0.422	0.422	0.421
2017	0.452	0.452	0.451	0.450	0.450	0.450	0.448
2018	0.486	0.484	0.484	0.483	0.482	0.481	0.480
2019	0.518	0.515	0.513	0.511	0.510	0.508	0.506
2020	0.543	0.541	0.540	0.540	0.537	0.535	0.533
2021	0.566	0.564	0.563	0.562	0.562	0.559	0.557
2022	0.592	0.589	0.588	0.584	0.582	0.580	0.579
2023	0.621	0.616	0.610	0.609	0.606	0.604	0.602
2024	0.645	0.641	0.639	0.637	0.635	0.629	0.626
Catch (mt)							
2013	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2014	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2015	1.5	2.0	2.5	3.0	3.5	4.0	4.5
2016	1.5	2.1	2.6	3.1	3.6	4.1	4.6
2017	1.6	2.1	2.7	3.2	3.7	4.2	4.8
2018	1.6	2.2	2.7	3.3	3.8	4.4	4.9
2019	1.7	2.3	2.8	3.4	3.9	4.5	5.0
2020	1.7	2.3	2.9	3.5	4.0	4.6	5.2
2021	1.8	2.4	3.0	3.6	4.1	4.7	5.3
2022	1.8	2.4	3.1	3.7	4.2	4.8	5.4
2023	1.9	2.5	3.1	3.7	4.4	5.0	5.6
2024	1.9	2.6	3.2	3.8	4.5	5.1	5.7

Table 10. Rebuilding reference points for model runs 17-23 (see text for run descriptions).

	Run						
	17	18	19	20	21	22	23
	ACL=5.0	ACL=5.5	ACL=6.0	ACL=6.5	ACL=7.0	ACL=7.5	ACL=8.0
Exploitation Rate in 2015	0.0045	0.0049	0.0054	0.0058	0.0063	0.0067	0.0072
50% prob. recovery by:	2019	2019	2019	2019	2019	2020	2020
2015 ACL (mt)	5.0	5.5	6.0	6.5	7.0	7.5	8.0
2015 ABC (mt)	45.8	45.8	45.8	45.8	45.8	45.8	45.8
2016 ACL (mt)	5.1	5.7	6.2	6.7	7.2	7.7	8.2
2016 ABC (mt)	*	*	*	*	*	*	*
Probability of recovery by							
2019 (new Tmin)	50.4%	50.4%	50.3%	50.2%	50.1%	49.99%	49.8%
2057 (new Tmax)	90.6%	90.2%	89.8%	89.6%	89.2%	88.8%	88.5%
2059 (old Tmin)	91.2%	90.7%	90.5%	90.0%	89.7%	89.4%	89.0%
2068 (current Ttarget)	93.1%	92.7%	92.4%	92.0%	91.5%	91.2%	90.9%
2097 (old Tmax)	96.0%	95.8%	95.5%	95.3%	95.0%	94.7%	94.3%

Table 11. Median depletion, female spawning biomass, probabilities of recovery, and catch for model runs 17-23 (see text for descriptions of individual runs). Bold values indicate $\Pr\{\text{recovery}\} \geq 0.5$.

	Run						
	17 ACL=5.0	18 ACL=5.5	19 ACL=6.0	20 ACL=6.5	21 ACL=7.0	22 ACL=7.5	23 ACL=8.0
Median depletion							
2013	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%	33.9%
2014	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%
2015	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%	36.0%
2016	37.1%	37.0%	37.0%	37.0%	37.0%	37.0%	37.0%
2017	38.1%	38.1%	38.1%	38.1%	38.0%	38.0%	38.0%
2018	39.2%	39.2%	39.1%	39.1%	39.0%	39.0%	38.9%
2019	40.3%	40.2%	40.2%	40.1%	40.0%	39.99%	39.9%
2020	41.3%	41.3%	41.2%	41.1%	41.0%	41.0%	40.9%
2021	42.3%	42.3%	42.2%	42.1%	42.0%	41.9%	41.8%
2022	43.4%	43.4%	43.3%	43.2%	43.1%	43.0%	42.9%
2023	44.5%	44.4%	44.3%	44.2%	44.2%	44.0%	43.9%
2024	45.6%	45.5%	45.4%	45.2%	45.1%	45.0%	44.9%
Median female SSB (mt)							
2013	524.5	524.5	524.5	524.5	524.5	524.5	524.5
2014	541.9	541.9	541.9	541.9	541.9	541.9	541.9
2015	559.4	559.4	559.4	559.4	559.4	559.4	559.4
2016	574.8	574.6	574.3	574.1	573.8	573.6	573.3
2017	593.1	592.6	592.1	591.6	591.1	590.6	590.1
2018	611.9	611.2	610.5	609.7	609.0	608.3	607.6
2019	628.8	627.9	627.0	626.1	625.1	624.2	623.2
2020	646.8	645.6	644.5	643.3	642.2	641.1	640.0
2021	664.8	663.3	661.9	660.6	659.4	658.2	657.1
2022	683.6	682.0	680.4	678.8	677.2	675.6	674.0
2023	703.0	701.2	699.4	697.5	695.8	694.0	692.3
2024	721.6	719.7	717.7	715.7	713.7	711.5	709.4
Probability of rebuilding							
2013	0.336	0.336	0.336	0.336	0.336	0.336	0.336
2014	0.363	0.363	0.363	0.363	0.363	0.363	0.363
2015	0.392	0.392	0.392	0.392	0.392	0.392	0.392
2016	0.420	0.420	0.420	0.419	0.419	0.419	0.418
2017	0.448	0.447	0.447	0.446	0.445	0.444	0.444
2018	0.479	0.478	0.475	0.472	0.471	0.470	0.467
2019	0.504	0.504	0.503	0.502	0.501	0.4999	0.498
2020	0.531	0.530	0.529	0.527	0.525	0.524	0.524
2021	0.555	0.551	0.549	0.547	0.546	0.543	0.542
2022	0.576	0.574	0.572	0.568	0.566	0.564	0.563
2023	0.599	0.597	0.594	0.591	0.587	0.584	0.582
2024	0.623	0.621	0.619	0.612	0.609	0.606	0.603
Catch (mt)							
2013	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2014	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2015	5.0	5.5	6.0	6.5	7.0	7.5	8.0
2016	5.1	5.7	6.2	6.7	7.2	7.7	8.2
2017	5.3	5.8	6.3	6.9	7.4	7.9	8.4
2018	5.4	6.0	6.5	7.0	7.6	8.1	8.6
2019	5.6	6.1	6.7	7.2	7.8	8.3	8.9
2020	5.7	6.3	6.9	7.4	8.0	8.5	9.1
2021	5.9	6.5	7.0	7.6	8.2	8.7	9.3
2022	6.0	6.6	7.2	7.8	8.4	8.9	9.5
2023	6.2	6.8	7.4	8.0	8.6	9.1	9.7
2024	6.3	6.9	7.5	8.1	8.7	9.3	9.9

Table 12. Rebuilding reference points for model runs 24-27 (see text for run descriptions).

	Run			
	24	25	26	27
50% prob. of recovery by:	2022	2025	2030	2035
Exploitation Rate in 2015	0.0203	0.0281	0.0356	0.0391
50% prob. recovery by:	2022	2025	2030	2035
2015 ACL (mt)	22.7	31.4	39.9	43.7
2015 ABC (mt)	45.8	45.8	45.8	45.8
2016 ACL (mt)	23.0	31.6	39.8	43.5
2016 ABC (mt)	*	*	*	*
Probability of recovery by				
2019 (new Tmin)	45.1%	42.9%	40.5%	39.8%
2057 (new Tmax)	74.3%	65.7%	59.2%	56.4%
2059 (old Tmin)	74.7%	66.3%	59.5%	56.6%
2068 (current Ttarget)	76.7%	67.5%	60.6%	57.5%
2097 (old Tmax)	79.8%	70.1%	62.3%	59.4%

Table 13. Median depletion, female spawning biomass, probabilities of recovery, and catch for model runs 24-27 (see text for descriptions of individual runs). Bold values indicate $\Pr\{\text{recovery}\} \geq 0.5$.

	Run			
	24 2022	25 2025	26 2030	27 2035
Median depletion				
2013	33.9%	33.9%	33.9%	33.9%
2014	35.0%	35.0%	35.0%	35.0%
2015	36.0%	36.0%	36.0%	36.0%
2016	36.4%	36.2%	35.9%	35.8%
2017	37.0%	36.5%	35.9%	35.7%
2018	37.6%	36.8%	36.0%	35.7%
2019	38.1%	37.2%	36.2%	35.7%
2020	38.8%	37.5%	36.3%	35.8%
2021	39.4%	37.9%	36.6%	36.0%
2022	40.0%	38.4%	36.8%	36.2%
2023	40.7%	38.9%	37.2%	36.5%
2024	41.3%	39.4%	37.7%	36.9%
Median female SSB (mt)				
2013	524.5	524.5	524.5	524.5
2014	541.9	541.9	541.9	541.9
2015	559.4	559.4	559.4	559.4
2016	565.9	561.6	557.4	555.5
2017	576.0	567.8	560.0	556.5
2018	586.5	574.3	562.9	557.8
2019	596.2	580.7	566.0	559.3
2020	606.8	588.8	571.2	563.2
2021	618.1	596.5	576.4	567.3
2022	630.7	605.8	581.6	571.0
2023	642.1	615.0	589.4	578.2
2024	654.7	624.5	596.3	584.2
Probability of rebuilding				
2013	0.336	0.336	0.336	0.336
2014	0.363	0.363	0.363	0.363
2015	0.392	0.392	0.392	0.392
2016	0.406	0.400	0.393	0.390
2017	0.420	0.407	0.395	0.390
2018	0.435	0.418	0.400	0.393
2019	0.451	0.429	0.405	0.398
2020	0.470	0.439	0.413	0.402
2021	0.484	0.450	0.422	0.408
2022	0.500	0.466	0.429	0.418
2023	0.517	0.476	0.441	0.424
2024	0.530	0.487	0.455	0.431
Catch (mt)				
2013	1.5	1.5	1.5	1.5
2014	1.5	1.5	1.5	1.5
2015	22.7	31.4	39.9	43.7
2016	23.0	31.6	39.8	43.5
2017	23.3	31.8	39.8	43.4
2018	23.7	32.1	40.0	43.4
2019	24.1	32.4	40.1	43.5
2020	24.4	32.8	40.4	43.7
2021	24.8	33.1	40.7	44.0
2022	25.2	33.6	41.1	44.3
2023	25.6	34.0	41.4	44.6
2024	26.1	34.4	41.8	45.0