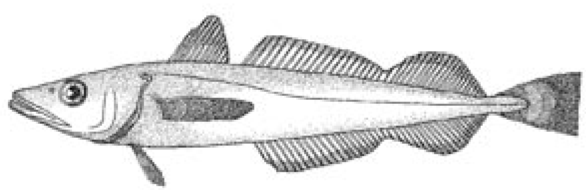
Status of the Pacific hake (Whiting) stock in U.S. and Canadian Waters in 2012



International Joint Technical Committee for Pacific hake

Final Document
2/29/2012

This document reports the collaborative efforts of the official U.S. and Canadian JTC members, as well as one previous assessment participant. The jointly-appointed 5th member has not yet been identified.

Authors of this document are (In no particular order):

Ian J. Stewart[1,2]
Robyn E. Forrest[3]
Nathan Taylor[1,3]
Chris Grandin[1,3]
Allan C. Hicks[1,2]

Additional contributions from:

Steven J.D. Martell[4]

[1]*Official member of the 2012 Joint Technical Committee*

[2]*Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd. East, Seattle, WA 98112, USA*

[3]*Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, Canada*

[4]*Fisheries Centre, AERL, 2202 Main Mall, University of British Columbia, V6T 1Z4, Canada*

Table of Contents

Executive Summary

Stock

This assessment reports the status of the coastal Pacific hake (or Pacific whiting, *Merluccius productus*) resource off the west coast of the United States and Canada. This stock exhibits seasonal migratory behavior, ranging from offshore and generally southern waters during the winter spawning season to coastal areas between northern California and northern British Columbia during the spring, summer and fall when the fishery is conducted. In years with warmer water temperatures the stock tends to move farther North during the summer and older hake tend to migrate farther than younger fish in all years. Separate, and much smaller, populations of hake occurring in the major inlets of the northeast Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California, are not included in this analysis.

Catches

Coast-wide fishery landings of Pacific hake averaged 222 thousand mt from 1966 to 2011, with a low of 90 thousand mt in 1980 and a peak of 363 thousand mt in 2005. Prior to 1966 the total removals were negligible relative to the modern fishery. The fishery in U.S. waters has averaged 166 thousand mt, or 74.7% of the average total landings over the time series, with the catch from Canadian waters averaging 56 thousand mt. During the first 25 years of the fishery, the majority of the removals were from foreign or joint-venture fisheries. In this stock assessment, the terms catch and landings are used interchangeably; estimates of discard within the target fishery are included, but discarding of Pacific hake in non-target fisheries is not. Discard from all fisheries is estimated to be less than 1% of landings and therefore is likely to be negligible with regard to the population dynamics.

Recent coast-wide landings from 2007-2011 have been above the long term average, at 261 thousand mt. Landings between 2001 and 2008 were predominantly comprised of fish from the very large 1999 year class, with the cumulative removal from that cohort exceeding 1.2 million mt. In 2008, the fishery began harvesting considerable numbers of the then emergent 2005 year class. Catches in 2009 were again dominated by the 2005 year class with some contribution from an emergent 2006 year class and relatively small numbers of the 1999 cohort. The 2010 fishery encountered very large numbers of two-year old hake from the 2008 year-class, while continuing to see substantial numbers from the 2005 and 2006 year-classes. In 2011, U.S. fisheries caught mostly 3-year old fish from the 2008 year class, while the Canadian fisheries encountered older fish from the 2005 and 2006 year classes more frequently than the U.S. fisheries.

Since implementation of the Magnuson-Stevens Fishery Conservation and Management Act in the U.S. and the declaration of a 200 mile fishery conservation zone in Canada in the late 1970s, annual quotas have been the primary management tool used to limit the catch of Pacific hake in both zones by foreign and domestic fisheries. During the 1990s, however, disagreement between the U.S. and Canada on the division of the total catch led to quota overruns; 1991-1992 quotas summed to 128% of the limit and overruns averaged 114% from 1991-1999. Since 2001, total catches have been below coast-wide fishery limits. The current treaty between the United States and Canada, establishes U.S. and Canadian shares of the coast-wide allowable biological catch at 73.88% and 26.12%, respectively, and this distribution has been adhered to since ratification of the Joint Treaty. From 2009 to 2011 much of the U.S. tribal allocation remained uncaught and Canadian catches have also been well below the limit.

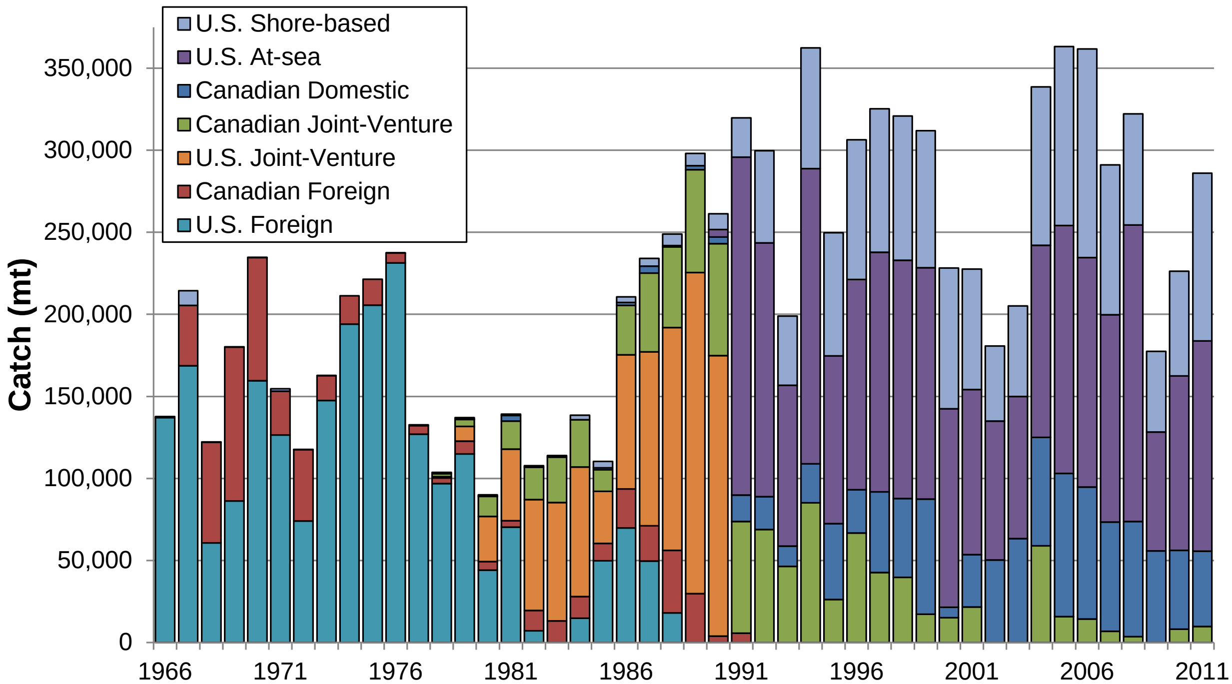


Figure a. Total Pacific hake catch used in the assessment by sector, 1966-2011. Tribal catches are included.

Table a. Recent commercial fishery catch (1000s mt). Tribal catches are included where applicable.

Year	US at-sea	US shore-based	US total	Canadian joint-venture	Canadian domestic	Canadian total	Total
2002	85	46	130	0	50	50	181
2003	87	55	142	0	63	63	205
2004	117	97	214	59	66	125	339
2005	151	109	260	16	87	103	363
2006	140	127	267	14	80	95	362
2007	126	91	218	7	67	73	291
2008	181	68	248	4	70	74	322
2009	72	49	122	0	56	56	177
2010	106	64	170	8	48	56	217
2011	128	102	230	10	46	56	286

Data and assessment

Following the 2010 assessment, nearly all of the data sources available for Pacific hake were reconstructed and thoroughly re-evaluated for 2011 from the original observations using consistent, and in some cases improved methods. These improved data streams have been updated for 2012 with the addition of new age distributions from the 2011 fishery and acoustic survey, as well as the 2011 acoustic survey biomass index.

This assessment reports a single base-case model representing the collective work of the Joint Technical Committee (JTC). The assessment depends primarily upon the acoustic survey biomass index (1995, 1998, 2001, 2003, 2005, 2007, 2009 and 2011) for information on the scale of the current hake stock. The 2011 index value is the lowest in the time-series. The aggregate fishery age-composition data (1975-2011) and the age-composition data from the acoustic survey contribute to the assessment model's ability to resolve strong and weak cohorts. Both sources show a strong 2008 cohort, but differ somewhat in the relative magnitude of the weaker 2005 and 2006 cohorts.

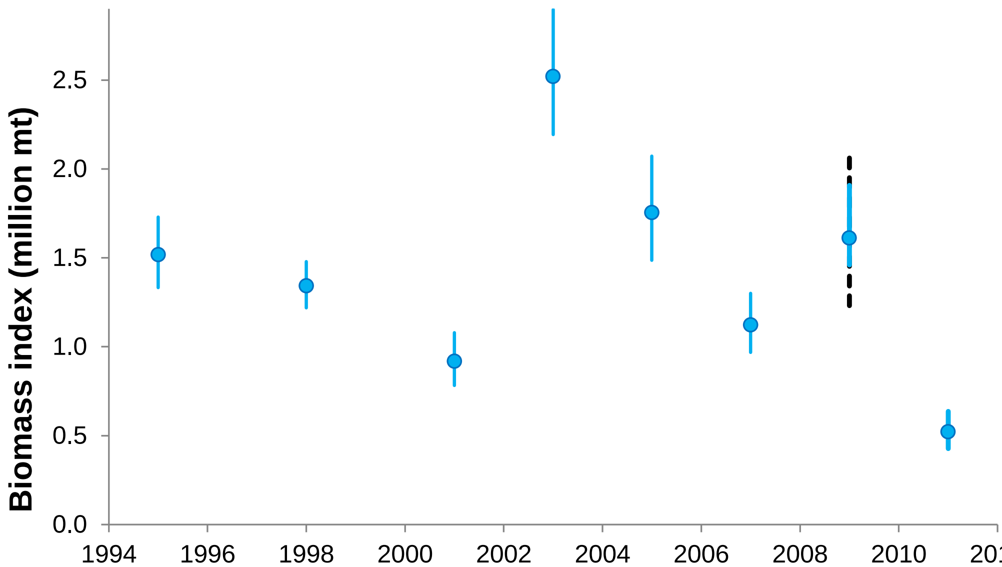


Figure b. Acoustic survey biomass indices (millions of metric tons). Approximate 95% confidence intervals are based on only sampling variability (1995-2007, 2011) in addition to squid/hake apportionment uncertainty (2009).

The assessment is fully Bayesian, with the base-case model incorporating prior information on two key parameters (natural mortality, *M*, and steepness of the stock-recruit relationship, *h*) and integrating over estimation and parameter uncertainty to provide results that can be probabilistically interpreted. Our exploration of uncertainty is not limited to parameter uncertainty (See Unresolved problems and major uncertainties section below).

Stock biomass

The base-case stock assessment model indicates that the Pacific hake female spawning biomass was well below the average unfished equilibrium in the 1960s and 1970s. The stock is estimated to have increased rapidly after two or more large recruitments in the early 1980s, and then declined rapidly after a peak in the mid- to late 1980s to a low in 2000. This long period of decline was followed by a brief increase to a peak in 2003 (median estimate of 1.29 million mt in the SS model) as the exceptionally large 1999 year class matured. The stock is then estimated to have declined with the aging 1999 year class to a time-series low of 0.38 million mt in 2009. This recent decline is much more extreme than that estimated in the 2011 assessment. The current median posterior spawning biomass is estimated to be 32.6% of the average unfished equilibrium level (SB_0). However, this estimate is quite uncertain, with 95% posterior credibility intervals ranging from historical lows to above the average unfished equilibrium levels. The estimate of 2012 is 0.62 million mt, much smaller than the two estimates in the 2011 assessment (1.87, and 2.18 million mt). This change is largely driven by the very low 2011 acoustic survey biomass index.

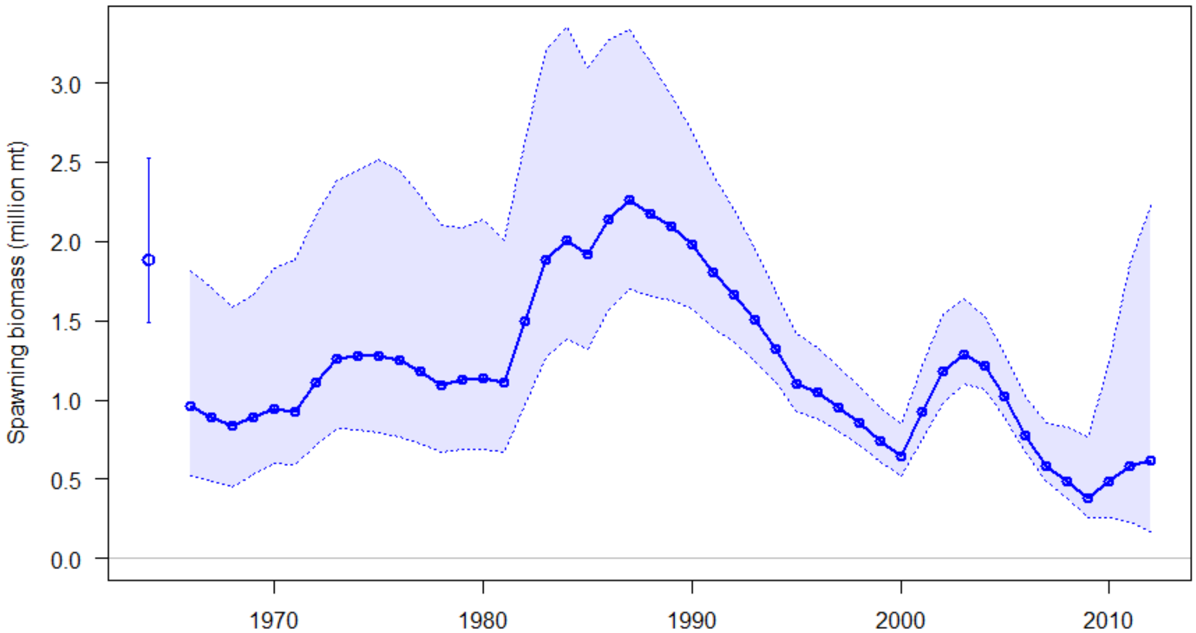


Figure c. Estimated female spawning biomass time-series with 95% posterior credibility intervals.

Table b. Recent trend in estimated Pacific hake female spawning biomass (million mt) and depletion level.

	Spawning biomass (mt)			Depletion		
Year	2.5th percentile	Median	97.5th percentile	2.5th percentile	Median	97.5th percentile
2003	1.100	1.288	1.638	53.3%	68.8%	86.7%
2004	1.064	1.219	1.525	50.9%	65.1%	81.7%
2005	0.892	1.020	1.292	42.9%	54.7%	68.4%
2006	0.670	0.774	1.022	32.6%	41.6%	52.7%
2007	0.482	0.580	0.855	23.8%	31.3%	41.5%
2008	0.379	0.491	0.828	19.2%	26.4%	40.0%
2009	0.261	0.384	0.769	13.5%	20.4%	36.4%
2010	0.261	0.483	1.237	13.9%	25.4%	57.9%
2011	0.231	0.588	1.857	12.8%	31.3%	86.6%
2012	0.169	0.616	2.228	9.4%	32.6%	102.2%

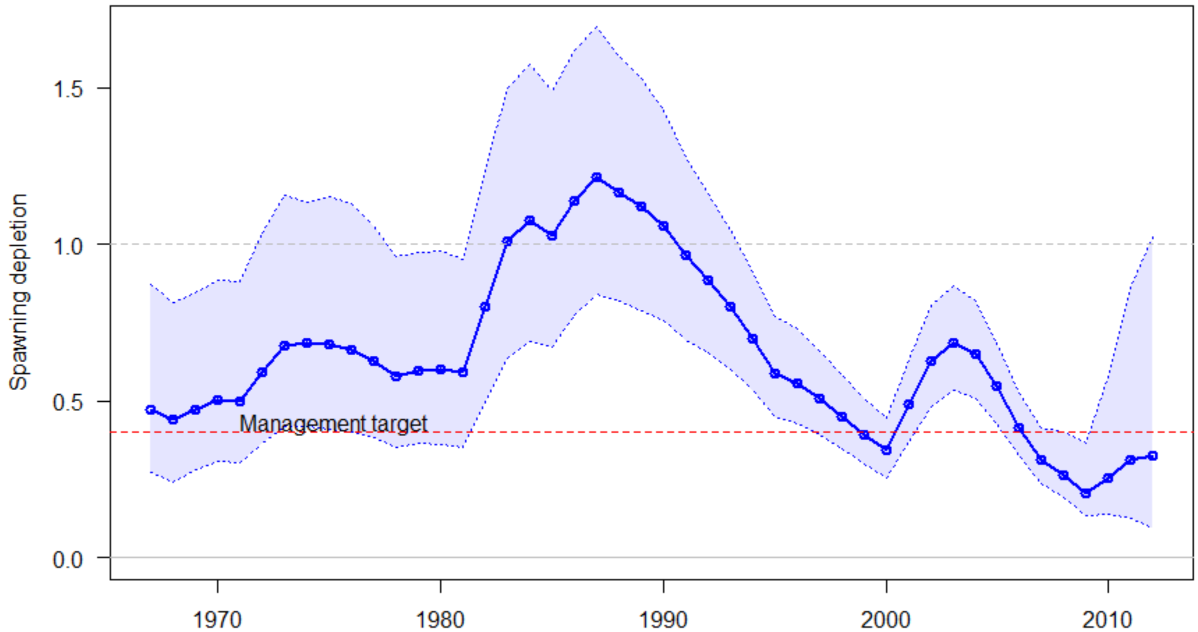


Figure d. Time-series of estimated spawning depletion through 2012 with 95% posterior credibility intervals.

Recruitment

Estimates of historical Pacific hake recruitment indicate very large year classes in 1980, 1984, 1999, and 2008. The strength of the 2008 cohort is estimated to be large (5.2 billion age-0 fish), although not nearly as large as was estimated in the 2010 stock assessment (16.2 billion). The U.S. fishery and acoustic age compositions both show the 2008 year class comprised a very large proportion of the observations in 2010 and 2011. Uncertainty in estimated recruitments is substantial, especially for 2008, as indicated by the broad posterior intervals.

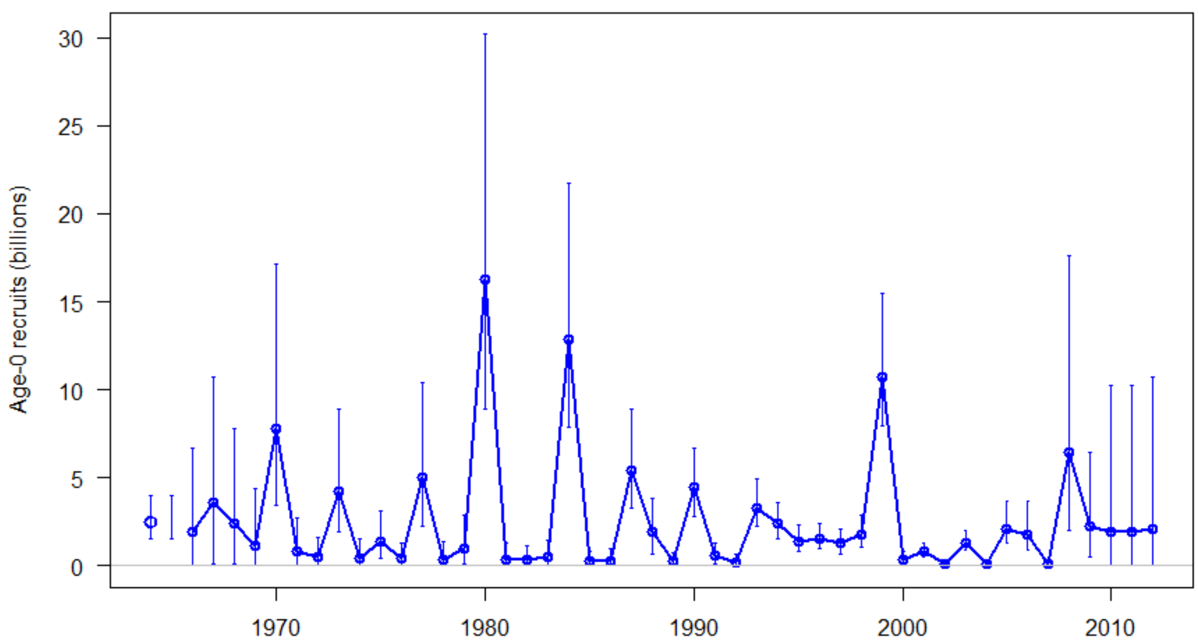


Figure e. Estimated Pacific hake recruitment time-series with 95% posterior credibility intervals (billions of age-0).

Table c. Recent trend in Pacific hake recruitment (billions of age-0).

Year	2.5th percentile	Median	97.5th percentile
2003	0.870	1.266	2.019
2004	0.011	0.064	0.211
2005	1.318	1.964	3.698
2006	0.892	1.579	3.690
2007	0.013	0.070	0.288
2008	2.043	5.248	17.581
2009	0.513	1.736	6.480
2010	0.055	0.932	10.261
2011	0.049	0.763	10.256
2012	0.041	0.762	10.733

Reference points

The average unexploited equilibrium spawning biomass estimate was 1.89 million mt, intermediate between the two estimates reported in the 2011 stock assessment. However, the uncertainty is very broad, with the 95% posterior credibility interval ranging from 1.49 to 2.53 million mt. The *MSY*-proxy target spawning biomass ($SB_{40\%}$) is estimated to be 0.76 million mt in the base-case model, slightly larger than the equilibrium spawning biomass implied by the $F_{40\%}$ default harvest rate target, 0.67 million mt. *MSY* is estimated to occur at an even smaller stock size, 0.46 million mt, with a yield of 317 thousand mt; only slightly higher than the equilibrium yield at the biomass target ($SB_{40\%}$), 290 thousand mt, and at the $F_{40\%}$ target, 299 thousand mt. The full set of reference points, with uncertainty intervals for the base case and among alternate sensitivity models, is reported in Table *f* below.

Exploitation status

The fishing intensity on the Pacific hake stock is estimated to have been below the $F_{40\%}$ target until 2007. Uncertainty in the value is large, and the base-case model estimates that the target has been exceeded in four of the last five years. The exploitation history in terms of both the biomass and *F*-target reference points is portrayed graphically via a phase-plot.

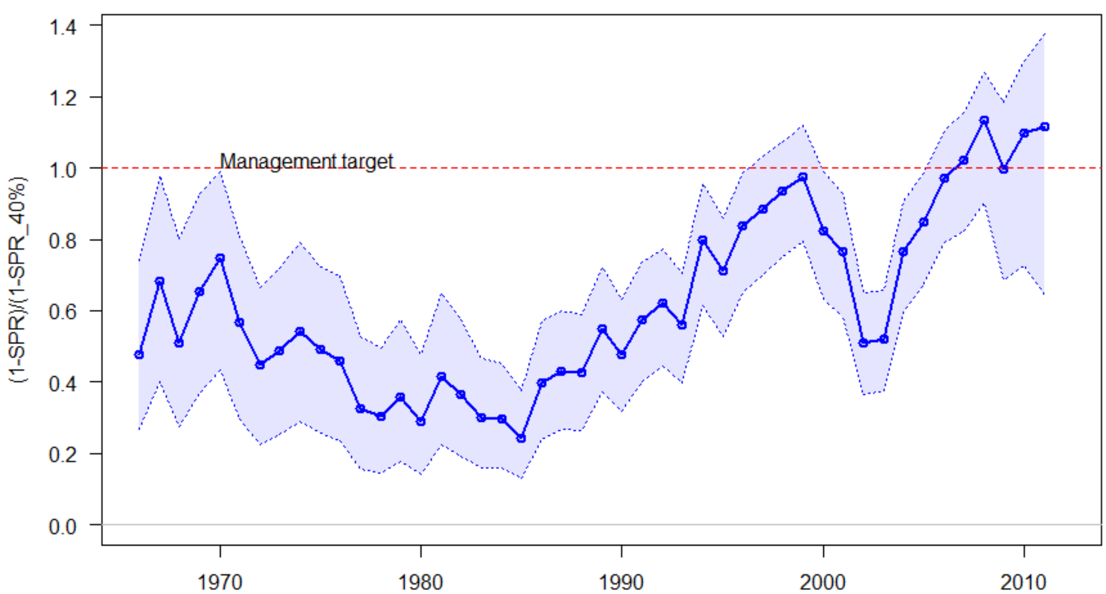


Figure f. Trend in fishing intensity (relative SPR) through 2011 with 95% posterior credibility intervals.

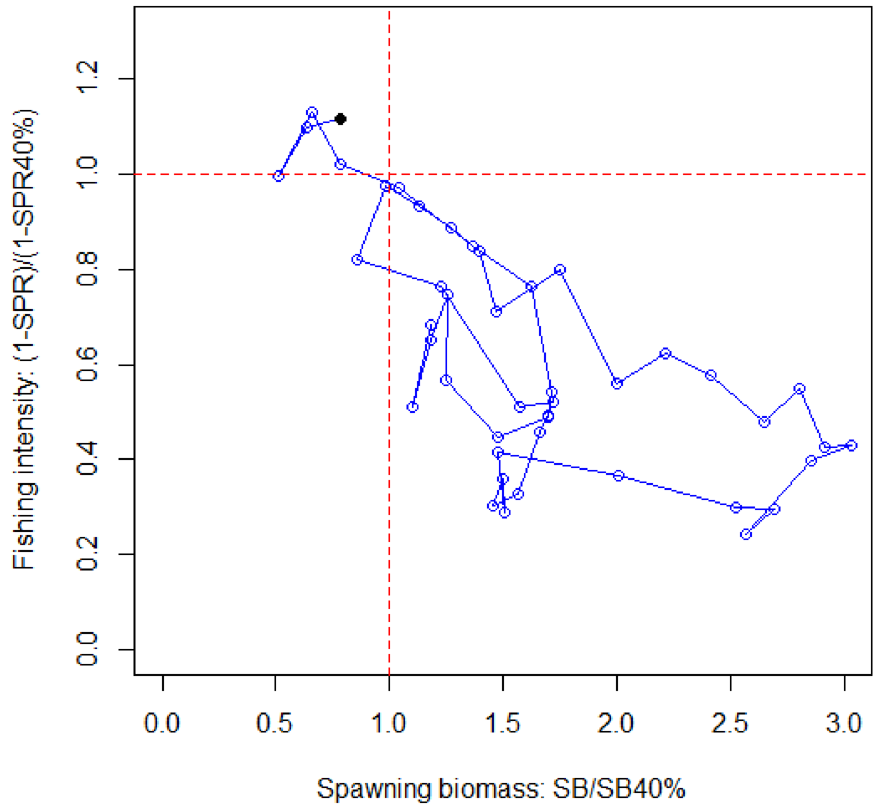


Figure g. Temporal pattern (phase plot) of posterior median fishing intensity vs. relative posterior median spawning biomass through 2011. The filled circle denotes 2011 and the line connects years through the time-series.

Table d. Recent trend in fishing intensity (relative spawning potential ratio; 1-SPR/1-$SPR_{40\%}$) and exploitation fraction.

	Fishing intensity			Exploitation fraction		
Year	2.5^{th} percentile	Median	97.5^{th} percentile	2.5^{th} percentile	Median	97.5^{th} percentile
2002	36.7%	51.0%	65.0%	3.7%	4.8%	5.7%
2003	37.6%	52.0%	65.8%	5.2%	6.6%	7.7%
2004	59.5%	76.5%	90.7%	10.6%	13.3%	15.2%
2005	67.4%	84.8%	98.7%	15.3%	19.5%	22.3%
2006	79.0%	97.2%	110.3%	17.9%	23.8%	27.5%
2007	82.5%	102.1%	115.7%	20.4%	29.1%	34.8%
2008	90.4%	113.2%	126.7%	18.8%	31.4%	40.2%
2009	68.5%	99.6%	118.4%	10.1%	20.3%	29.7%
2010	72.6%	109.8%	130.1%	15.0%	34.3%	58.3%
2011	64.4%	111.6%	137.4%	7.4%	23.3%	49.9%

Unresolved problems and major uncertainties

The base case assessment model integrates over the substantial uncertainty associated with several important model parameters including: acoustic survey catchability (*q*), the productivity of the stock (via the steepness parameter, *h*, of the stock-recruitment relationship), and the rate of natural mortality (*M*). Although the Bayesian results presented include estimation uncertainty, this within-model uncertainty is likely a gross underestimate of the true uncertainty in current stock status and future projections, since it does not include structural modeling choices, data-weighting uncertainty and scientific uncertainty in selection of prior probability distributions.

The JTC investigated a broad range of alternate models, and we present a subset of key sensitivity analyses in order to provide a broad qualitative comparison of structural uncertainty with the base case. The primary axis of this uncertainty is the structural approach to fishery and survey selectivity parameterization. The alternate models were run on two independent modeling platforms: (i) Stock Synthesis (SS), used for the base case and for previous Pacific hake stock assessments; and (ii) the Canadian Catch at Age Model (CCAM), first developed at the University of British Columbia (Martell 2011) and customized at the Pacific Biological Station for this assessment. Both models are thoroughly described in this assessment document. We report additional sensitivity analyses in the main text of this document.

Pacific hake displays the highest degree of recruitment variability of any west coast groundfish stock, resulting in large and rapid changes in stock biomass. This volatility, coupled with a dynamic fishery, which potentially targets strong cohorts, and a biennial rather than annual fishery-independent acoustic survey, will continue to result in highly uncertain estimates of current stock status and even less-certain projections of future stock trajectory. Currently uncertainty in this assessment is largely a function of the disparate survey indices in 2009 and 2011 coupled with the large, but uncertain 2008 year-class. The vast uncertainty in current status and future trends will likely persist as long as the acoustic survey is conducted only every other year, since the dynamics of Pacific hake are elastic enough for the assessment model to respond dramatically to each new biennial survey observation.

Given the uncertainty in stock status and magnitude, the JTC proposes that a Management Strategy Evaluation (MSE) be developed to explore topics including testing of the basic performance of the current harvest control rule. Many Pacific hake stock-assessment uncertainties may not be resolvable, but it may be possible to design management, data collection, and modeling strategies that provide an adequate trade-off in performance among stock and fishery objectives using MSE. The Pacific hake fishery is relatively data-rich, with a directed, fishery-independent survey program, substantial biological sampling for both commercial fisheries and the acoustic survey, and reliable estimates of catch. However, the data are apparently insufficient to resolve key uncertainties that can produce large differences in stock-status estimates between years, as observed in the acoustic index observations directly, or when all data are synthesized within an assessment model. The MSE approach is distinct from traditional stock assessment in that it seeks to find a management strategy that is robust to uncertainties and provides explicit evaluation of the expected trade-offs among conservation and yield objectives even when the current best assessment is in error. The process of identifying appropriate performance indicators required for a full MSE is very time consuming and should include management and stakeholder input, but one issue that could be tested immediately is analysis of whether stock assessment performance could be improved by investing in annual, rather than biennial, surveys. The experiment would consist of simulating the stock assessment procedure using the current biennial vs. annual surveys, under different assumptions about observation and process error, the number of survey stations, the harvest control rule and assessment procedures. Management procedures could, for example, be evaluated based on three main performance categories: catch, catch variability, and conservation (Cox and Kronlund 2008). For example, catch and catch variability could be represented by average annual catch and average absolute variation in catch (Punt and Smith 1999) and conservation could be represented in terms of the proportion of years that the stock was below target biomass levels.

Forecast decision table

In order to better reflect the considerable uncertainty in this assessment all forecasts are reported in two decision tables: one representing uncertainty within the base-case model; and the other representing uncertainty among alternate models. This allows for the evaluation of alternative management actions based on both types of uncertainty. The decision tables are organized such that the projected implications for each potential management action (the rows, containing a range of potential catch levels) can be evaluated across the quantiles of the posterior distribution for the base-case model (the columns), or among median estimates from the alternate models. For clarity, each decision table is divided into two sections: the first table projects the depletion estimates, the second the degree of fishing intensity (based on the relative SPR; see table legend). Fishing intensity exceeding 100% indicates fishing in excess of the $F_{40\%}$ default harvest rate. A set of management metrics were identified during the Scientific Review Group (SRG) review of this stock assessment, based on input from the Joint Management Committee (JMC), Advisory Panel (AP) and other attendees. These metrics summarize the probability of various outcomes from the base case model given each potential management action (Table g.5 below). Although not linear, probabilities can be interpolated from this table for intermediate catch values.

The median stock estimate from the base-case model is projected to increase or remain constant from 2012 to 2013 for all management actions considered except the *status quo*. However, the posterior distribution is highly uncertain, and either increasing or decreasing trends are possible over a broad range of 2012 catch levels. The base-case model predicts a rapid increase in the absence of future fishing, surpassing the management target with a 50% probability in 2013; this is attributable largely to the strong 2008 cohort. However, the difference between this trajectory and that conditioned on the default harvest rate is extremely small, relative to the uncertainty in the current stock status. There is 47% chance of exceeding the harvest target in 2012 for catch levels approaching the default harvest rate, however this level of catch corresponds to a 47% chance of having a smaller stock in 2013 than in 2012.

Among the key alternate sensitivity models, there is also considerable uncertainty in current status and future trends. Although these models fall within the ‘envelope’ of the posterior distribution from the base-case model, the median trajectories under each potential management action are somewhat more robust to alternate management actions.

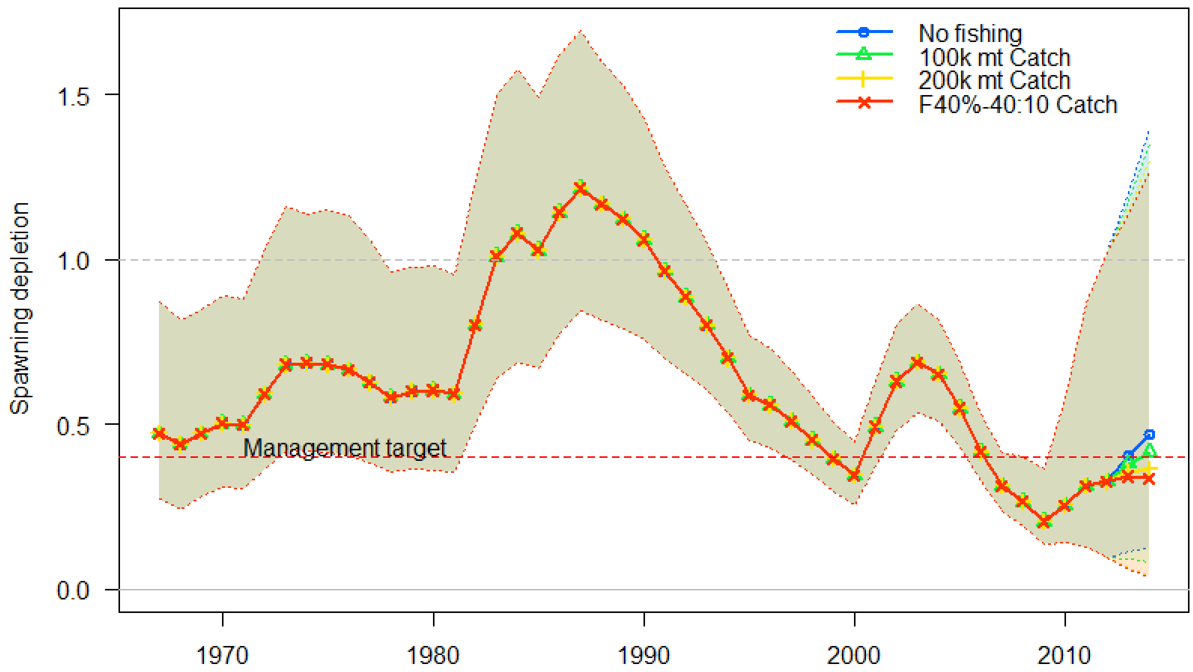


Figure h. Time-series of estimated spawning depletion through 2012 from the base-case model, and forecast trajectories for several arbitrary management options from the decision table, with 95% posterior credibility intervals.

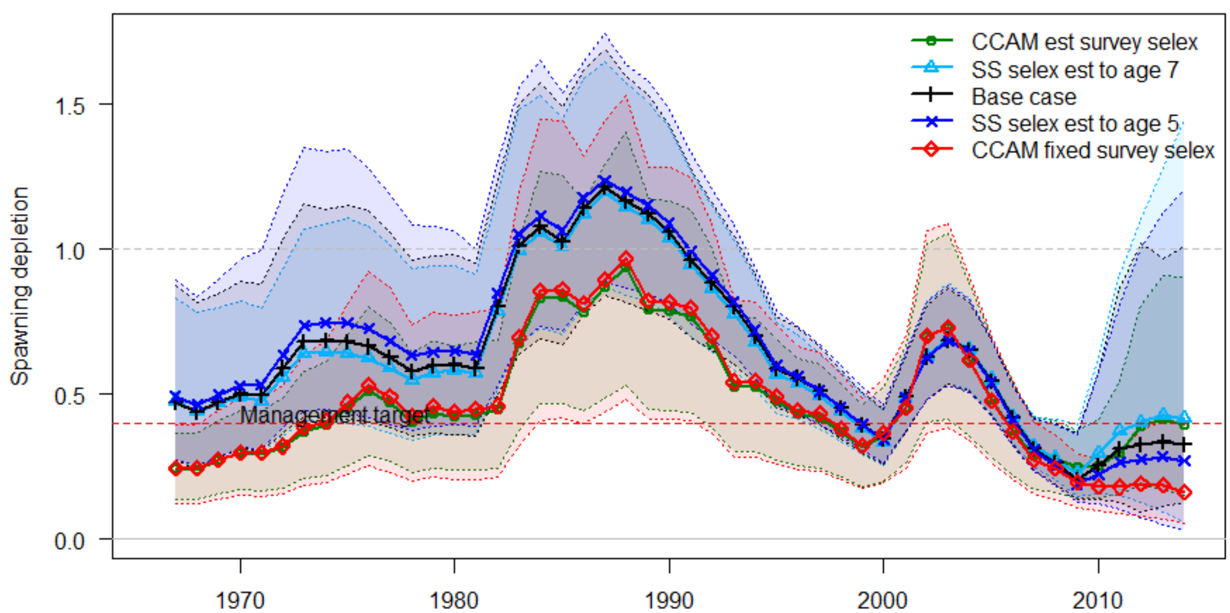


Figure i. Time-series of estimated spawning depletion through 2012 from the base-case model, with 95% posterior credibility intervals, and among alternate sensitivity models, with forecast trajectories for the $F_{40\%}$-40:10 default harvest rate catch level from the base-case model.

Table e.1. Posterior distribution quantiles for Pacific hake relative **depletion** (at the beginning of the year before fishing takes place) from the base model. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g).

Within model quantile			5%	25%	50%	75%	95%
Management Action							
	Year	Catch (mt)	**Beginning of year depletion**				
a	2012	0	11%	22%	33%	51%	86%
	2013	0	14%	28%	40%	60%	104%
	2014	0	18%	32%	47%	67%	120%
b	2012	50,000	11%	22%	33%	51%	86%
	2013	50,000	13%	27%	39%	59%	103%
	2014	50,000	15%	30%	44%	65%	117%
c	2012	100,000	11%	22%	33%	51%	86%
	2013	100,000	12%	25%	38%	58%	102%
	2014	100,000	13%	27%	41%	63%	115%
d	2012	150,000	11%	22%	33%	51%	86%
	2013	150,000	10%	24%	37%	57%	101%
	2014	150,000	10%	25%	39%	60%	113%
e	2012	200,000	11%	22%	33%	51%	86%
	2013	200,000	9%	23%	36%	56%	99%
	2014	200,000	8%	22%	37%	58%	111%
f	2012	251,809	11%	22%	33%	51%	86%
	2013	267,146	8%	21%	34%	54%	98%
	2014	277,887	6%	19%	34%	55%	109%
g	2012	393,751	11%	22%	33%	51%	86%
	2013	393,751	7%	18%	30%	51%	95%
	2014	393,751	5%	13%	27%	49%	102%

Table e.2. Posterior distribution quantiles for Pacific hake **fishing intensity (**spawning potential ratio; 1-SPR/1-$SPR_{40\%}$; values greater than 100% denote fishing in excess of the $F_{40\%}$ default harvest rate) from the base model. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g).

Within model quantile			5%	25%	50%	75%	95%
Management Action							
	Year	Catch (mt)			**Fishing intensity**		
	2012	0	0%	0%	0%	0%	0%
a	2013	0	0%	0%	0%	0%	0%
	2014	0	0%	0%	0%	0%	0%
	2012	50,000	13%	24%	36%	52%	79%
b	2013	50,000	11%	21%	31%	44%	71%
	2014	50,000	10%	18%	26%	38%	63%
	2012	100,000	25%	42%	59%	79%	107%
c	2013	100,000	22%	38%	53%	72%	104%
	2014	100,000	19%	33%	48%	66%	100%
	2012	150,000	35%	56%	76%	95%	121%
d	2013	150,000	31%	52%	71%	91%	122%
	2014	150,000	27%	47%	65%	87%	123%
	2012	200,000	43%	67%	87%	106%	129%
e	2013	200,000	39%	64%	84%	105%	132%
	2014	200,000	35%	59%	80%	104%	133%
	2012	251,809	51%	77%	97%	115%	133%
f	2013	267,146	49%	76%	97%	118%	135%
	2014	277,887	46%	74%	97%	120%	136%
	2012	393,751	68%	95%	113%	128%	137%
g	2013	393,751	65%	95%	116%	131%	138%
	2014	393,751	61%	94%	119%	132%	138%

Table e.3. Median of the posterior distribution for Pacific hake relative **depletion** (at the beginning of the year before fishing takes place) from alternate modeling approaches. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g). See main text for descriptions of alternative models.

Alternate models			CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Management action							
	Year	Catch (mt)			**Beginning of year depletion**		
a	2012	0	19%	27%	33%	40%	39%
	2013	0	25%	35%	40%	49%	48%
	2014	0	30%	40%	47%	55%	53%
b	2012	50,000	19%	27%	33%	40%	39%
	2013	50,000	24%	33%	39%	47%	47%
	2014	50,000	27%	37%	44%	52%	50%
c	2012	100,000	19%	27%	33%	40%	39%
	2013	100,000	23%	32%	38%	46%	45%
	2014	100,000	25%	35%	41%	50%	48%
d	2012	150,000	19%	27%	33%	40%	39%
	2013	150,000	21%	31%	37%	45%	44%
	2014	150,000	22%	32%	39%	47%	45%
e	2012	200,000	19%	27%	33%	40%	39%
	2013	200,000	20%	30%	36%	44%	43%
	2014	200,000	19%	30%	37%	45%	43%
f	2012	251,809	19%	27%	33%	40%	39%
	2013	267,146	19%	28%	34%	43%	42%
	2014	277,887	16%	27%	34%	42%	39%
g	2012	393,751	19%	27%	33%	40%	39%
	2013	393,751	15%	25%	30%	39%	38%
	2014	393,751	12%	21%	27%	35%	33%

Table e.4. Median of the posterior distribution for Pacific hake **fishing intensity** (spawning potential ratio; 1-SPR/1-$SPR_{40\%}$; values greater than 100% denote fishing in excess of the $F_{40\%}$ default harvest rate) from alternate modeling approaches. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g). See main text for descriptions of alternative models.

Alternate models			CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Management action							
	Year	Catch (mt)	**Fishing intensity**				
a	2012	0	0%	0%	0%	0%	0%
	2013	0	0%	0%	0%	0%	0%
	2014	0	0%	0%	0%	0%	0%
b	2012	50,000	58%	41%	36%	31%	34%
	2013	50,000	47%	33%	31%	26%	26%
	2014	50,000	40%	30%	26%	24%	22%
c	2012	100,000	86%	67%	59%	52%	57%
	2013	100,000	75%	57%	53%	46%	46%
	2014	100,000	69%	54%	48%	44%	41%
d	2012	150,000	102%	83%	76%	67%	72%
	2013	150,000	95%	75%	71%	62%	62%
	2014	150,000	91%	73%	65%	60%	57%
e	2012	200,000	113%	96%	87%	78%	84%
	2013	200,000	109%	89%	84%	74%	74%
	2014	200,000	108%	89%	80%	74%	71%
f	2012	251,809	121%	105%	97%	88%	93%
	2013	267,146	122%	103%	97%	87%	87%
	2014	277,887	126%	107%	97%	90%	88%
g	2012	393,751	132%	120%	113%	105%	110%
	2013	393,751	134%	122%	116%	106%	107%
	2014	393,751	135%	126%	119%	110%	110%

Table e.5. Probabilities of various management metrics given different catch alternatives. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt, 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case, and the *status quo* catch target.

Catch	$P(SB_{2013}>SB_{2012})$	$P(SB_{2013}>SB_{40\%})$	$P(SB_{2013}>SB_{25\%})$	$P(SB_{2013}>SB_{10\%})$	P(Fishing intensity in 2012 > 40% Target)
0	>99%	51%	80%	99%	0%
50,000	99%	49%	78%	98%	<1%
100,000	88%	46%	76%	96%	7%
150,000	74%	44%	73%	95%	17%
200,000	58%	42%	70%	94%	31%
251,809	47%	40%	68%	93%	47%
393,751	28%	35%	61%	91%	70%

Research and data needs

There are many areas of research that could improve stock assessment efforts, however we focus here on those efforts that might appreciably reduce the uncertainty (both perceived and unknown) in short-term forecasts for management decision-making. This list is in prioritized order:

1) Conduct an annual acoustic survey.

2) Develop management strategy evaluation (MSE) tools to evaluate major sources of uncertainty relating to data, model structure and the harvest control rule for this fishery and compare potential methods to address them.

3) Continue to explore alternative indices for juvenile or young (0 and/or 1 year old) Pacific hake.

4) Apply bootstrapping methods to the acoustic survey time-series in order to bring more of the relevant components into the variance calculations. These factors include the target strength relationship, subjective scoring of echograms, thresholding methods, the species-mix and demographic estimates used to interpret the acoustic backscatter, and others.

5) Routinely collect life history information, including maturity and fecundity data for Pacific hake. Explore possible relationships among these observations as well as with growth and population density. Currently available information is limited and outdated.

6) Evaluate the quantity and quality of historical biological data (prior to 1988 from the Canadian fishery, and prior to 1975 from the U.S. fishery) for use in developing age-composition data.

7) Conduct further exploration of ageing imprecision and the effects of large cohorts via simulation and blind source age-reading of samples with differing underlying age distributions – with and without dominant year classes.

8) Continue to explore process-based assessment modeling methods that may be able to use the large quantity of length observations to reduce model uncertainty and better propagate life-history variability into future projections.

9) Investigate meta-analytic methods for developing a prior on degree of recruitment variability (σ_r), and for refining existing priors for natural mortality (M) and steepness of the stock-recruitment relationship (h).

Table f.1. Summary of Pacific hake reference points for the base-case model.

Quantity	2.5th percentile	Median	97.5th percentile
Unfished female *SB* (SB_0, millions mt)	1.489	1.888	2.529
Unfished recruitment (R_0, billions)	1.540	2.326	3.976
Reference points based on $SB_{40\%}$			
Female spawning biomass ($SB_{40\%}$ million mt)	0.595	0.755	1.011
$SPR_{SB40\%}$	40.6%	43.5%	52.1%
Exploitation fraction resulting in $SB_{40\%}$	13.5%	18.6%	23.2%
Yield at $SB_{40\%}$ (million mt)	0.207	0.290	0.433
Reference points based on $F_{40\%}$			
Female spawning biomass ($SB_{F40\%}$ million mt)	0.501	0.670	0.902
$SPR_{MSY\text{-}proxy}$	0.40	0.40	0.40
Exploitation fraction corresponding to SPR	18.1%	21.4%	25.7%
Yield at $SB_{F40\%}$ (million mt)	0.210	0.299	0.443
Reference points based on estimated MSY			
Female spawning biomass (SB_{MSY} million mt)	0.291	0.460	0.781
SPR_{MSY}	18.3%	28.9%	47.9%
Exploitation fraction corresponding to SPR_{MSY}	15.9%	33.0%	56.9%
MSY (million mt)	0.215	0.317	0.482

Table f.2. Summary of Pacific hake reference points (median values) across alternate sensitivity models. Note that recruits are defined as age-0 in SS and age-1 in CCAM.

Quantity	CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Unfished female *SB* (SB_0, million mt)	1.905	1.912	1.888	1.909	1.963
Unfished recruitment (R_0, billions)	1.631	2.367	2.326	2.367	1.776
Reference points based on $SB_{40\%}$					
*F*emale spawning biomass ($SB_{40\%}$ million mt)	0.762	0.765	0.755	0.764	0.785
$SPR_{SB40\%}$	42.7%	43.6%	43.5%	43.7%	42.6%
Exploitation fraction resulting in $SB_{40\%}$	16.5%	18.5%	18.6%	18.8%	17.0%
Yield at $SB_{40\%}$ (million mt)	0.264	0.293	0.290	0.295	0.285
Reference points based on $F_{40\%}$					
Female spawning biomass ($SB_{F40\%}$ million mt)	0.697	0.680	0.670	0.676	0.724
$SPR_{MSY\text{-}proxy}$	0.40	40%	40%	40%	0.4
Exploitation fraction corresponding to SPR	18.4%	21.3%	21.4%	21.5%	18.7%
Yield at $SB_{F40\%}$ (million mt)	0.271	0.302	0.299	0.302	0.292
Reference points based on estimated MSY					
Female spawning biomass (SB_{MSY} million mt)	0.441	0.470	0.460	0.471	0.449
SPR_{MSY}	26.2%	28.9%	28.9%	29.4%	26.2%
Exploitation fraction corresponding to SPR_{MSY}	31.2%	32.6%	33.0%	32.5%	32.4%
MSY (million mt)	0.293	0.320	0.317	0.318	0.319

1. Introduction

Prior to 1997, separate Canadian and U.S. assessments for Pacific hake were submitted to each nation's assessment review process. This practice resulted in differing yield options being forwarded to each country's managers for this shared trans-boundary fish stock. Multiple interpretations of Pacific hake status made it difficult to coordinate an overall management policy. Since 1997, the Stock Assessment and Review (STAR) process for the Pacific Fishery Management Council (PFMC) has evaluated assessment models and the PFMC council process, including NOAA Fisheries, has generated management advice that has been largely utilized by both nations. The Joint US-Canada treaty on Pacific hake was formally ratified in 2006 (signed in 2007) by the United States as part of the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act. Although the treaty has been considered in force by Canada since June 25, 2008, an error in the original U.S. text required that the treaty be ratified again before it could be implanted. This second ratification occurred in 2010. Under the treaty, Pacific hake stock assessments are to be prepared by the Joint Technical Committee (JTC) comprised of both U.S. and Canadian scientists and reviewed by the Scientific Review Group (SRG), with memberships to both groups appointed by both parties to the agreement.

In keeping with the spirit of the treaty, this stock assessment document represents the work of a joint U.S. and Canadian JTC and their associates. Extensive modeling efforts conducted during 2010 and 2011 as well as highly productive discussions among analysts have resulted in unified documents for both the 2011 and 2012 (present) assessments.

This assessment reports a single base-case model representing the collective work of the Joint Technical Committee (JTC). The assessment depends primarily upon the acoustic survey biomass index (1995, 1998, 2001, 2003, 2005, 2007, 2009 and 2011) for information on the scale of the current hake stock. The 2011 index was the lowest in the time-series. The aggregate fishery age-composition data (1975-2011) and the age-composition data from the acoustic survey contribute to the models ability to resolve strong and weak cohorts. Both sources show a strong 2008 cohort, but differ somewhat in the relative magnitude of the weaker 2005 and 2006 cohorts.

The assessment is fully Bayesian, with the base-case model incorporating prior information on two key parameters (natural mortality, M, and steepness of the stock-recruit relationship, h) and integrating over estimation and parameter uncertainty to provide results that can be probabilistically interpreted. From a range of alternate models investigated by the JTC, a subset of sensitivity analyses are also reported in order to provide a broad qualitative comparison of structural uncertainty with the base case. The primary axis of this uncertainty is the structural approach to fishery and survey selectivity parameterization. The alternate models were run on two independent modeling platforms: (i) Stock Synthesis (SS), used for the base case and in previous Pacific hake stock assessments; and (ii) the Canadian Catch at Age Model (CCAM), developed at the University of British Columbia (Martell et al. 2011) and customized for this assessment by the authors of this assessment. Both models are thoroughly described in this assessment document.

The current document highlights progress made during 2011, residual areas of needed research, as well as ongoing scientific uncertainties in modeling choices, such that future technical working groups will enjoy a much easier working environment which fosters collaborative solutions to these difficult issues.

1.1 Stock structure and life history

Pacific hake (*Merluccius productus*), also referred to as Pacific whiting, is a semi-pelagic schooling species distributed along the west coast of North America generally ranging from 25^0 N. to 55^0 N. latitude. It is among 18 species of hake from four genera (being the majority of the family *Merluccidae),* which are distributed worldwide in both hemispheres of the Atlantic and Pacific oceans and recently generate around 1.25 million mt of catch annually (Alheit and Pitcher 1995, Lloris et al. 2005). The coastal stock of Pacific hake is currently the most abundant groundfish population in the California Current system. Smaller populations of this species occur in the major inlets of the Northeast Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California. Genetic studies indicate that Strait of Georgia and the Puget Sound populations are genetically distinct from the coastal population (Iwamoto et al. 2004; King et al. 2012). Genetic differences have also been found between the coastal population and hake off the west coast of Baja California (Vrooman and Paloma 1977). The coastal stock is also distinguished from the inshore populations by larger body size and seasonal migratory behavior.

The coastal stock of Pacific hake typically ranges from the waters off southern California to southern Alaska, with the northern boundary related to fluctuations in annual migration. However, a recent genetic and parasite-load study found evidence of some summer mixing with inshore stocks in Queen Charlotte Sound (King et al. 2012). Distributions of eggs, larvae, and infrequent observations of spawning aggregations indicate that Pacific hake spawning occurs off south-central California during January-March. Due to the difficulty of locating major offshore spawning concentrations, details of spawning behavior of hake remains poorly understood (Saunders and McFarlane 1997). In spring, adult Pacific hake migrate onshore and to the north to feed along the continental shelf and slope from northern California to Vancouver Island. In summer, Pacific hake form extensive mid-water aggregations in association with the continental shelf break, with highest densities located over bottom depths of 200-300 m (Dorn 1991, 1992). Pacific hake feed on euphausiids, pandalid shrimp, and pelagic schooling fish (such as eulachon and Pacific herring) (Livingston and Bailey 1985). Larger Pacific hake become increasingly piscivorous, and Pacific herring are commonly a large component of hake diet off Vancouver Island. Although Pacific hake are cannibalistic, the geographic separation of juveniles and adults usually prevents cannibalism from being an important factor in their population dynamics (Buckley and Livingston 1997).

Older Pacific hake exhibit the greatest northern migration each season, with two- and three-year old fish rarely observed in Canadian waters north of southern Vancouver Island. During El Niño events (warm ocean conditions, such as 1998), a larger proportion of the stock migrates into Canadian waters, apparently due to intensified northward transport during the period of active migration (Dorn 1995, Agostini et al. 2006). El Niño conditions also result in range extensions to the north, as evidenced by reports of hake off of southeast Alaska during these warm water years. Throughout the warm period experienced in 1990s, there were changes in typical patterns of hake distribution. Spawning activity was recorded north of California. Frequent reports of unusual numbers of juveniles off of Oregon to British Columbia suggest that juvenile settlement patterns also shifted northwards in the late 1990s (Benson et al. 2002, Phillips et al. 2007). Because of this shift, juveniles may have been subjected to increased cannibalistic predation and fishing mortality. However, the degree to which this was significant, and the proportion of the spawning and juvenile settlement that was further north than usual is unknown. Subsequently, La Nina conditions (colder water) in 2001 resulted in a southward shift in the stock’s distribution, with a much smaller proportion of the population found in Canadian waters in the 2001 survey. Hake were distributed across the entire range of the survey in 2003, 2005, 2007 (Figures 1 and 2) after displaying a very southerly distribution in 2001. Although a few adult hake (primarily from the 1999 cohort) were observed north of the Queen Charlotte Islands in 2009 most of the stock appears to have been distributed off Oregon and Washington. The 2011 acoustic survey observed what appears to have been the most southerly distribution of Pacific hake since 2001. Some adult hake were observed in the Quatsino area (northwest Vancouver Island), but most of the stock was found off the coasts of Washington, Oregon, and California (Figure 1).

1.2 Ecosystem considerations

Pacific hake are an important contributor to ecosystem dynamics in the Eastern Pacific due to their relatively large total biomass and potentially large role as both prey and predator in the Eastern Pacific Ocean. The role of hake predation in the population dynamics of other groundfish species is likely to be important (Harvey et al. 2008), although difficult to quantify. Hake migrate farther north during the summer during relatively warm water years and their local ecosystem role therefore differs year-to-year depending on environmental conditions. Recent research indicates that hake distributions may be growing more responsive to temperature, and that spawning and juvenile hake may be occurring farther North (Phillips et al. 2007; Ressler et al. 2007). Given long-term climate-change projections and changing distributional patterns, considerable uncertainty exists in any forward projections of stationary stock productivity and dynamics.

Hake are also important prey items for many piscivorous species including lingcod (*Ophiodon elongatus*) and Humboldt squid (also known as jumbo flying squid, *Dosidicus gigas*). In recent years, the coastal U.S. lingcod stock has rebuilt rapidly from an overfished level and jumbo flying squid have intermittently extended their range northward from more tropical waters to the west coast of North America. Recent Humboldt squid observations in the hake fishery, recreational fisheries, and scientific surveys in the U.S. and Canada reflect a very large increase in squid abundance as far north as southeast Alaska (e.g., Gilly et al., 2006; Field et al., 2007) during the same portions of the year that hake are present, although the number and range vary greatly between years. While the relative biomass of these squid and the cause of such range extensions are not completely known, squid predation on Pacific hake is likely to have increased substantially in some years. There is evidence from the Chilean hake (a similar gadid species) fishery that squid may have a large and adverse impact on abundance, due to direct predation on individuals of all sizes (Alarcón-Muñoz et al., 2008). Squid predation as well as secondary effects on schooling behavior and distribution of Pacific hake may become important for future assessments, however it is unlikely that the current data sources will be able to detect squid-related changes in population dynamics (such as an increase in natural mortality) until well after they have occurred, if at all. There is considerable ongoing research to document relative abundance, diet composition and habitat utilization of Humboldt squid in the California current ecosystem (e.g., J. Field, SWFSC, and J. Stewart, Hopkins Marine Station, personal communication, 2010; Gilly et al., 2006; Field et al., 2007) which should be considered in future assessments. However, there were very few Humboldt squid present in the California Current during 2010 and 2011, despite the great abundance in 2009. Given the volatility of squid populations, future presence and abundance trends are impossible to predict.

1.3 Fisheries

The fishery for the coastal population of Pacific hake occurs along the coasts of northern California, Oregon, Washington, and British Columbia primarily during April-November. The fishery is conducted almost exclusively with mid-water trawls. Most fishing activity occurs over bottom depths of 100-500 m, while offshore extensions of fishing activity have occurred in recent years to reduce bycatch of depleted rockfish and salmon. The history of the coastal hake fishery is characterized by rapid changes brought about by the development of substantial foreign fisheries in 1966, joint-venture fisheries by the early 1980s, and domestic fisheries in 1990s (Table 1).

Large-scale harvesting of Pacific hake in the U.S. zone began in 1966, when factory trawlers from the Soviet Union began targeting Pacific hake. During the mid-1970s, factory trawlers from Poland, Federal Republic of Germany, the German Democratic Republic and Bulgaria also participated in the fishery. During 1966-1979, the catch in U.S. waters is estimated to have averaged 137,000 t per year (Table 1, Figure 3). A joint-venture fishery was initiated in 1978 between two U.S. trawlers and Soviet factory trawlers acting as mother-ships (the practice where the catch from several boats is brought back to the larger, slower ship for processing and storage until the return to land). By 1982, the joint-venture catch surpassed the foreign catch, and by 1989, the U.S. fleet capacity had grown to a level sufficient to harvest the entire quota, and no further foreign fishing was allowed, although joint-venture fisheries continued for another two years. In the late 1980's, joint ventures involved fishing companies from Poland, Japan, the former Soviet Union, the Republic of Korea and the People's Republic of China.

Historically, the foreign and joint-venture fisheries produced fillets as well as headed and gutted products. In 1989, Japanese mother-ships began producing surimi from Pacific hake using a newly developed process to inhibit myxozoan-induced proteolysis. In 1990, domestic catcher-processors and mother ships entered the Pacific hake fishery in the U.S. zone. These vessels had previously and continue to engage in Alaskan walleye pollock (*Theragra chalcogramma*) fisheries. The development of surimi production techniques for pollock was expanded to include Pacific hake as a viable alternative. Similarly, shore-based processors of Pacific hake had been constrained by a limited domestic market for Pacific hake fillets and headed and gutted products. The construction of surimi plants in Newport and Astoria, Oregon, led to a rapid expansion of shore-based landings in the U.S. fishery in the early 1990's, when the Pacific council set aside an allocation for that sector. In 1991, the joint-venture fishery for Pacific hake in the U.S. zone ended because of the increased level of participation by domestic catcher-processors and mother ships, and the growth of shore-based processing capacity. In contrast, Canada, at its discretion, allocates a portion of the Pacific hake catch to joint-venture operations once shore-side capacity is filled.

The sectors involved in the Pacific hake fishery in Canada exhibit a similar historical pattern, although phasing out of the foreign and joint-venture fisheries has proceeded more slowly relative to the U.S. (Table 1). Since 1968, more Pacific hake have been landed than any other species in the groundfish fishery on Canada's west coast. Prior to 1977, the fishing vessels from the former Soviet Union caught the majority of Pacific hake in the Canadian zone, with Poland and Japan accounting for much smaller landings. After declaration of the 200-mile extended fishing zone in 1977, the Canadian fishery was divided among shore-based, joint-venture, and foreign fisheries. In 1992, the foreign fishery ended, but the demand of Canadian shore-based processors remained below the available yield, thus the joint-venture fishery continues today, although no joint-venture fishery took place in 2002, 2003, or 2009. The majority of the shore-based landings of the coastal hake stock is processed into fillets for human consumption, surimi, or mince by processing plants at Ucluelet, Port Alberni, and Delta, British Columbia. Although significant aggregations of hake are found as far north as Queen Charlotte Sound, in most years the fishery has been concentrated below 49° N. latitude off the south coast of Vancouver Island, where there have been sufficient quantities of fish in proximity to processing plants.

1.4 Management of Pacific hake

Since implementation of the Magnuson-Stevens Fishery Conservation and Management Act in the U.S. and the declaration of a 200-mile fishery conservation zone in Canada in the late 1970's, annual harvest quotas have been the primary management tool used to limit the catch of Pacific hake. Scientists from both countries historically collaborated through the Technical Subcommittee of the Canada-U.S. Groundfish Committee (TSC), and there were informal agreements on the adoption of annual fishing policies. During the 1990s, however, disagreements between the U.S. and Canada on the allotment of the catch limits between U.S. and Canadian fisheries led to quota overruns; 1991-1992 quotas summed to 128% of the limit, while the 1993-1999 combined quotas were 107% of the limit on average. In the current Pacific hake agreement, the United States is allocated 73.88% of the total coast-wide harvest and Canada 26.12%.

In the last decade, the total coast-wide catch has tracked the harvest targets reasonably closely (Table 2). In 2002, after Pacific hake was declared overfished by the U.S., the catch of 181 thousand metric tons exceeded the target; however it was still below the limit of 208 thousand mt. In 2004, after Pacific hake was declared rebuilt, and when the large 1999 cohort was at near-peak biomass, the catch fell well short of the catch target of 501 thousand mt which is larger than the largest catch ever realized. Constraints imposed by bycatch of canary and widow rockfishes limited the commercial U.S. catch target to 259 thousand mt. Neither the U.S. portion nor the total catch has substantially exceeded the harvest guidelines in any recent year, indicating that management procedures have been effective.

1.4.1 United States

In the U.S. zone, participants in the directed fishery are required to use pelagic trawls with a codend mesh that is at least 7.5 cm (3 inches). Regulations also restrict the area and season of fishing to reduce the bycatch of Chinook salmon and several depleted rockfish stocks. More recently, yields in the U.S. zone have been restricted to levels below optimum yields due to bycatch of overfished rockfish species, primarily widow and canary rockfishes, in the Pacific hake fishery. At-sea processing and night fishing (midnight to one hour after official sunrise) are prohibited south of 42° N. latitude. Fishing is prohibited in the Klamath and Columbia River Conservation zones, and a trip limit of 10,000 pounds is established for Pacific hake caught inside the 100-fathom contour in the Eureka INPFC area. During 1992-1995, the U.S. fishery opened on April 15; however in 1996 the opening date was changed to May 15. Shore-based fishing is allowed after April 1 south of 42° N. latitude, but is limited to 5% of the shore-based allocation being taken prior to the opening of the main shore-based fishery. The main shore-based fishery opens on June 15. Prior to 1997, at-sea processing was prohibited by regulation when 60 percent of the harvest guideline was reached. The current allocation agreement, effective since 1997, divides the U.S. non-tribal harvest guideline among factory trawlers (34%), vessels delivering to at-sea processors (24%), and vessels delivering to shore-based processing plants (42%). Since 1996, the Makah Indian Tribe has conducted a separate fishery with a specified allocation in its "usual and accustomed fishing area", and beginning in 2009 there has also been a Quileute tribal allocation.

1.4.2 Industry actions

Shortly after the 1997 allocation agreement was approved by the PFMC, fishing companies owning factory trawlers with U.S. west coast groundfish permits established the Pacific Whiting Conservation Cooperative (PWCC). The primary role of the PWCC is to allocate the factory trawler quota among its members to allow more efficient allocation of resources by fishing companies, improvements in processing efficiency and product quality, and a reduction in waste and bycatch rates relative to the former "derby" fishery in which all vessels competed for a fleet-wide quota. The PWCC also initiated recruitment research to support hake stock assessment. As part of this effort, PWCC sponsored a juvenile recruit survey in the summers of 1998 and 2001, which since 2002 has become an ongoing collaboration with NMFS. In 2009, the PWCC contracted a review of the 2009 stock assessment which was discussed in the 2010 stock assessment and was one of the contributing factors to the extensive re-analysis of historical data and modeling methods subsequent to that assessment.

1.5 Overview of Recent Fisheries

1.5.1 United States

In 2005 and 2006, the coast-wide ABCs were 531,124 and 661,680 mt respectively. The OYs for these years were set at 364,197 and 364,842 and were nearly fully utilized with abundant 1999 year-class comprising nearly all of the catch. For the 2007 fishing season the PFMC adopted a 612,068 mt ABC and a coast-wide OY of 328,358 mt. This coast-wide OY continued to be set considerably below the ABC in order to avoid exceeding bycatch limits for overfished rockfish. In 2008, the PFMC adopted an ABC of 400,000 mt and a coast-wide OY of 364,842 mt, based upon the 2008 stock assessment. This ABC was set below the overfishing level indicated by the stock assessment, and therefore the difference between the ABC and OY was substantially less than in prior years. However, the same bycatch constraints caused a mid-season closure in the U.S. in both 2007 and 2008 and resulted in final landings being below the OY in both years. Based on the 2009 assessment, the Pacific council adopted a U.S.-Canada coast-wide ABC of 253,582 mt, and a U.S. ABC of 187,346 mt. The council adopted a U.S.-Canada coast-wide OY of 184,000 mt and a U.S. OY of 135,939 mt, reflecting the agreed-upon 73.88% of the OY apportioned to U.S. fisheries and 26.12% to Canadian fisheries. Bycatch limits were assigned to each sector of the fishery for the first time in 2009, preventing the loss of opportunity for all sectors if one sector exceeded the total bycatch limit. This greatly reduced the 'race for fish' as bycatch accumulated during the season. In total, the 2009 U.S. fishery caught 121,110 mt, or 89.1% of the U.S. OY, without exceeding bycatch limits. In 2010 the Pacific council adopted a U.S.-Canada coast-wide ABC of 455,550 mt, a U.S.-Canada coast-wide OY of 262,500 mt and a U.S. OY of 190,935 mt, reflecting the agreed-upon apportionment. As in 2009, tribal fisheries did not harvest the full allocation granted them (49,939 mt in 2010), and two reapportionments were made to other sectors during the fishing season. In total, the 2010 U.S. fishery caught 170,109 mt, or 89.1% of the U.S. OY. Bycatch rates were generally not a problem, although known areas of high historical bycatch were still (anecdotally) being avoided. For periods during the fishing season and in certain areas of the coasts, many fishermen found it difficult to avoid the large schools of age-2 hake (200-300 grams) present off the U.S. coast. There were reports that increased search time resulted from efforts to avoid the schools of smaller fish. This was especially so for the shore-side fishery, which due to the presence of these small fish, and to avoid bycatch of canary rockfish, opted for a voluntary stand-down between June 30 to July 20. Some processors were able to make changes during the season in order to process the smaller fish. The U.S. tribal fishery reported a reduced amount of hake in their fishing areas and generally smaller sized fish.

The Pacific Council adopted a U.S.-Canada coast-wide overfishing level (OFL) of 973,700 mt in 2011, with an annual catch limit (ACL) of 393,751 mt. The U.S. annual catch limit was 290,903 mt, after apportioning the coast-wide ACL by the agreed upon U.S.-Canada apportionment. Tribal allocation was 17.5% of the U.S. ACL plus 16,000 mt, resulting in 66,908 mt. Therefore, given 3,000 mt for research catch and bycatch in non-groundfish fisheries, the 2011 non-tribal U.S. catch limit of 220,995 mt was allocated to the catcher/processor (34%), mothership (24%), and shore-based (42%) commercial sectors. Therefore, the at-sea fleet (catcher/processors and motherships) was allocated 128,177 mt and the shore-based fleet was allocated 92,818 mt.

The 2011 U.S. fisheries caught 78.7% of their catch limit (229,067 mt) and were below the 2011 catch limit mainly due to smaller tribal catches. This year was the first time that motherships participated under the co-op system, thus were able to pool bycatch limits. Remaining mothership bycatch allocations were transferred to the catcher/processor sector in mid-December. This was also the first year that the shore-based fleet operated under the new catch shares program with individual fishing quotas (IFQ). All U.S. sectors encountered smaller fish in the 35–40 cm range, dominated by the 2008 year class. In previous years, the fishery may have avoided these small fish, but markets for smaller fish appear to be developing in 2011. The at-sea fleet encountered larger fish in May, which were encountered less often in June and rarely after then. The at-sea fleet additionally encountered even smaller fish in October through December, ranging in size from 24–34 cm, which likely corresponds to the 2009 year class and possibly the 2010 year class. Bycatch was generally not an issue, but anecdotal evidence suggests that the fishery was avoiding aggregations of larger fish to avoid bycatch of rockfish.

1.5.2 Canada

The Canadian fishery has operated under an Individual Vessel Quota (IVQ) management system since 1997. Groundfish trawl vessels are allocated a set percentage of the Canadian TAC that is fully transferable within the trawl sector. Additionally the IVQ management regime allows an opportunity for vessel owners to exceed license holding by up to 15% and have these overages deducted from the quota for the subsequent year. Conversely, if less than the quota is taken, up to 15% can be carried over into the next year. For example, an apparent overage in 1998 was due to carry-over from 1997 when 9% of the quota was not taken; this policy has not resulted in catch exceeding the coast-wide OY in the past 8 years (Table 1).

Canadian Pacific hake quotas were fully utilized in the 2005 fishing season with 85,284 mt and 15,178 mt taken by the shore-based and joint venture fisheries, respectively. In 2006, the joint-venture and shore-based fisheries harvested 13,700 mt and 80,000 mt, respectively. During the 2007 fishing season, Canadian fisheries harvested 85% of the 85,373 mt allocation. In 2008, Canadian fisheries harvested 78% of the 95,297 mt allocation with joint-venture and shore-based sectors catching 3,590 mt and 70,160 mt, respectively. During the 2009 season, no catches were made under joint-venture program. The Canadian shore-based fishery harvested 55,620 mt in 2009, or 115.7% of the Canadian OY. The 2010 season had an established TAC of 68,565 mt, or 26.12% of the coast-wide OY taking into account the 2010 assessment, and in agreement with actions of the PFMC on setting the coast-wide OY. The carry forward from the 2009 season was 5,877 mt resulting in a total allowable harvest of 74,442 mt. This was allocated as 65,942 mt for delivery to shore-based facilities and 8,500 mt for delivery to the joint-venture fleet. The total catch for each fleet was 48,833 mt and 8,242 mt respectively, giving a total of 57,075 mt, or 77.0% of the 2010 quota. Since 23% of the quota was not captured in 2010, the Canadian fishery carried over the maximum 15% into the 2011 season, as an overage allowance for 2011. The total catch for 2011 was 56,050mt split between the domestic and JV fisheries as 46,333mt and 9,717mt respectively, far less than the TAC for the year. This difference means there will again be a 15% overage allowance for the 2012 fishery. The JV fishery ended in early September due to lack of fish.

The 2011 fishery commenced in January near the La Perouse area off the west coast of Vancouver Island. There were approximately 24 mt landed from January 1- March 3, 2011. In April the fishery began to catch more significant amounts, with most of the landings taking place in the summer and fall as follows: August with 15,403 mt, September with 12,607 mt, October with 10,767 mt, and November with 6,039 mt.

From July to mid-August, most of the fishing took place in the traditional area around La Perouse Bank. In August, the fishery was divided between Queen Charlotte Sound and South La Perouse, near the US-Canada border, with JV and domestic fisheries working in both areas. This spatial shift of the fishery to Queen Charlotte Sound has been occurring for the past four years. From September through the end of November much of the fishing took place in the Quatsino Sound area, near Brooks Peninsula on the northwest coast of Vancouver Island, an area which has not been targeted to this extent before. Unlike the 2009 and 2010 fishery, there were no significant catches in the Strait of Juan de Fuca in 2011.

2. Available data sources

Nearly all of the data sources available for Pacific hake were re-evaluated during 2010. That process included obtaining the original raw data, reprocessing the entire time-series with standardized methods, and summarizing the results for use in the 2011 stock assessment. These sources have been updated with all newly available information for 2012. Primary fishery-dependent and -independent data sources used here (Figure 4) include:

- Total catch from all U.S. and Canadian fisheries (1966-2011).
- Age compositions from the U.S. fishery (1975-2011) and Canadian fishery (1990-2011).
- Biomass indices and age compositions from the Joint U.S. and Canadian integrated acoustic and trawl survey (1995, 1998, 2001, 2003, 2005, 2007, 2009, and 2011).

Some sources were not included but have been explored, used for sensitivity analyses, or discarded in recent stock assessments (these data are discussed in more detail below):

- Fishery and acoustic survey length composition information.
- Fishery and acoustic survey age-at-length composition information.
- Biomass indices and age compositions from the Joint U.S. and Canadian integrated acoustic and trawl survey (1977, 1980, 1983, 1986, 1989, 1992).
- NWFSC/SWFSC/PWCC coast-wide juvenile hake and rockfish survey (2001-2009).
- Bycatch of Pacific hake in the trawl fishery for pink shrimp off the coast of Oregon, 2004-2005, 2007-2008.
- Historical biological samples collected in Canada prior to 1990, but currently not available in electronic form.
- Historical biological samples collected in the U.S. prior to 1975, but currently not available in electronic form or too incomplete to allow analysis with methods consistent with more current sampling programs.
- CalCOFI larval hake production index, 1951-2006. The data source was previously explored and rejected as a potential index of hake spawning stock biomass, and has not been revisited since the 2008 stock assessment.
- Joint-U.S. and Canada Acoustic survey index of age-1 Pacific hake.

The assessment model also used biological relationships derived from external analysis of auxiliary data. These include:

- Mean observed weight (at both size and age) from fishery and survey catches, 1975-2011.
- Mean observed length-at-age from fishery and survey catches, 1975-2011.
- Proportion of individual female hake mature by size and/or age from a sample collected in 1995.
- Aging-error matrices based on cross-read and double-blind-read otoliths.

2.1 Fishery-dependent data

2.1.1 Total catch

The catch of Pacific hake for 1966-2011 by nation and fishery sector is shown in Table 1. Catches in U.S. waters prior to 1978 are available only by year from Bailey et al. (1982) and historical assessment documents. Canadian catches prior to 1989 are also unavailable in disaggregated form. For more recent catches, haul or trip-level information was available to partition the removals by month, during the hake fishing season, and estimate bycatch rates from observer information at this temporal resolution. This has allowed a more detailed investigation of shifts in fishery timing (See Figure 5 in Stewart et al. 2011). Although the application of monthly bycatch rates differed from previous, simpler analyses, it resulted in less than a 0.3% change in aggregate catch during the time-series. The U.S. shore-based landings are from the Pacific Fishery Information Network (PacFIN), foreign and joint-venture catches for 1981-1990 and domestic at-sea catches for 1991-2011 are estimated from the AFSC's and, subsequently, the NWFSC's at-sea hake observer programs stored in the NORPAC database. Canadian joint-venture catches from 1989 are from the Groundfish Biological (GFBio) database, the shore-based landings from 1989 to 1995 are from the Groundfish Catch (GFCatch) database, then from 1996 from the Pacific Harvest Trawl (PacHarvTrawl) database. Discards are nominal relative to the total fishery catch. The majority of vessels in the U.S. shore-based fishery have operated under experimental fishing permits that required them to retain all catch and bycatch for sampling by plant observers. All U.S. at-sea vessels and Canadian joint-venture catches are monitored by at-sea observers. Observers use volume/density methods to estimate total catch. Domestic Canadian landings are recorded by dockside monitors using total catch weights provided by processing plants.

One of the concerns identified in recent assessments has been the presence of shifts in the within-year distribution of catches during the time series. Subsequent to the ascension of the domestic fleet in the U.S. and both the domestic and Joint-Venture fleets in Canada, the fishery shifted most of the catch to the early spring during the 1990s (Table 1). This fishery gradually spread out over the summer and fall, and in recent years has seen some of the largest catches in the fall through early winter. This pattern is likely to continue in U.S. waters, as the fishery proceeds under the individual trawl quota system adopted in 2011.

2.1.2 Fishery biological data

Biological information from the U.S. at-sea commercial Pacific hake fishery was extracted from the NORPAC database. This yielded length, weight and age information from the foreign and joint-venture fisheries from 1975-1990, and from the domestic at-sea fishery from 1991-2011. Specifically these data include sex-specific length and age data which observers collect by selecting fish randomly from each haul for biological data collection and otolith extraction. Biological samples from the U.S.

shore-based fishery, 1991-2011, were collected by port samplers located where there are substantial landings of Pacific hake: primarily Crescent City, Newport, Astoria, and Westport. Port samplers routinely take one sample per offload (or trip) consisting of 100 randomly selected fish for individual length and weight and from these, 20 fish are randomly selected for otolith extraction. The Canadian domestic fishery is subject to 100% observer coverage on the two processing vessels *Viking Enterprise* and *Osprey*, which together make up 25% of the coast-wide catch. The joint-venture fishery has 100% observer coverage on their processing vessels, which in 2011 made up 16% of the Canadian catch. The total of these for 2011 is 42% observer coverage, with 100% electronic coverage (video) on all vessels for catch records. On observed trips, otoliths (for ageing) and lengths are sampled from Pacific hake caught in the first haul of the trip, with length samples taken on subsequent hauls. Sampled weight from which biological information is collected must be inferred from year-specific length-weight relationships. For unobserved trips, port samplers obtain biological data from the landed catch. Observed domestic haul-level information is then aggregated to the trip level to be consistent with the unobserved trips that are sampled in ports. For the Canadian joint-venture fishery, an observer aboard the factory ship estimates the codend weight for each delivery from a companion catcher boat. Length samples are collected every second day of fishing operations, and otoliths are collected once a week. Length and age samples are taken randomly from a given codend. Since the weight of the sample from which biological information is taken is not recorded, sample weight must be inferred from a weight-length relationship applied to all lengths taken and summed over haul.

The sampling unit for the shore-based fisheries is the trip, while the haul is the primary unit for the at-sea fisheries. Since detailed haul-level information is not recorded on trip landings documentation in the shore-based fishery, and hauls sampled in the at-sea fishery cannot be aggregated to a comparable trip level, there is no least common denominator for aggregating at-sea and shore-based fishery samples. As a result, samples sizes are simply the summed hauls and trips for fishery biological data. The magnitude of this sampling among sectors and over time is presented in Table 3.

Biological data were analyzed based on the sampling protocols used to collect them, and expanded to estimate the corresponding statistic from the entire landed catch by fishery and year when sampling occurred. In general, the analytical steps can be summarized as follows:

1) Count the number of fish (or lengths) at each age (or length bin) within each trip (or haul), generating “raw” frequency data.
2) Expand the raw frequencies from the trip (or haul) based on the fraction of the total haul sampled.
3) Weight the summed frequencies by fishery sector landings and aggregate.
4) Calculate sample sizes (number of trips or hauls) and normalize to proportions that sum to unity within each year.

To complete step (2), the expansion factor was calculated for each trip or haul based on the ratio of the total estimated catch weight divided by the total weight from which biological samples were taken. In cases where there was not an estimated sample weight, a predicted sample weight was computed by multiplying the count of fish in the sample by a mean individual weight, or by applying a year-specific length-weight relationship to the length of each fish in the sample, then summing these predicted weights. Anomalies can emerge when very small numbers of fish are sampled from very large landings; these were avoided by constraining expansion factors to not exceed the 95th percentile of all expansion factors calculated for each year and fishery. The total number of trips or hauls sampled is used as either the initial multinomial sample size input to the SS stock assessment model (prior to iterative reweighting) or as a relative weighting factor among years. Motivated by a recent downward trend in fishery sampling for ages in the Canadian sector, the method of weighting the fleet-specific proportions (Step 3) was revised in 2012 to be based on the estimated numbers in the total sector catch, rather than the number of samples collected from that catch. This allows for adequate representation of even sparsely sampled sectors.

The aggregate fishery age-composition data (1975-2011) confirm the well-known pattern of very large cohorts born in 1980, 1984 and 1999, with a small proportion from the 1999 year class (12 years old in 2011) still present in the fishery (Figure 5). The most recent age-composition data from the 2010 and 2011 fisheries suggest the presence of an above average 2008 year class, with a large proportion of the catch represented by this cohort. The previously strong 2005 and 2006 year classes appear to have declined in strength in the 2011 fishery, compared to previous years. We caution that the age-composition data contains information about the relative numbers-at-age, such that the absolute size of incoming cohorts cannot be precisely determined until it has been observed several times.

Both the weight- and length-at-age information suggest that hake growth has changed markedly over time. This is particularly evident in the frequency of larger fish (> 55 cm) before 1990 and a shift to much smaller fish in more recent years. The treatment of length-at-age and weight-at-length are described in more detail in section 2.3.3 and 2.3.4 below. Although length composition data are not fit explicitly in the base case assessment models presented here, the presence of the 2008 year class is clearly observed in both of the U.S. fishery sectors.

2.1.3 Catch per unit effort

Catch-per-unit-effort (CPUE) is a common source of information about relative population trend in stock assessments world-wide, although numerous studies question its utility. Calculation of a reliable CPUE metric is particularly problematic for Pacific hake, however, and it has never been used as a tuning index for assessment of this stock. This is mainly because the basic concept of “effort” is difficult to define for the hake fishery, as the use of acoustics, communication among vessels, extensive time spent searching and transit time between fishing ports and known areas of recurrent hake aggregations means that, by the time a trawl net is put in the water, catch rates can be predicted by the fishing vessel reasonably well. Factory trawlers may continue to fish the same aggregation for days, while shore-based sectors may be balancing running time with hold capacity and therefore opt for differing catch rates. Further, during the last decade, the hake fishery has been severely constrained in some areas due to avoidance of rockfish bycatch. Periodic voluntary ‘stand-downs’, and temporary in-season closures have resulted from high bycatch rates, and in some years fishermen have changed their fishing behavior and fishing areas, in order to reduce bycatch of overfished rockfish species. Furthermore, the US at-sea fleet generally leaves the hake fishing grounds for a period during the season to participate in the Bering Sea pollock fishery. It is unlikely that such fleet dynamics and inter-species effects can be dealt with adequately in order to produce a reliable index for Pacific hake based on fishery CPUE data.

2.2 Fishery independent data

2.2.1 Acoustic survey

The joint U.S. and Canadian integrated acoustic and trawl survey has been the primary fishery independent tool used to assess the distribution, abundance and biology of coastal Pacific hake, along the west coasts of the United States and Canada. Coast-wide surveys were carried out jointly by the Alaska Fisheries Science Center (AFSC) and the Pacific Biological Station (PBS) of the Canadian Department of Fisheries and Oceans (DFO) in 1995, 1998, and 2001. Following 2001, the responsibility for the U.S. portion of the survey was transferred to the Fishery Resource Analysis and Monitoring (FRAM) Division of NOAA's Northwest Fisheries Science Center (NWFSC). The survey was scheduled on a biennial basis, with joint acoustic surveys conducted by FRAM and PBS from 2003 to 2011. Between 1977 and 1992, acoustic surveys of Pacific hake were conducted every three years by the AFSC. However, these early surveys (1977–1992) covered only a reduced depth range and focused on U.S. waters. Therefore, they are not used in the current assessment because of concerns over both bias due to arbitrary expansion factors used to extrapolate to the entire depth and latitudinal range of the survey. More details are given in Stewart et al (2011). Only acoustic surveys performed in 1995, 1998, 2001, 2003, 2005, 2007, 2009, and 2011 were used in this assessment (Table 4). The acoustic survey includes all waters off the coasts of the U.S. and Canada thought to contain portions of the coastal hake stock and all portions of the hake stock older than age-1. Age-0 and age-1 hake have been historically excluded from the survey efforts, due to largely different schooling behavior relative to older hake and concerns over markedly different catchability by the trawl gear.

The distribution of Pacific hake can vary greatly between years. It appears that northward migration patterns are related to the strength of subsurface flow of the California Current (Agostini et al. 2006) and upwelling conditions (Benson et al. 2002). Distributions of hake backscatter plotted for each acoustic survey since 1995 illustrate the variable spatial patterns among years (Figure 1). The 1998 acoustic survey is notable because it shows an extremely northward occurrence that is thought to be related to the strong 1997-1998 El Nino (Figure 2). In contrast, the distribution of hake during the 2001 survey was compressed into the lower latitudes off the coast of Oregon and Northern California. In 2003, 2005 and 2007 the distributions generally followed the "normal" coast-wide pattern, but in 2009 and 2011, the majority of the hake distribution was again found in U.S. waters. Pacific hake also tend to migrate farther north as they age. Figure 2 shows the mean location of Pacific hake observed in the acoustic survey by age and year. Age-2 hake are located in the southern portion of their distribution, while older age classes are found in more northerly locations within the same year. The mean locations of Pacific hake age-6 and older tend to be more similar among years than those for the younger ages. With the aging of the strong 1999 year class causing a reduction in the number of older fish, a more southerly distribution has been observed in recent surveys.

For the 2012 assessment of Pacific hake, acoustic survey data from 1995 onward were analyzed using geostatistical techniques (kriging), which accounts for spatial correlation to provide an estimate of total biomass as well as an estimate of the year-specific sampling variability due to patchiness of hake schools and irregular transects (Petitgas 1993; Rivoirard et al. 2000; Mello & Rose 2005; Simmonds and MacLenann, 2005). Advantages to the kriging approach are: 1) it simultaneously provides the estimates of the hake biomass and associated sample while properly accounting for spatial correlation along and between transects; 2) it provides biomass estimates in the area beyond transect lines but within the correlation distance; 3) it provides maps of hake biomass and variance that take into account the heterogeneous and patchy hake distribution; and 4) it allows for greater flexibility (and potentially efficiency) in survey transect design, in that transects do not need to be more or less perpendicular to the coast line. A comparison of the kriged estimates to previous conventional design-based estimates was presented in Stewart et al. (2011), and showed a reasonable degree of consistency between the two methods.

During the acoustic surveys, mid-water trawls are made opportunistically to determine the species composition of observed acoustic marks and to obtain the length data necessary to scale the acoustic backscatter into biomass (see Table 4 for the number of trawls in each survey year). Biological samples collected from these trawls are post-stratified, based on similarity in size composition and geographic proximity. Results from research done in 2010 on representativeness of the biological data (i.e., repeated trawls on the same aggregation of hake) showed that trawl sampling and post-stratification is only a small source of variability among all of the sources of variability inherent to the acoustic analysis (see Stewart et al 2011).

The composite length frequency developed from the biological sampling was used to characterize the hake size distribution along each transect and to predict the expected backscattering cross section for Pacific hake based on the fish size-target strength (TS) relationship TS_{db} = 20logL-68 (Traynor 1996). Recent target strength work (Henderson and Horne 2007), based on in-situ and ex-situ measurements, estimated a regression intercept of 4-6 dB lower than that of Traynor (1996), suggesting that an individual hake reflects less acoustic energy, resulting in a larger estimated biomass than when using Traynor's (1996) equation. This difference would be accounted for directly in estimates of acoustic catchability within the assessment model, but variability in the estimated biomass due to uncertainty in target strength is not explicitly accounted for.

Figure 6 shows the backscatter of age-2+ hake as observed in the 2011 survey. It can be seen that a considerable amount of hake were observed off Cape Mendocino in Northern California, and near the U.S./Canadian border. There were few locations in Canada with assigned hake backscatter, mainly off of the northern portion of West Vancouver Island. Although small numbers of hake were sampled in some trawls in areas far north of Vancouver Island, it was determined that these hake were a very small part of the observed backscatter due to mixing with smaller species such as euphausiids or eulachon, and no backscatter was assigned to the regions on these transects (Figure 6). Comparing the distribution of backscatter in 2011 to the distribution of backscatter in previous surveys (Figure 1) shows that the stock was distributed more southerly in 2011, and was found in a narrower band across depth contours (East to West). The distribution of hake in 2011 was most similar to the distribution of hake in 2001, when the population was also dominated by young fish.

The 2011 acoustic survey biomass estimate is 521,476 metric tons, the lowest observed in the time series and approximately one-third of the 2009 estimate (Figure 7). Only 7% of this biomass was observed in Canadian waters. A smaller correlation distance estimated from the kriging analysis suggested that the hake schools encountered in 2011 were consistently smaller than the average size of schools over the longer time-series. No Humboldt squid were observed in 2011, although considerable numbers were caught in both the survey and fishery in 2009.

The variability of the 2011 biomass estimate, measured as a coefficient of variance (CV), is 10.2%, the second largest in the series (Figure 7). These estimates of uncertainty account for sampling variability (and the variability due to squid in 2009), but several additional sources of observation error are also possible. For example, haul-to-haul variation in size and age, target strength uncertainty of hake as well as the presence of other species in the backscatter and interannual differences in catchability likely comprise additional sources of uncertainty in the acoustic estimates. In the future, it is possible that a bootstrapping analysis that incorporates of many of these sources of variability can be conducted and the estimation of variance inflation constants in the assessment may become less important (O’Driscoll 2004). At present, though, there is strong reason to believe that all survey variance estimates are underestimated relative to the true variability.

As with the fishery data, age compositions were used to reconstruct the age structure of the hake observed by this survey. Proportions-at-age for the eight acoustic surveys are summarized in Figure 8 and clearly show the strong 1999 and 2008 year classes. The large 2005 and 2006 year classes appeared to be very strong in the 2009 survey but contribute less to the total age composition in 2011. The 2011 survey attributed 63% of the estimated number of hake observed to the 2008 year-class, and a total of 88% to the 2008 and 2009 year-classes combined. While this finding supports the previously estimated strength of these incoming cohorts, it differs substantially from 2011 stock assessment model predictions which, while uncertain, indicated that the 2005 and 2006 year classes would be important contributors to survey catches during 2011. The acoustic survey data in this assessment do not include age-1 fish (and therefore give no indication of the strength of the 2010 year-class), although a separate age-1 index is being developed (see below).

2.2.2 Bottom trawl surveys

The Alaska Fisheries Science Center conducted a triennial bottom trawl survey along the west coast of North America from 1977 to 2001 (Wilkins et al. 1998). This survey was repeated for a final time by the Northwest Fisheries Science Center in 2004. In 1999, the Northwest Fisheries Science Center began to take responsibility for bottom trawl surveys off of the U.S. west coast, and, in 2003, the Northwest Fisheries Science Center survey was extended shoreward to a depth of 55 m to match the shallow limit of the triennial survey (Keller et al., 2008). Despite similar seasonal timing of the two surveys, the 2003 and subsequent annual surveys differ from the triennial survey in size/horsepower of the chartered fishing vessels and bottom trawl gear used. As such, the two were determined (at a workshop on the matter in 2006) to be separate surveys which cannot be combined into one. In addition, the presence of significant densities of hake, both offshore and to the North of the area covered by the trawl survey, coupled with the questionable effectiveness of bottom trawls in catching mid-water schooling hake, limits the usefulness of this survey to assess the hake population. For these reasons neither the triennial, nor the Northwest Fisheries Science Center shelf trawl survey, have been used in recent assessments. With the growing time-series length of the NWFSC survey (now 8 years), future assessments should re-evaluate the use of the survey as an index of the adult and/or juvenile (age 0-1) hake population.

2.2.3 Pre-recruit survey

From 1999-2009, the NWFSC and Pacific Whiting Conservation Cooperative (PWCC), in coordination with the SWFSC Rockfish survey have conducted an expanded survey (relative to historical efforts) targeting of juvenile hake and rockfish. The SWFSC/NWFSC/PWCC pre-recruit survey used a mid-water trawl with an 86' headrope and ½" codend with a 1/4” liner to obtain samples of juvenile hake and rockfish (identical to that used in the SWFSC Juvenile Rockfish Survey). Trawling was done at night with the head rope at 30 m at a speed of 2.7 kt. Some trawls were made before dusk to compare day/night differences in catch. Trawl tows of 15 minutes duration at target depth were conducted along transects at 30 nm intervals along the coast. Stations were located along each transect, at bottom depths of 50, 100, 200, 300, and 500 m. Since 2001, side-by-side comparisons were made between the vessels used for the survey.

Trends in the coast-wide index have shown very poor correlations with estimated year-class strengths in recent assessment models, thus it has not been used in them. Because the survey has not been conducted since 2009, it has not been revisited in subsequent stock assessments.

2.2.4 Age-1 Index from the acoustic survey

The acoustic survey has historically focused its at-sea and analysis efforts on the age-2+ portion of the Pacific hake stock. The rationale for this included: inshore and southerly distribution of age-1 fish required additional survey time to provide adequate geographic coverage; relatively lower catchability of age-1 fish in the trawl net used by the survey; and perhaps greater difficulty in identifying these schools from other small pelagic fish. This choice was also consistent with the needs of early stock assessments, where recruitments were modeled as at age-2. Despite these reasons for excluding age-1 fish historically, a reliable index of age-1 hake would now be extremely valuable for this stock assessment. An age-1 index could potentially reduce uncertainty around the strength of incoming cohorts much more rapidly than only the biennial survey estimates for age-2+ fish and the annual commercial fishery data.

During 2011, the acoustic survey team re-processed all echogram data available, spanning the period from 1995 to 2011. All age-1 aggregations were identified and the backscatter integrated following the simple polygon methods that were used for the adult stock prior to development of the kriging method currently employed. The results of this analysis were made available to the JTC just prior to the completion of this document. The number of data points is currently very small. Unfortunately, correlation analysis for the index and assessment-estimated year-class strengths is hampered by low variability among the years for which age-1 hake have been enumerated by the acoustic survey. However, the results are generally consistent with a large 2008 cohort (Figure 9). With no other data yet available with which to corroborate this index, it is premature to draw conclusions on the strength of the 2010 cohort, although the estimate in the age-1 index is larger than that for the 2008 (Figure 9). The JTC encourages a continuation of this effort, which, in addition to an annual survey could reduce assessment model uncertainty in the future.

2.3 Externally analyzed data

2.3.1 Maturity

The fraction mature, by size and age, is based on data reported in Dorn and Saunders (1997) and has remained unchanged since the 2006 stock assessment. These data consisted of 782 individual ovary collections based on visual maturity determinations by observers. The highest variability in the percentage of each length bin that was mature within an age group occurred at ages 3 and 4, with virtually all age-one fish immature and age 4+ hake mature. Within ages 3 and 4, the proportion of mature hake increased with larger sizes, such that only 25% were mature at 31 cm while 100% were mature at 41 cm. Less than 10% of the fish smaller than 32 cm are predicted to be mature, while 100% maturity is predicted by 45 cm. Histological samples have been collected during recent U.S. bottom trawl surveys, and these collections are currently under evaluation at the NOAA Fisheries NWFSC. The JTC anticipates receiving these data during 2012 and revisiting the maturity schedule used in the stock assessment for 2013.

2.3.2 Aging error

The large inventory of age determinations for Pacific hake include many duplicate reads of the same otolith, either by more than one laboratory, or by more than one age-reader within a lab. Recent stock assessments have utilized the cross- and double-reads to generate an ageing error vector describing the imprecision in the observation process as a function of fish age. New data and analysis was used in the 2009 assessment to address an additional process influencing the ageing of hake: cohort-specific ageing error related to the relative strength of a year-class. This process reflects a tendency for uncertain age determinations to be assigned to predominant year classes. The result is a tendency towards reduced mis-ageing of strong year classes, and increased mis-ageing of neighboring year-classes. To account for this process in the model, year-specific ageing-error matrices (or vectors of standard deviations of observed age at true age) are applied, where the standard deviations of strong year classes were reduced by a constant proportion. For the 2009 and 2010 assessments this proportion was determined empirically by comparing double-read error rates for strong year classes with rates for other year classes. In 2010, a blind double-read study was conducted using otoliths collected across the years 2003-2009. One read was conducted by a reader who was aware of the year of collection, and therefore of the age of the strong year classes in each sample, while the other read was performed by a reader without knowledge of the year of collection, and therefore with little or no information to indicate which ages would be more prevalent. The resulting data were analyzed via an optimization routine to estimate both ageing error and the cohort effect. The resultant ageing error was similar to the ageing error derived from the 2008 analysis. This approach, unchanged from the 2011 assessment has been retained for 2012.

2.3.3 Weight-at-length and age

A matrix of empirically derived population weight at age is required as input for the current assessment models. Mean weight at age was calculated from samples pooled from all fisheries and the acoustic survey for the years 1975 to 2011 (Figure 10). Ages 15 and over were pooled and assumed to have the same weight at age. For ages 2 to 15+, 99% of the combinations of year and age had samples from which to calculate mean weight at age. At age 1, 58% of the years had samples available. Linear interpolation over both age and year dimensions was used to fill in missing values. However, the number of samples is generally proportional to the amount of catch, so the combinations of year and age with no samples have very little importance in the overall estimates of the population dynamics. The use of empirical weight at age is a convenient method to capture the variability in both the weight-at-length relationship within and among years, as well as the variability in length-at-age, without requiring parametric models to represent these relationships. However, this method requires the assumption that observed values are not biased by strong selectivity at length or weight and that the spatial and temporal patterns of the data sources provide a representative view of the underlying population

2.3.4 Length-at-age

In both 2011 assessment models, and in models used for management prior to the 2006 stock assessment, variability in length-at-age was included in stock assessments via the calculation of empirical weight-at-age. In the 2006 and subsequent assessments that attempted to estimate the parameters describing a parametric growth curve, strong patterns have been identified in the observed data indicating sexually dimorphic and temporally variable growth. Parametric growth models fit externally to data collected prior to 1990 and afterward show the same dramatically different rates of growth when it has been estimated inside the assessment model in recent years. Hake show very rapid growth at younger ages, and the length-at-age trajectories of individual cohorts also vary greatly, as has been documented in previous assessments.

In aggregate, these patterns result in a greater amount of process error for length-at-age than is easily accommodated with parametric growth models. This means that even complex approaches to modeling growth (and therefore fitting to length or age-at-length data explicitly) will have great difficulty in making predictions that mimic the observed data. This has been particularly evident in the residuals to the length-frequency data from models prior to 2011. We have not revisited the potential avenues for explicitly modeling variability in length- and weight-at age in this model, but retain the empirical approach to weight-at-age described above.

2.4 Prior probability distributions

The informative prior probability distributions used in this stock assessment are reported in Table 5. A summary of the priors used for the base-case model and the alternate CCAM model is provided in Tables 6 and 7. Several important distributions are discussed in detail below.

2.4.1 Natural Mortality

In recent stock assessments, the natural mortality rate for Pacific hake has either been fixed at a value of 0.23 per year, or estimated using an informative prior to constrain the probability distribution to a reasonable range of values. The 0.23 estimate was originally obtained via tracking the decline in abundance of individual year classes (Dorn et. al 1994). Pacific hake longevity data, natural mortality rates reported for Merluciids in general, and previously published estimates for Pacific hake natural mortality indicate that natural morality rates in the range 0.20-0.30 could be considered plausible for Pacific hake (Dorn 1996).

Beginning in the 2008 assessment, Hoenig's (1983) method for estimating natural mortality (M), was applied to hake, assuming a maximum age of 22. The relationship between maximum age and M was recalculated using data available in Hoenig (1982) and assuming a log-log relationship (Hoenig, 1983), while forcing the exponent on maximum age to be -1. The recalculation was done so that uncertainty about the relationship could be evaluated, and the exponent was forced to be -1 because theoretically, given any proportional survival, the age at which that proportion is reached is inversely related to M (when free, the exponent is estimated to be -1.03). The median value of M via this method was 0.193. Two measures of uncertainty about the regression at the point estimate were calculated. The standard error, which one would use assuming that all error about the regression is due to observation error (and no bias occurred) and the standard deviation, which one would use assuming that the variation about the regression line was entirely due to actual variation in the relationship (and no bias occurred). The truth is likely to be between these two extremes (the issue of bias not withstanding). The value of the standard error in log space was 0.094, translating to a standard error in normal space of about 0.02. The value of the standard deviation in log space was 0.571, translating to a standard deviation in normal space of about 0.1. Thus Hoenig's method suggests that a prior distribution for M with mean of 0.193 and standard deviation between 0.02 and 0.1 would be appropriate if it were possible to accurately estimate M from the data, all other parameters and priors were correctly specified, and all correlation structure was accounted for.

In several previous assessments (2008-2010) natural mortality has been allowed to increase with age after age 13, to account for the relative scarcity of hake at age 15+ in the observed data. This choice was considered a compromise between using dome-shaped selectivity - and assuming the oldest fish were extant but unavailable to the survey or fishery - and specifying increasing natural mortality over all ages, which tended to create residual patterns for ages with far more fish in them. The reliability of this approach has been questioned repeatedly, and it makes little difference to current assessment results, so in the interest of parsimony, natural mortality is considered to be constant across age and time for all models reported in this assessment document.

For the 2011 assessment and again this year, a combination of the informative prior used in recent Canadian assessments and the results from Hoenig's method described above support the use of a log-normal distribution with a mean of 0.2 and a log-standard deviation of 0.1. Sensitivity to this prior is evaluated by examination of the posterior distribution, as updated by the data, as well as the use of alternate priors, specifically a larger standard deviation about the point estimate (see Section 3.4.7).

2.4.2 Steepness

The prior for steepness is based on the median (0.79), 20th (0.67) and 80th (0.87) percentiles from Myers et al. (1999) meta-analysis of the family Gadidae, and has been used in previous U.S. assessments since 2007. This prior is distributed $\beta(9.76,2.80)$. We tested the CCAM model's sensitivity to alternative priors on steepness (reported in section 3.4.7).

2.4.3 Acoustic survey catchability (q)

There was no prior placed on the value for survey catchability in the base case. A lognormal prior was placed on the survey catchability parameter q, in the CCAM alternate models, with mean corresponding to 1 and log-standard deviation 0.1 (95% confidence interval of 0.82 and 1.22). The prior was used to help achieve model convergence. Although it might be considered overly precise, sensitivity tests were done to evaluate the influence of the standard deviation of this prior (see Section 3.4.7).

3. Stock assessment

3.1 Modeling history

Age-structured assessment models of various forms have been used to assess Pacific hake since the early 1980s, using total fishery landings, fishery length and age compositions, and abundance indices. Modeling approaches have evolved as new analytical techniques have been developed. Initially, a cohort analysis tuned to fishery CPUE was used (Francis et al. 1982). Later, the cohort analysis was tuned to NMFS triennial acoustic survey estimates of absolute abundance at age (Francis and Hollowed 1985, Hollowed et al. 1988a). In 1989, the hake population was modeled using a statistical catch-at-age model (Stock Synthesis) that utilized fishery catch-at-age data and survey estimates of population biomass and age-composition data (Dorn and Methot, 1991). The model was then converted to AD Model Builder (ADMB; Fournier et al. 2011) in 1999 by Dorn et al. (1999), using the same basic population dynamics equations. This allowed the assessment to take advantage of ADMB's post-convergence routines to calculate standard errors (or likelihood profiles) for any quantity of interest. Beginning in 2001, Helser et al. (2001, 2003, and 2004) used the same ADMB model to assess the hake stock and examine important assessment modifications and assumptions, including the time-varying nature of the acoustic survey's selectivity and catchability. The acoustic survey catchability coefficient (q) was one of the major sources of uncertainty in the model. The 2004 and 2005 assessments presented uncertainty in the final model result as a range of biomass. The lower end of the biomass range was based upon the conventional assumption that the acoustic survey q was equal to 1.0, while the higher end of the range represented a q=0.6 assumption.

In 2006, the coastal hake stock was modeled using the Stock Synthesis (SS) modeling framework written by Dr. Richard Methot (U.S. National Marine Fisheries Service, Northwest Fisheries Science Center) in AD Model Builder. Conversion of the previous hake model into SS2 was guided by three principles: 1) incorporate less *derived* data, favoring the inclusion of unprocessed data where possible, 2) explicitly model the underlying hake growth dynamics, and 3) pursue parsimony in model complexity. “Incorporating less *derived* data” entailed fitting observed data in their most elemental form. For instance, no pre-processing to convert length data to age-compositional data was performed. Also, incorporating conditional age-at-length data for each fishery and survey allowed explicit estimation of expected growth, dispersion about that expectation, and its temporal variability, all conditioned on selectivity. In both 2006 and 2007, as in 2004 and 2005, assessments presented two models (which were assumed equally likely) in an attempt to bracket the range of uncertainty in the acoustic survey catchability coefficient, *q*. The lower end of the biomass range was again based upon the conventional assumption that the acoustic survey *q* was equal to 1.0, while the higher end of the range allowed estimation of q with a fairly tight prior about q = 1.0 (effective q = 0.6 - 0.7). The 2006 and 2007 assessments were collaborative, including both U.S. and Canadian scientists.

During 2008, three separate stock assessments were prepared independently by U.S. and Canadian scientists. The U.S. model was reviewed during the STAR panel process, and both the VPA and TINSS models were presented directly to the SSC, but were not formally included in the U.S. assessment review and management process. The post-STAR-panel U.S. model freely estimated q for the first time, and this resulted in very large relative stock size and yield estimates. In 2009, the U.S. assessment model incorporated further uncertainty in the degree of recruitment variability (σ_R) as well as more flexible time-varying fishery selectivity. Additionally, the 2009 assessment incorporated further refinements to the ageing-error matrices, including both updated data and cohort-specific reductions in ageing error to reflect “lumping” effects due to strong year classes. The 2009 U.S. model continued to integrate uncertainty in acoustic survey *q* and selectivity and in *M* for older fish. Residual patterns that had been present in the age and length data were discussed at length, and efforts were undertaken to build the tools necessary to re-evaluate input data to allow more flexibility in potential modeling approaches.

In 2010, two competing models (one built using TINSS, Martell 2010; and one in SS, Stewart and Hamel 2010) were presented to the STAR panel. Estimates of absolute stock size and yields differed greatly between the two models, and the causes of these differences went largely unidentified. The SSC recommended that the Pacific Council base management advice on both models.

In 2011, two models were again put forward by a joint stock assessment team comprised of U.S. and Canadian scientists collaborating in the spirit of the as-yet unimplemented treaty. Results from both models were presented in a single document (Stewart et al. 2011). Considerable efforts were made to refine both models to better understand the reasons for previous differences among models and to better present the uncertainty in current stock status. The exercise resulted in two models that were structurally very similar, although they still contained some fundamental differences in underlying assumptions about certain likelihood components and prior assumptions about the productivity and scale of the population. Both models were deemed equally plausible by the STAR panel, in terms of their ability to capture the dynamics of the Pacific hake stock and provide advice for management in the face of considerable scientific uncertainty. The models achieved a greater degree of parsimony compared with some earlier versions. Notably, neither model attempted to fit to observed lengths at age. Annual variability in length at age was instead captured through use of empirically-derived estimates of weight at age in the data files.

In 2012, members of a provisional Joint Technical Committee (JTC), comprised of Canadian and U.S. scientists, continued to collaborate in the production of a single stock assessment document. Now under treaty, members of the provisional JTC agreed on a single base-case model, using the SS3 modeling platform configured almost identically to that used in the 2011 assessment. Sensitivity to structural and parameter uncertainty was analyzed using this model and a new statistical catch at age model (CCAM), originally developed at the University of British Columbia (Martell 2011) and customized by members of the JTC.

3.2 Response to recent review recommendations

3.2.1 2012 SRG review

Subsequent to the distribution of the draft 2012 stock assessment for SRG review and prior to the review meeting an error was discovered in the 2011 acoustic survey biomass index calculations. In response to this error, the base case and key sensitivity models were updated to include the revised results. The SRG endorsed the use of these revised models for 2012. Other recommendations for this assessment made during the SRG review also included inclusion of a table of management metrics that were of particular interest to meeting participants and several adjustments to some technical terms to improve the readability of the assessment results.

3.2.2 2011 STAR Panel and SSC review

The 2011 STAR panel (7-11 February, 2011) conducted a thorough review of the data, analyses and modeling conducted by the joint technical team (a full summary can be found in the STAR panel report). During the course of the review, several aspects of the TINSS model were improved, leading to results that were more similar to those from the SS model. Further, several errors and inconsistencies were identified in the underlying code, and these were rectified during the review. Subsequent to the STAR review, several additional inconsistencies in the treatment of weight-at-age for various calculations were discovered. These issues were corrected, and the revised results presented to the SSC during the PFMC meeting (5 March, 2011). At the request of the SSC, the posterior distributions for management-related quantities from the SS and TINSS models were combined with equal weight in order to provide model-averaged estimates.

3.2.3 2011 STAR Panel recommendations

The 2011 STAR panel made the following recommendations (in no particular order).

1. *Conduct the acoustic survey annually. Reason: the survey is now biennial. An annual survey would help to the reduce CI on the current biomass estimate. Consideration should be given to a joint government / industry survey.*

> Response: The JTC strongly supports this recommendation, and especially supports an interim survey in 2012. Discussions on this topic among scientists and managers from the U.S. and Canada have already begun.

2. *Conduct target strength research. Reason: the relationship used in the biomass estimate calculations is dated and more recent research indicates substantial differences in the target strength / fish length relationship.*

> Response: Although some target strength research was planned for 2011, there were no suitable opportunities for collecting appropriate observations of individual hake targets of identifiable size.

3. *Conduct further work to validate haul representativeness and sampling design of the trawling component of the acoustic survey. Reason: uncertainty remains in the representativeness of the hauls used to characterize the biological composition of the acoustic survey.*

Response: The JTC supports this recommendation but there have so far been no opportunities to carry out this work. This type of work is typically done in even-numbered years (between biannual surveys). However, given the extremely low acoustic index estimate in 2011, an interim biomass survey would appear to be a greater need in 2012.

4. *Explore alternative spatial analyses using different regression techniques with the kriging data. Reason: Spatial and temporal variation of hake influence the level of homogeneity in the acoustic biomass estimates.*

Response: A workshop to evaluate acoustic survey design and methods is being planned.

5. *Explore fundamental differences in assumptions that drive output differences in the TINSS and SS models. Reason: the fundamental structure of the two models differs and an explicit evaluation of assumptions will help to evaluate reasons for differences in the resulting advice for management coming from the two models.*

Response: We continued the comparison of alternate assessment models subsequent to the 2011 review. This included the transition from TINSS to CCAM and additional work comparing the TINSS and CCAM code, behavior and results with those from SS. During preliminary modelling for the 2012 assessment, committee members felt that they had succeeded in generating very comparable behavior among the three models (especially CCAM and SS) and were comfortable that the assessment results were very robust to the choice of one platform or the other. Much of this work is documented here (see Appendix E). Further, the JTC concluded that extensive time spent comparing relatively small differences among specific model implementations had the potential to significantly detract from discussion of greater areas of uncertainty in the 2012 stock assessment. For this reason, we present a single base-case model and utilize the work that has been done to provide an extended sensitivity analysis (see sections below) including alternate structural assumptions within and among SS and CCAM.

6. *Further evaluate the method of age composition weighting and the different approaches taken in TINSS and SS models.*

Response: It is noted that TINSS is no longer used by for the hake assessment, although its replacement CCAM, uses the same likelihood function for the age-composition data as TINSS. We find that despite differences in specific likelihood calculations and weighting of data sources the SS and CCAM models produce very similar results. We conclude that additional exploration of this topic, while of some scientific interest, is likely to be of little importance to the results for Pacific hake.

7. *Further explore time-varying growth and alternate model structures, as appropriate, to characterize this phenomenon.*

Response: The JTC did not have the resources to successfully revisit more detailed approaches to explicitly modelling time-varying growth for 2012. The empirically derived weight-at-age method employed appears to capture this variability and specific alternatives are not currently identified.

8. *Further explore time-varying selectivity and alternate model structures, as appropriate, to characterize this phenomenon.*

Response: The use of time-varying selectivity has been a topic of extensive discussion during assessment reviews over the last decade. Assessment models have applied approaches ranging from selectivity smoothed over time and age, for multiple explicit fishing fleets to simple parametric curves that were assumed to be time-invariant. Many of these models were criticised as being overparameterized, failing to achieve parsimony, lacking robust estimation properties, and requiring too many subjective decisions regarding the specific structure of breaks, nodes or joints in time-varying functions. In the 2011 assessment, the assessment team simplified both the fleet structure and the selectivity approach in the two models. The goal was to represent the central tendency of the realized selectivity for a single fishing fleet representing an amalgamation of sectors, targeting strategies and temporal behavior over both time and space. This approach propagates the uncertainty in selectivity without requiring a large number of parameters which reduce computational efficiency and robustness. For 2012, the JTC spent some time investigating preliminary model configurations that employed time-varying components, but concluded that without adequate simulation studies to investigate the estimation properties of these approaches they were not yet ready for management use.

9. *Produce an age 0 or age 1 recruit index. Reason: recruitment variability is a major driver in the uncertainty of the hake assessment.*

Response: Extensive work was completed on this topic during 2011 and is reported above. It is likely to be several years before the reliability of the acoustically derived age-1 index can be determined and it can be quantitatively included in the stock assessment.

10. *Update the maturity-at-age relationship by collecting new data and using histological analysis techniques. Reason: substantial changes in growth in early 1990s may have resulted in maturation changes.*

Response: This work is underway, and described more fully herein. It is expected that a revised maturity schedule will be available for the 2013 assessment.

11. *Explore the role of ecological covariates that could inform the stock assessment.*

Response: The JTC agrees with this recommendation, particularly with respect to ecological covariates that could lead to a better understanding of variability in the distribution of hake. An initial project begun in 2010 is still ongoing at the U.S. NOAA Fisheries NWFSC, but it is not currently clear which personnel or resources will be allocated to continue this work. The JTC recommends that this be given consideration by the Joint Management Committee in 2012. However, it is noted that correlations with environmental variables have not always proved consistent enough to inform stock assessment. For this reason, the JTC recommends serious consideration be given to allocation of resources to develop a Management Strategy Evaluation (as recommended by previous STAR panels and by this and previous stock assessment teams). Management Strategy Evaluation can be used to search for management and assessment approaches that are robust to uncertainty in terms of achieving pre-defined objectives for the fishery.

3.3 2011 Model descriptions

3.3.1 Base-case model (using Stock Synthesis)

The base-case model reported in this assessment uses the Stock Synthesis (SS) modeling framework developed by Dr. Richard Methot at the NWFSC. The Stock Synthesis application provides a general framework for modeling fish stocks that permits the complexity of population dynamics to vary in response to the quantity and quality of available data. In the base model, both the complexity of the data and the dynamics of the model are intended to be quite simple, and efforts have been made to be as consistent with the CCAM model as possible. Additional complexity is explored via sensitivity analysis, and sources of difference between the two models are highlighted where they have been identified.

The basic model structure, aggregation-level and treatment of data, as well as parameterizations for key processes remain unchanged from the 2011 assessment. The Pacific hake population is assumed to be a single coast-wide stock along the Pacific coast of the United States and Canada. Sexes are combined within all data sources, including fishery and survey age compositions, as well as in the model dynamics. The accumulator age for the internal dynamics of the population is set at 20 years, well beyond the expectation of asymptotic growth. The modeled period includes the years 1966-2011 (last year of available data), with forecasts extending to 2014. The population was assumed to be in equilibrium 20 years prior to the first year of the model, allowing a 'burn-in' of recruitment estimates such that the age structure in the first year of the model was free of all equilibrium assumptions. Since there were no large-scale commercial fisheries for hake until the arrival of foreign fleets in the mid- to late 1960s, no fishing mortality is assumed prior to 1966.

The model structure, including parameter specifications, bounds and prior distributions (where applicable) is summarized Table 6. The assessment model includes a single fishery representing the aggregate catch from all sectors in both nations). The effect of modeling the U.S. foreign, joint-venture, at-sea and shore-based fisheries, as well as the Canadian foreign, joint-venture and domestic fisheries as separate fleets is explored in a sensitivity analysis. Estimated selectivity for both the acoustic survey and commercial fishery does not change over time. However, the selectivity curves were modeled as non-parametric functions estimating age-specific values for each age beginning at age 2 for the acoustic survey, since age-1 fish are not included in the design, and age-1 for the fishery, as small numbers are observed in some years. Selectivity is forced to be constant after age-6 (increased from age-5 in the 2011 assessment). The decision to increase the number of estimated selectivity parameters was motivated by the intention to let the data better inform the assessment results (a likelihood ratio test, although not strictly applicable to integrated stock assessments supports this choice), as well as propagation of uncertainty related to selectivity at age. Further, the JTC had sufficient time to ensure that estimation of these additional two parameters was reliable and robust in both a maximum likelihood and Bayesian context. The results of models using selectivity constant after age-5 and age-7 (bracketing the current base case assumption) are included, but this restriction is evaluated via sensitivity analysis, as are alternate parameterizations using the CCAM model.

Growth is represented via the externally derived matrix of weight-at-age described above. Alternate models including a time-varying von Bertalanffy function, dimorphic growth and seasonally explicit growth within years were compared via sensitivity analyses during the 2011 assessment but did not provide substantially different results.

For the base model, the instantaneous rate of natural mortality (*M*) is estimated with a lognormal prior having a mean of 0.2 and σ (in log-space) of 0.1 (described above). The stock-recruitment function is a Beverton-Holt parameterization, with the log of the mean unexploited recruitment freely estimated. This assessment uses the Beta-distributed prior for stock-recruit steepness (*h*) applied to previous assessments and described above. Year-specific recruitment deviations were estimated from 1946-2011. The standard deviation, σ_r, for recruitment variability, serving as both a recruitment deviation constraint and bias-correction, is fixed at a value of 1.4 in this assessment. This value is based on consistency with the observed variability in the time-series, and represents a small increase from the iterative value derived in 2011, although this change had a negligible effect on the model results. Maturity and fecundity relationships are assumed to be time-invariant and fixed values remain unchanged from recent assessments.

The acoustic survey index of abundance was fit via a log-normal likelihood function, using the observed sampling variability, estimated via kriging as year-specific weighting. An additional constant and additive log(SD) component is included, which was freely estimated to accommodate unaccounted for sources of process and observation error. Survey catchability was freely estimated with a uniform (noninformative) prior in log-space. A Multinomial likelihood was applied to age-composition data, weighted by the sum of the number of trips or hauls actually sampled across all fishing fleets, and the number of trawl sets in the research surveys. Input sample sizes were then iteratively down-weighted to allow for additional sources of process and observation error. This process resulted in tuned input sample sizes roughly equal to the harmonic mean of the effective sample sizes after model fitting.

3.3.2 CCAM

The Canadian catch-age model (CCAM), an age-structured model conditioned on historical catch, was used to evaluate the sensitivity of the base case results to structural uncertainty. The model was developed at the University of British Columbia and has been posted as an open source project by its original author, Dr. Steven Martell, with the title ISCAM (Integrated Statistical Catch Age Model). The model has been further developed and customized by the Canadian authors of this document to calculate the outputs needed for this assessment. We therefore refer to it as CCAM to distinguish this customized version from the original software. The model is fully described in Appendix F. The original ISCAM source code and additional documentation are available at http://code.google.com/p/iscam-project/source/checkout.

The main differences between CCAM and SS are: the negative log-likelihood function for catch-at-age residuals; approach to partitioning of observation and process error; use of an informative prior on survey catchability *q*; and use of parametric selectivity functions. In other respects, the model is structurally very similar to the base case SS model for Pacific hake. Where possible, sensitivity to these factors is reported below.

The fundamental difference between the CCAM model presented here and the TINSS model used in the 2011 assessment (Stewart et al. 2011) is that it is no longer parameterized in terms of management parameters *MSY* and F_{MSY} (although management-oriented parameterization is now an optional switch in the CCAM version of the model). The decision to switch to a model with biological leading parameters (steepness and unfished recruitment) was taken by the provisional JTC late in 2011, due to difficulties in interpreting and initializing a management-oriented model in the presence of large changes in weight at age during the history of the fishery; and also because of future interest in modeling the effects of time-varying selectivity. Initial comparisons of CCAM with management-oriented key parameters compared to "biological-oriented" parameters have revealed some of the possible sources of difference between TINSS and SS in the 2011 assessment (Appendix E). Further comparative work on this subject may provide more insights into relative advantages and disadvantages of each alternative parameterization for volatile stocks like Pacific hake.

As with TINSS in the 2011 assessment, the CCAM model is not initialized at equilibrium. Instead, annual recruitment is estimated as the product of an estimated mean recruitment (estimated in log space) and log-normally distributed annual recruitment deviations, with a separate estimated log mean recruitment and estimated vector of fifteen years of log deviates used to initialize the numbers-at-age matrix (the same approach as in SS). Recruitment residuals are constrained to conform to a Beverton-Holt stock recruitment relationship, as in SS, with the stock-recruit parameters derived from the leading parameters B_0 and h. The validity of the assumption of equilibrium starting conditions has been questioned in previous assessments, particularly because the stock displays a high degree of recruitment variability. The decision to remove this assumption was made in 2011 by the joint hake technical working group.

As is the case for most statistical catch age models, the approach of CCAM is to fit an age-structured population dynamics model to time-series information on relative abundance, and age-composition data from the commercial fishery and survey using a Bayesian estimation framework. CCAM is conditioned on the total landings where the fishing mortality rate each year is estimated directly, but is constrained so that catches conform to the instantaneous Baranov catch equation using the observed total landings and the estimated vulnerable biomass (see Appendix F). The model is fit to the acoustic survey index (Table 4 and Figure 7), assuming that these data are proportional to the vulnerable biomass seen by the survey and also that observation errors are lognormal. Survey data were weighted multiplicatively in the objective function by the relative CVs from the kriging estimates (Table 4).

As with TINSS, CCAM estimates the inverse of the total standard deviation φ^{-1} as well as the variance ratio, ρ, which partitions the total standard deviation into the standard deviations used for observation and process error (i.e., ρ represents the proportion of the total error that is due to observation error). Therefore, the process error standard deviation is calculated as $\sigma_R = (1 - \rho)/\varphi^{-1}$ and the observation error as $\sigma_I = \rho/\varphi^{-1}$ (see Punt and Butterworth 1993, Deriso et al. 2007).

The objective function contains five major components: 1) the negative log-likelihood of the relative abundance data; 2) the negative log-likelihood of the catch-at-age proportions in the commercial fishery; 3) the negative log-likelihood of the catch-at-age proportions in the acoustic survey; 4) the prior distributions for model parameters, and 5) two penalty functions that constrain the estimates of steepness to lie between 0.2 and 1, and prevent annual exploitation rates from exceeding 1. Note that the value of the penalty functions was zero for all samples from the posterior distribution. The joint posterior distribution was numerically approximated using the Markov Chain Monte Carlo routines built into AD Model Builder (Otter Research 2008). Posterior samples were drawn systematically every 15,000 iterations from a chain of length 30 million, resulting in 2,000 posterior samples (the first 1,000 samples were dropped to allow for sufficient burn-in). Convergence was diagnosed using visual inspection of the trace plots and examination of autocorrelation in posterior chains.

The biomass index was treated as a relative abundance index that is directly proportional to the survey vulnerable biomass halfway through the year. It is assumed that the observation errors in the relative abundance index are log-normally distributed. The survey catchability parameter q is treated as an uncertain parameter, but the maximum likelihood estimate of q is used in the calculation of the objective function (see Walters and Ludwig 1994). A normal prior with mean = 0.0 and SD = 0.1 was placed on log q. Sensitivity to the standard deviation of this prior was tested. Fishing mortality in the assessment model was conditioned on the observed total catch weight (combined US and Canada catch), and it was assumed that total catch is known and reported without error.

Age-composition information was assumed to come from a multivariate logistic distribution, where the predicted proportion-at-age is a function of the predicted population age-structure and the age specific vulnerability to the fishing gear (Richards and Schnute 1998). The likelihood for the age-composition data was evaluated at the conditional maximum likelihood estimate of the variance (i.e., no subjective weighting scheme was used to scale likelihood for the age-composition information). Unlike the base SS model, no ageing errors were assumed in CCAM.

Historical observations on mean weight-at-age show systematic declines after the mid-1970s and increases again in late 1990s (Figure 12). A number of the historical cohorts have growth trajectories that initially increase from age-2 to age-8 then decline or stay relatively flat (e.g., the 1977 cohort). Given these data, there are at least three alternative explanations for the observed decreases in mean weight-at-age: 1) changes in condition factor associated with food availability or density dependence; 2) intensive size selective fishing mortality with differential fishing mortality rates on faster growing individuals; and 3) apparent changes in selectivity over time. All three of these variables are confounded, and it is not possible to capture decreasing weight-at-age using the von Bertalanffy growth model and a fixed allometric relationship between length and weight. As such, like SS, CCAM uses the observed mean weight-at-age data from the commercial fishery to scale population numbers to biomass.

Selectivity, or vulnerability-at-age, to the fishing gear was assumed to be age-specific, time-invariant, and is represented by an asymptotic logistic function. Selectivity in the acoustic survey was also assumed to be asymptotic, following a logistic function, and time-invariant. The model results showed considerable sensitivity to the parameters of the survey selectivity function. Survey selectivity was therefore treated as a major source of structural uncertainty in this assessment. Age-specific fecundity was assumed to be proportional to the product of mean body-weight-at-age and the proportion-at-age that are sexually mature.

A total of 117 model parameters are conditionally estimated (Table 7). A summary of the input data is provided in Appendix D. The technical description of the model is provided in Appendix F. See Appendix E for documentation of steps bridging between the 2011 TINSS model and the current CCAM model.

3.4 Modeling results

3.4.1 Changes from 2011

A set of ‘bridging’ models in SS was constructed to clearly illustrate the component-specific effects of all changes to the base-case model from 2011 to 2012. The first link in this bridge analysis was to update to the most recent version of the Stock Synthesis software (3.23b, 2011; 5 November, 2011). This change produced no observable difference in the model results (MLE; Figure 11). The second change involved updating all historical (<=2010) catch estimates to reflect any changes in the underlying databases and to get a final estimate for 2010 to replace the preliminary estimate available at the time the 2011 stock assessment; this also produced no discernible difference in results. The third change included recalculating the age-frequency distributions for the stock assessment to include additional historical ages read after the 2011 assessment; this too produced very little difference in model results (Figure 11).

The second phase of the bridging analysis consisted of adding the 2011 acoustic survey data (pre-SRG panel revision) and the 2011 commercial fishery data, both individually and in combination. The results show unambiguously that the acoustic survey data from 2011 causes the stock assessment results to be revised downward very dramatically (Figure 12). Further, the age-composition data from the commercial fishery does not contain sufficient information to adjust the model results from either the bridge model or the model containing the 2011 acoustic data. The primary source of the change from 2011 lies in the rescaling of the 2005, 2006 and 2008 cohorts, precipitated by the 2011 acoustic survey results.

3.4.2 Model selection and evaluation

Both the SS and CCAM modeling frameworks allow the fitting of a wide range of model complexities with only relatively small changes to input files and data organization. With the extensive structural explorations conducted during the 2011 stock assessment (see Stewart et al. 2011 for a thorough description of these analyses, ranging from simple production models to seasonal, sex-fleet/sector-specific approaches incorporating time-varying growth) as a springboard, the JTC attempted to focus on a smaller subset of structural choices for 2012. Of the many models investigated, only a small subset representing those with the best estimation behavior was selected to illustrate the dominant sources of uncertainty via sensitivity analyses. The ability to use two independent model platforms for this exploration dramatically increased the breadth of the assessment team's efforts. Of the sensitivity analyses presented, those alternate models focusing on fishery and acoustic survey selectivity were selected for more in-depth investigation and reporting and are used to illustrate the among-model uncertainty for comparison with the base case within-model estimates. We report additional sensitivity analyses below.

Iterative reweighting of the composition data in the base case SS model did not produce large changes in the results, and resulted in a down-weighting of the fishery sample sizes to 12%, and the acoustic data to 94%, of the observed number of trips/hauls, while retaining the relative differences in sampling among years. This is virtually unchanged from the 2011 assessment and is consistent with the high degree of correlation among fishery tows for the at-sea fleet and the much greater temporal and spatial spread of the acoustic hauls. The additional variance component for the acoustic survey was estimated to be 0.46 at the median of the posterior distribution, indicating substantial additional process error, beyond simple sampling variability was present (as expected). This estimate is much larger than that from the 2011 assessment (0.26) reflecting the *post hoc* deduction that the 2009 survey observation is largely inconsistent with the trend over adjacent years. Despite the relatively large amount of combined process and observation error for the acoustic time-series, fit to this data source still provides the strongest information available in the assessment on the scale of the current Pacific hake stock.

The CCAM model is provided as a supplement to the SS models in order to test the effects of certain structural assumptions. In the present assessment, every attempt has been made to understand the reasons for different results given by the different models, even though the general results from each model were more similar than has been achieved in recent years. Both models contain aggregated fishery information, empirical weights at age and similar prior assumptions where possible. A fundamental difference is the multivariate logistic likelihood function used to calculate residuals in the commercial and survey age compositions. The multivariate logistic likelihood function (Richards et al. 1997) uses the conditional maximum likelihood estimate of the variance to weight the age-composition data. This likelihood function had been originally introduced into the TINSS models in response to problems encountered in previous assessments, where the age-composition data had to be subjectively down-weighted to reduce retrospective bias (Martell 2010). In general, the multivariate logistic likelihood is robust to weighting problems, although it does assume a single variance across all years, which may produce overly large residuals in some years.

A summary of the fit to the age-composition data (for the base case) and survey index (for both models) can be found in the model results section below.

3.4.3 Assessment model results

For the base-case model, the MCMC chain was run for 10,000,000 iterations with the first 10,000 discarded to eliminate 'burn-in' effects. Each $10{,}000^{th}$ value thereafter was retained, resulting in 999 samples from the posterior distributions for model parameters and derived quantities. Stationarity of the posterior distribution for model parameters was assessed via a suite of standard diagnostic tests. The objective function, as well as all estimated parameters and derived quantities, showed good mixing during the chain and no evidence for lack of convergence. Autocorrelation was low and correlation-corrected effective sample sizes were sufficient to summarize the posterior distributions (Figures 13-15). Neither the Geweke nor the Hiedelberger and Welch statistics for these parameters exceeded critical values more frequently than expected via random chance (Figure 15). Correlations among key parameters were generally low (Figure 16), with the exception of natural mortality and the average unexploited equilibrium recruitment level (R_0).

The modeled time series fit to the acoustic survey biomass index is shown in Figure 17. The fit to the acoustic survey biomass time series is quite reasonable, given the sum of the input and estimated variance components. The 2001 data point was well below the predictions made by any model we evaluated, and no direct cause for this is known, however it was conducted about one month earlier than all other surveys between 1995 and 2009 (Table 4), which may explain some portion of the anomaly. The 2009 index is much higher than any predicted value observed during model evaluation. The uncertainty of this point is also higher than in other years, due to the presence of large numbers of Humboldt squid during the survey. This has been accounted for in both the data and the models.

Selectivity at age for both the fishery and survey is relatively uncertain (an important property of the non-parametric selectivity option) but generally consistent with the observation that fish are fully selected by the time they reach their full size (Figure 18). Fits to the age-composition data in the SS model are also reasonably good, with close correspondence to the dominant cohorts observed in the data and also identification of small cohorts, where the data give a consistent signal (Figures 19-21). These fits are improved over simpler models that do not include ageing error and the cohort effect on ageing error. Residual patterns to the fishery and survey age data do not show particularly evident trends that would indicate systematic bias in model predictions (Figures 22 and 23).

Posterior distributions for model parameters showed that for both steepness and natural mortality the prior distributions were likely strongly influencing the posterior (Figure 24). All other parameters showed substantial updating from noninformative priors to stationary posterior distributions.

The base-case stock assessment model indicates that the Pacific hake female spawning biomass was well below the average unfished equilibrium level at the start of the fishery and during the 1970s (Figure 25 and Tables 8-9). The stock increased rapidly after two or more large recruitment events in the early 1980s and then declined rapidly after a peak in the mid- to-late 1980s to a low in 2000 (Figures 26-27 and Table 10). This long period of decline was followed by a brief increase to a peak in 2003 (median estimate of 1.29 million mt in the SS model) as the exceptionally large 1999 year class matured. The stock is then estimated to have declined with the ageing 1999 year class to a time-series low of 0.38 million mt in 2009. This recent decline is much more extreme than that estimated in the 2011 assessment. At the beginning of 2012 spawning biomass is estimated to be increasing based on the strength of the 2008 year class; however this estimate is quite uncertain, with 95% posterior credibility intervals ranging from historical lows to above the equilibrium levels. The current median posterior spawning biomass equates to 32.6% of the average unfished equilibrium level (SB_0, Figure 28). Estimates of uncertainty in current relative depletion are extremely broad, from 9.4%-102% (Figure 28). The estimate of spawning biomass for 2012 is 0.62 million mt, much smaller than the two 2011 estimates from the 2011 assessment (1.87, and 2.18 million metric tons from SS and TINSS, respectively). This change is largely due to the very low 2011 acoustic survey biomass index.

Estimates of historical Pacific hake recruitment indicate very large year classes in 1980 and 1999 in both assessment models, with 1970, 1984 and 2008 accounting for the other three of the five largest estimated to have occurred in the last 40 years. The strength of the 2008 cohort is estimated to be large (5.2 billion), although not nearly as large as was estimated in the 2011 stock assessment (16.2 billion). In both the U.S. fishery and acoustic age compositions, the 2008 year class comprised a very large proportion of the observations. Uncertainty in estimated recruitments is substantial, especially for 2008, as indicated by the broad posterior intervals (Figure 26). The stock-recruit estimates (based on MLE) are provided in Figure 29; both the extremely large variability about the expectation and the lack of relationship between spawning stock and subsequent recruitment are clearly evident in this plot.

3.4.4 Model uncertainty

Both assessment models integrate over the substantial uncertainty associated with several important model parameters including: acoustic survey catchability (*q*) and the productivity of the stock (via the steepness, *h*, of the stock-recruitment relationship and natural mortality, *M*). Although the Bayesian results presented include estimation uncertainty, this within-model uncertainty is likely a gross underestimate of the true uncertainty in current stock status and future projections, since it does not include structural modeling choices, data-weighting uncertainty and scientific uncertainty in selection of prior probability distributions. In an effort to capture some of these additional sources of uncertainty, especially with respect to treatment of selectivity, we provide an extended set of key sensitivity analyses, using both SS and CCAM (see section below).

The Pacific hake stock displays the highest degree of recruitment variability of any west coast groundfish stock, resulting in large and rapid changes in stock biomass. This volatility, coupled with a dynamic fishery, which potentially targets strong cohorts and a biennial rather than annual fishery independent acoustic survey, will continue to result in highly uncertain estimates of current stock status and even more uncertain projections of stock's future trajectory. The JTC considers the primary source of uncertainty that is relevant to management decision-making for the 2012 fishing season to be the selectivity in both the acoustic survey and the fishery. In both models the fit to the 2011 survey index point (Figure 30) and the estimated scale of the hake population (Figure 31) was highly sensitive to estimates of selectivity. The sensitivity cases evaluated explore an axis of uncertainty related primarily to parameterization of fishery and survey selectivity, although the independent platforms used also provide a much broader exploration than is routinely conducted in many stock assessments.

The primary axis of uncertainty in the 2011 assessment was considered to be the magnitude of the 2008 cohort, which had only been seen once, and only in commercial catch-composition data. The 2011 stock assessment team expressed concern that the large proportion of two year old fish in the commercial age-composition data could possibly be explained by a change in fishing practices or other factors affecting gear selectivity in the commercial fishery. To some extent, age composition data from the 2011 fishery and acoustic survey support the hypothesis of a strong 2008 cohort, although estimates of its magnitude have been reduced somewhat by the low index of abundance in 2011. Uncertainty in the magnitude of this year class will likely persist until the cohort has been seen by the survey and the fishery for several more years, although its relative influence on model uncertainty is expected to diminish as it moves through the fishery.

3.4.5 Reference points

The average unexploited equilibrium spawning biomass estimate was 1.89 million mt (Table 11), intermediate between the two estimates reported in the 2011 stock assessment. However, the uncertainty is very broad, with the 95% posterior credibility interval ranging from 1.49 to 2.53 million mt. The *MSY*-proxy target spawning biomass ($SB_{40\%}$) is estimated to be 0.76 million mt in the base-case model, slightly larger than the equilibrium spawning biomass implied by the $F_{40\%}$ default harvest rate target, 0.76 million mt. *MSY* is estimated occur at an even smaller stock size, 0.46 million mt, with a yield of 317 thousand mt; only slightly higher than the equilibrium yield at the biomass target ($SB_{40\%}$), 290 thousand mt, and the $F_{40\%}$ target, 299 thousand mt. The full set of reference points with uncertainty intervals for the base case and among alternate sensitivity models are reported in Table 11.

The fishing intensity on the Pacific hake stock is estimated to have been below the $F_{40\%}$ target until 2008 (Figure 32). Uncertainty in the recent SPR estimates is large, and the estimates from the base-case model indicate that the catch has exceeded the target in four of the last five years. The exploitation history, in terms of both the biomass and *F* targets, is portrayed graphically via a phase-plot (Figure 33).

3.4.6 Model projections

In order to better reflect the considerable uncertainty in this assessment, all forecasts are reported in two decision tables: one representing uncertainty within the base-case model; and the other representing uncertainty among alternate models (see Section 3.4.7 for description of models). This allows for the evaluation of alternative management actions based on both types of uncertainty. The decision tables are organized such that the projected implications for each potential management action (the rows, containing a range of potential catch levels) can be evaluated across the quantiles of the posterior distribution for the base-case model (the columns), or among median estimates from the alternate models. For clarity, each decision table is divided into two sections: the first table projects the depletion estimates, the second the degree of fishing intensity (based on the relative SPR; see table legend). Fishing intensity exceeding 100% indicates fishing in excess of the $F_{40\%}$ default harvest rate. A set of management metrics were identified during the Scientific Review Group (SRG) review of this stock assessment, based on input from JMC, AP and other attendees. These metrics summarize the probability of various outcomes from the base case model given each potential management action. Although not linear, probabilities can be interpolated from this table for intermediate catch values.

The median stock estimate from the base-case model is projected to increase or remain constant from 2012 to 2013 for all management actions considered except the *status quo*. (Table 12). However, the posterior distribution is highly uncertain, and either increasing or decreasing trends are possible over a broad range of 2012 catch levels. The base-case model predicts a rapid increase in the absence of future fishing, surpassing the management target with a 50% probability in 2013; this is attributable largely to the strong 2008 cohort. However, the difference between this trajectory and that conditioned on the default harvest rate is extremely small, relative to the uncertainty in the current stock status (Figure 34). There is 47% chance of exceeding the harvest target in 2012 for catch levels approaching the default harvest rate, however this level of catch corresponds to a 47% chance of having a smaller stock in 2013 than in 2012.

Among alternate sensitivity models, there is also considerable uncertainty in current status and future trends (Table 12-13, Figure 35). Although these models fall within the 'envelope' of the posterior distribution from the base-case model, the median trajectories under each potential management action show less sensitivity to alternate management actions than the extreme quantiles from the base case.

3.4.7 Sensitivity and retrospective analyses

A number of sensitivity analyses were done to test the effect of priors, structural choices, and the modeling platform itself on the base-case model results. Some of these analyses were conducted prior to the 2012 SRG review and therefore do not reflect the final 2011 acoustic survey data as updated during that meeting. The results of these investigations, as well as retrospective analyses, are presented below. Since this assessment is fully Bayesian, posterior parameter distributions for the base case are provided instead of the frequently reported likelihood profiles, which are an imperfect proxy for the actual posteriors. The maximum likelihood estimates (technically an approximation to the maximum of the posterior density as implemented in ADMB) for model parameters and derived quantities are on the same scale, but the posterior distributions better reflect the asymmetry inherent in the uncertainty estimates (compared to the multivariate normal approximation applied to the maximum likelihood estimates). A comparison of this asymmetry is provided in Table 14 and Figure 36.

During preliminary model investigation, the assessment team found the 2012 assessment model results were highly sensitive to the specific parameterization of the selectivity functions for the acoustic survey and the commercial fishery. For this reason, this 'axis of uncertainty' was selected for representation in the second set of decision tables. Although the base case and CCAM models differ in many structural respects, the behavior and sensitivity to selectivity parameterization and/or application of priors was very similar between the two. Note that for the discussion below we refer to the CCAM model with survey selectivity parameters estimated as the "CCAM base model".

Adjusting the oldest age for which selectivity was independently estimated in the base model produced a difference in the scaling of the 2008 cohort strength, which is highly correlated with the 2012 stock size estimate (Figure 31). The CCAM model most comparable with the base case model (CCAM with estimated survey selectivity) is summarized in Table 7. As an alternate to that model, a second CCAM model is presented as a 'bounding case' with fixed survey selectivity, such that 50% of age-2 fish are fully selected and 100% of age-3 fish are fully selected. This run is intended to capture what the stock assessment would predict if it is the case that the survey selectivity is nearly knife-edged. A similar scaling pattern was observed for the CCAM model when the selectivity curve was fixed, compared to when survey selectivity parameters were freely estimated (Figure 37). However, these four alternate models all fit the acoustic survey index very similarly: capturing the trend over 2003 to 2011, but entirely missing the 2009 observation (Figure 30). None of the models investigated were able to fit the 2001 survey observation. This is likely due to the *post hoc* knowledge that the 1999 year-class was very large, and therefore, for any reasonable degree of selectivity for age-2 hake the stock, never reached a size as small as is implied by the survey observation.

The influence of the prior distribution for natural mortality (*M*) and the fixed value for the degree of recruitment variability (σ_r; iteratively tuned following the procedure of Methot and Taylor, 2011) were investigated using the base-case model. When the standard deviation on the prior for *M* was increased to 0.2, or 0.3 (from 0.10), the result was a modest increase in the posterior median estimate, indicating that the prior was having a limiting effect on the posterior distribution (Table 15). The assessment model adjusted to this increase in natural mortality by increasing the relative estimated magnitude of the largest cohorts (including 2008) and generally increasing the absolute scale of the population size (Figure 38). However, convergence diagnostics for these sensitivity analyses revealed a very high degree of parameter confounding between natural mortality and the logarithm of equilibrium recruitment (Figure 39). This confounding led to posterior chains that were extremely slow to converge (an effective sample size of less than 25% of the base case, even when the chain length was increased by a factor of 6) and therefore the reliability of these results should be considered suspect. In contrast, estimating the degree of recruitment variability with a moderately informative prior had very little effect on the model results (Figure 38), although it too revealed poor convergence. In summary, these alternate models were not reliable enough for use as a base model, but did reveal that more research into informative priors for hake could be warranted in future stock assessments.

The CCAM model also showed poor convergence diagnostics as the standard deviation on the normal prior for log natural mortality was increased, also due to confounding among model parameters (particularly *M* with R_0 and average recruitment). It should be noted here that the two key CCAM sensitivity cases described above were updated following the SRG meeting to include the revised 2011 survey index point. The 6% decrease in the 2011 data point had a stronger influence on CCAM model behavior than was seen in SS. MCMC diagnostics indicated that the model had failed to converge after 20 million iterations with the standard deviation on the prior for log(*M*) set to 0.1 (as in SS). Therefore, the assessment team agreed to reduce the standard deviation on the prior for log(*M*) to 0.05 in the CCAM 'base case' (with survey selectivity parameters estimated) to improve model diagnostics and predictive capability. Alternatively, it was not possible to achieve convergence in the alternate CCAM case (survey selectivity parameters fixed) unless the standard deviation on the prior for log(*M*) was increased to 0.2, highlighting confounding between estimates of selectivity and productivity in this problem. Therefore comparisons among the CCAM key sensitivity cases and the SS cases should bear in mind the effect of the different priors on log(*M*) (see Table 17; Figure 41 and text below for discussion on the effect of the prior on log (*M*)). We caution that the CCAM fixed selectivity case still showed strong autocorrelation in the MCMC chains, and reiterate that this sensitivity case is presented as an extreme example intended to bracket the probable lower bound of the uncertainty surrounding survey selectivity.

In addition to the two CCAM sensitivity cases described above, we explored several additional sensitivities using CCAM. We note that the cases discussed below were not updated to include the new 2011 survey index point, upon direction from the SRG. The qualitative direction of change caused by the alternative prior settings would not be expected to change given the new index point. However, we also point out that the standard deviation on the prior for log(*M*) for the "base case" discussed below was set to 0.2, higher than the 0.05 used in the CCAM base case discussed above. This discrepancy is unfortunate, but is a result of the correction to the 2011 survey index that occurred very late in the assessment cycle, precluding re-running of all the sensitivity cases as direct comparisons with the new CCAM base case.

The main axes of uncertainty that were considered were: steepness (*h*); the standard deviation for the prior on log(*M*); the mean of the prior on log(*M*); and the standard deviation for the prior on log survey *q* (Tables 16-19). For these analyses, the MCMC chain was run for 20,000,000 iterations and every subsequent 10,000th value was retained, resulting in 2,000 samples from the posterior distributions for model parameters and derived quantities (the first 1,000 samples were dropped to allow for sufficient burn-in). Stationarity of the posterior distribution for model parameters was assessed by visualization of trace plots and analysis of lagged autocorrelation. We caution that for those cases in which we increased the standard deviation on priors for log(*q*), and log(*M*), the convergence properties of the MCMC deteriorated so that the presented within-model uncertainties of some quantities may be unreliable. However, the objective of performing these sensitivity analyses was to illustrate a more complete presentation of structural uncertainty.

For sensitivity on the steepness prior, we based priors on the median steepness estimates of the Gadiform fishes using the Myers et al. 1999 meta-analysis of stock-recruitment time series. Due to time limitations, we did not simulate beta-distribution priors like those used for the CCAM and the SS base cases. Instead, we used the mean of the medians for: all Gadidae excluding Pacific hake (*Z*_gadids_noHake, Figure 40); the genus *Merluccius* including and excluding Pacific hake (*Z*_Merluccius wHake and *Z*_Merluccius_NoHake, respectively). The rational for excluding the steepness estimates of Pacific hake in the computation of the priors is that the data used for the Myers et al (1999) meta-analysis contained some data that are also analyzed in this stock assessment. In order for the model to converge and produce reasonable estimates, the coefficient of variation for the steepness prior had to be set to 0.1. Furthermore, readers should note that the paper states that family-level estimates for the Gadiform fishes should be used with caution so that any prior simulated using the Myers et al. (1999) meta-analysis may be unreliable. Future analyses to simulate steepness priors for hake could be based on life-history information using the method proposed by Mangel et al. (2010).

The sensitivities of CCAM estimates of spawning stock biomass and age-1 recruitment to alternative priors for steepness all fell within the uncertainty envelope of the base case, but the reference point estimates differed (Table 16). The posterior medians of steepness were lower than the CCAM model with estimated survey selectivity for the steepness productivity cases, as expected from the lower mean of the priors. In general, the median estimated 2012 biomass for the steepness sensitivity cases were lower than for CCAM with estimated survey selectivity (Figure 40). Similarly, median estimates of age-1 recruitment for the steepness sensitivity cases were lower than the medians of the case with estimated survey selectivity, but were within the 95% credible intervals (Figure 40). Estimates of 2012 depletion were also lower for these cases, and estimated exploitation fractions corresponding to $SB_{40\%}$, $SPR_{40\%}$, and *MSY*, respectively, tended to be higher (Table 16), although effects on the exploitation fraction were somewhat offset by the increased estimates of *M* that accompanied the decreased estimates of steepness (Table 16). Estimated exploitation fractions for the CCAM steepness sensitivity cases were also larger than those from the SS base case (Table 13).

Increasing the standard deviation of the prior on log natural mortality had a large effect on the CCAM estimates of spawning stock biomass, recruitment and reference points. As the standard deviation of the prior was increased, posterior medians of log(*M*), the estimated 2012 spawning biomass and recruitment increased (Table 17 and Figure 41). As the prior standard deviation on log(*M*) increased, CCAM estimated higher R_0. Exploitation fractions corresponding to $SB_{40\%}$, $SPR_{40\%}$, and *MSY* also increased, implying that stocks with higher productivity can tolerate higher exploitation rates (Table 17).

Varying the mean for the prior on log natural mortality also had a significant effect on CCAM's predictions. When the mean of the prior was increased, median spawning stock biomass estimates were marginally higher. When it was decreased to 0.175, the median estimates were much smaller (Table 18, Figure 42). Similarly, estimates of reference-point exploitation fractions were higher than the CCAM base when the mean was set to log(0.225), but lower when the mean was set to log(0.175).

CCAM median estimates of survey *q* were proportional to the standard deviation of the prior on log(*q*). The median estimates of *q* increased as the standard deviation was increased to 0.15, 0.25 and 0.3 respectively. Therefore base-case results will differ from those reported for the updated base case. Associated with these increased estimates of survey *q*, were lower initial, historical and current spawning biomass estimates (Figure 43) as well as exploitation rate reference points lower than the CCAM base. We note, as discussed above, that the 'base case' referred to here was not updated to include the corrected 2011 survey index point.

Retrospective analyses were conducted by systematically removing the terminal year's data sequentially for five years. For the base SS model, the effect of the 2011 data (almost entirely attributable to the survey index) is dramatic, as was observed in the bridge analysis (Figure 44). A retrospective pattern may seem to be present in recent estimates of spawning biomass, but this can be explained by the recent large year-classes supporting the spawning biomass. As data are removed, less information is available to accurately estimate these recruitments, thus they move towards equilibrium recruitment, and the estimated spawning biomass becomes lower. This pattern is most pronounced for the 1999 year class, estimates of which increase in magnitude as data are added since observations of this cohort are persistent through time. This further illustrates how multiple observations are needed to accurately determine the strength of the largest cohorts – it is not until they are nearly completely gone that we have precise estimates of their magnitude. Parameter estimates showed no clear patterns except that the additional variability on the acoustic survey index increased in 2011 and the estimate of unexploited biomass or recruitment decreased sharply (Table 20).

A comparison of the models put forward for management since 1991 (a retrospective among assessment models) shows that there has been considerable uncertainty in the Pacific hake stock biomass and status (Figure 45). Model-to-model variability (especially in the early portion of the time-series) is larger than the uncertainty reported in any single model, and this pattern does not appear to dampen as subsequent assessments are developed. An important aspect of this historical perspective is the inclusion of alternate values for survey catchability during 2004-2007, and then subsequently freely estimated values from 2008-the present. Prior to that period, catchability was ubiquitously assumed to be equal to 1.0. The 2012 base model estimates appear to be consistent with many previous time-series, and the uncertainty intervals bracket a large proportion of those historical estimates.

3.4.8 Potential Management Strategy Evaluation Analyses

Many Pacific hake stock assessment uncertainties may not be resolvable. Pacific hake is a relatively data-rich fishery, with a directed fishery-independent survey program, biological sampling from both commercial fisheries and the survey, and reliable estimates of catch. However, the data are apparently insufficient to resolve key uncertainties that can produce large differences in stock-status estimates between years. One reason is that the acoustic survey observations themselves are highly variable, due to factors including sampling error, uncertainty in acoustic target identification, and the distribution and movement of the target species. Furthermore, the assessment is very sensitive to small changes in assumptions: for example, small differences in the parameterization of selectivity can produce stock-status estimates that range from over-exploited to above target biomass levels. The actual magnitude of uncertainty is much larger than is typically represented in any given decision table; different assessment approaches may produce very different biomass reconstructions (Ralston et al. 2011). Moreover, recruitment, weight at age and natural mortality are affected by time-varying changes in productivity and predation regimes that make historical data poor predictors of the future (Hilborn and Walters 1992, Walters 1986, Walters and Martell 2004) making stock-assessment model predictions unreliable.

Rather than struggling to find a "best assessment model" in the face of uncertainty that cannot be resolved at the present time, it may be possible to design management, data collection, and modeling strategies that provide adequate trade-off performance among stock and fishery objectives. The design process involves simulation testing of candidate management strategies against plausible scenarios for a 'true' stock and fishery that encompass the range of known or suspected uncertainties. The Management Strategy Evaluation, or MSE, approach seeks to find a management strategy that is robust to the uncertainties and provides explicit evaluation of the expected trade-offs among conservation and yield objectives (Smith et al. 1999). There have been many precursers to MSE, some dating back several decades: Walters and Hilborn (1978) reviewed how to design optimization analyses that applied controls to modeled ecological systems in order to maximize objectives; and simulation studies on management procedures have been applied at the International Whaling Commission since the mid-1980s (e.g., de la Mare 1986). In a seminal paper on the subject, de la Mare (1998) proposed formulating management objectives that are measurable; specifying sets of decision rules, and the data and methods to be used, all in such a way that the properties of the resultant system could be prospectively evaluated. He called this the "management oriented paradigm", which has since been referred to as Management Procedure Evaluation (MPE) or MSE. The literature on MSE is too large to be reviewed here, but there have been several applications in the North Pacific (A'Mar et al. 2009; 2010; Cox and Kronlund 2008; Kurota et al. 2010; Punt et al. 2008; Punt and Ralston 2007).

More generally, MSE is a useful tool to investigate whether management strategies have a low probability of causing irreversible harm to the stock. Noting that it offers several advantages over annual stock assessments, Butterworth (2007) argued that the annual (or biennial) assessment approach suffers from: variability in "best assessments" from year to year; inability to compare longer-term tradeoffs; lengthy haggling over annual TACs; and default decisions of no change. Many of these difficulties have been observed in historical Pacific hake stock assessments and management. He suggests that MSE can help resolve some these difficulties but that lengthy development time, overly rigid frameworks, unavailable data inputs, and reference-case selection are some of the key disadvantages.

Acknowledging concerns about the high cost of MSE, it is likely that for Pacific hake, defining objectives and evaluating the performance harvest control rules, as well as achieving consensus among parties to agree to such modifications under the treaty, may be very time-consuming. However, there are some issues that could be dealt with now. One issue is to consider whether stock assessment performance could be improved by investing in annual, instead of biennial, surveys. This may help to resolve the current situation, where in non-survey years, the only available data on which to base an assessment are commercial catch-at-age observations that may produce unreliable updates to stock size.

Furthermore, a simulation experiment could be designed to investigate how the current harvest control rule (40:10-$F_{40\%}$) performs. The MSE would consist of simulating the stock assessment procedure using the current biannual vs. annual surveys, under different assumptions about observation error, the number of survey stations, control rules and assessment procedures. Management procedures could, for example, be evaluated based on three main performance categories: catch, catch variability, and conservation (Cox and Kronlund 2008). Catch and catch variability could be represented by average annual catch and average absolute variation in catch (Punt and Smith 1999) and conservation could be represented in terms of the proportion of years that the stock was below particular biomass levels.

4. Acknowledgements

This assessment relies heavily on text and analyses from previous assessments spanning the last several decades, we thank those authors for the use of their work. We thank the following individuals who contributed technical assistance, analysis tools, data, or comments to this assessment: Dezhang Chu, Julia Clemons, Karina Cooke, Ken Cooke, George Cronkite, Steve Deblois, Cassandra Donavan, Melissa Haltuch, Jim Hastie, Larry Huffnagle, Rob Kronlund, Lisa Lacko, Shayne MacLennan, Patrick McDonald, Megan O'Connor, Chelsea Stanley, Brad Stenberg, Ian Taylor, Rebecca Thomas, and Vanessa Tuttle. We also thank the many attendees at the two official JTC meetings who provided valuable insight into the 2011 commercial fisheries in Canada and the U.S., as well as additional perspective on the acoustic survey. We thank the 2012 SRG review panel members and attendees for their constructive and insightful comments on the assessment and on this document.

5. Bibliography

Agostini, V.N., R.C. Francis, A.B. Hollowed, S.D. Pierce, C. Wilson, and A.N. Hendrix. 2006. The relationship between Pacific hake (*Merluccius productus*) distribution and poleward subsurface flow in the California Current system. Can. J. Fish. Aquat. Sci. 63:2648-2659.

Alarcón-Muñoz, R., L. Cubillos, and C. Gatica. 2008. Jumbo squid (*Dosidicus gigas*) biomass off central Chile: Effects on Chilean hake (*Merluccius gayi*). Calif. Coop. Oceanic Fish. Invest. Rep. 49: 157-166.

Alheit J. and T.J. Pitcher. 1995. Hake: biology, fisheries, and markets. Chapman and Hall. London. 477 p.

A'Mar, Z.T., Punt, A.E., and Dorn, M.W. 2009. The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. ICES Journal of Marine Science. 66: 1614-1632.

A'Mar, Z.T., Punt, A.E., and Dorn, M.W. 2010. Incorporating ecosystem forcing through predation into a management strategy evaluation for the Gulf of Alaska walleye pollock (*Theragra chalcogramma*) fishery. Fisheries Research 102: 98-114.

Anon, 1993. “Report of the workshop on the applicability of spatial techniques to acoustic survey data,” ICES Coop. Res. Rep. 195, 87pp.

Bailey, K.M., R.C. Francis, and E.R. Stevens. 1982. The life history and fishery of Pacific whiting, *Merluccius productus*. Calif. Coop. Oceanic Fish. Invest. Rep. 23:81-98.

Benson, A.J., G.A. McFarlane, S.E. Allen, and J.F. Dowler. 2002. Changes in Pacific hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift. Can. J. Fish. Aquat. Sci. 59: 1969-1979.

Bentley, N., Breen, P.A., Kim, S.W., and Starr, P.J. 2005. Can additional abundance indices improve harvest control rules for New Zealand rock lobster (*Jasus edwardsii*) fis heries? New Zealand journal of marine and freshwater research 39: 629-644.

Buckley, T.W. and P. A. Livingston. 1997. Geographic variation in the diet of Pacific hake, with a note on cannibalism. Calif. Coop. Oceanic Fish. Invest. Rep. 38:53-62.

Butterworth, D.S. 2007. Why a management procedure approach? Some positives and negatives. *ICES J. Mar. Sci.* 64: 613-617.

Cox, S.P., and Kronlund, A.R. 2008. Practical stakeholder-driven harvest policies for groundfish fisheries in British Columbia, Canada. Fisheries Research 94: 224-237.

de La Mare, W.K. 1986. Simulation studies on management procedures. Reports of the International Whaling
Commission.. 36: 429-450.

de La Mare, W.K. 1998. Tidier fisheries management requires a new MOP (management-oriented paradigm). Reviews in Fish Biology and Fisheries 8: 349-356.

Deriso, R. B., M. N. Maunder, and J.R. Skalski. 2007. Variance estimation in integrated assessment models and its importance for hypothesis testing. Can. J. Fish. Aquat. Sci. 64: 187-197.

Dorn, M.W. 1991. Spatial and temporal patterns in the catch of Pacific whiting in the U.S. management zone during 1978-88. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/NWC-205, 68 p.

Dorn, M.W. and R.D. Methot. 1991. Status of the coastal Pacific whiting resource in 1990. U.S. Dept. Commer., NOAA Tech. Memo. NMFS F/AFSC-47, 101 p.

Dorn, M.W. 1992. Detecting environmental covariates of Pacific whiting (*Merluccius productus*) growth using a growth-increment regression model. Fish. Bull. U.S. 90: 260-275.

Dorn, M.W. 1995. The effects of age composition and oceanographic conditions on the annual migration of Pacific whiting *Merluccius productus*. Calif. Coop. Oceanic Fish. Invest. Rep. 36:97-105

Dorn, M.W. 1996. Status of the coastal Pacific whiting resource in 1996. In Pacific Fishery Management Council, Appendix Volume I: Status of the Pacific Coast groundfish fishery through 1996 and recommended acceptable biological catches in 1997, p. A1-A77. (Document prepared for the Council and its advisory entities.) Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Dorn, M.W., E.P. Nunnallee, C.D. Wilson and M.E. Wilkins. 1994. Status of the coastal Pacific whiting resource in 1993. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/AFSC-47, 101 p.

Dorn, M.W. and M.W. Saunders. 1997. Status of the coastal Pacific whiting stock in U.S. and Canada in 1997. In Pacific Fishery Management Council, Appendix: Status of the Pacific Coast groundfish fishery through 1997 and recommended acceptable biological catches in 1998: Stock assessment and fishery evaluation. Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Dorn, M.W., M.W. Saunders, C.D. Wilson, M.A. Guttormsen, K. Cooke, R. Kieser, and M.E. Wilkins. 1999. Status of the coastal Pacific hake/whiting stock in U.S. and Canada in 1998. In Pacific Fishery Management Council, Appendix: Status of the Pacific Coast groundfish fishery through 1998 and recommended acceptable biological catches in 1999: Stock assessment and fishery evaluation. Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Field, J.C., K. Baltz, A.J. Phillips, and W.A. Walker. 2007. Range expansion and trophic interactions of the jumbo squid, *Dosidicus gigas*, in the California Current. Calif. Coop. Oceanic Fish. Invest. Rep. 48: 131-146.

Fleischer, G.W., K.D. Cooke, P.H. Ressler, R.E. Thomas, S.K. de Blois, L.C. Hufnagle, A.R. Kronlund, J.A. Holmes, and C.D. Wilson. 2005. The 2003 integrated acoustic and trawl survey of Pacific hake, Merluccius productus, in U.S. and Canadian waters off the Pacific coast. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-65, 45 p.

Forrest, R.E., S.J.D. Martell, M.C. Melnychuk and C.J. Walters. 2008. An age-structured model with leading management parameters, incorporating age-specific selectivity and maturity. . Can. J. Fish. Aquat. Sci 65, 286-296.

Fournier, D. A., H. J. Skaug, et al. 2011. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software: 1-17.

Francis, R.C., G.L. Swartzman, W.M. Getz, R. Harr, and K. Rose. 1982. A management analysis of the Pacific whiting fishery. U.S. Dep. Commer., NWAFC Processed Report 82-06. 48 p.

Francis, R.C., and A.B. Hollowed. 1985. History and management of the coastal fishery for Pacific whiting, *Merluccius productus*. Mar. Fish. Rev. 47(2):95-98.

Gelman, A., Carlin, J.B., Stern, H.S., and Rubin, D.B. 2004. Bayesian data analysis, 2nd Edition. Chapman and Hall, New York.

Gilly, W.F., U. Markaida, C.H. Baxter, B.A. Block, A. Boustany, L. Zeidberg, K. Reisenbichler, B. Robison, G. Bazzino and C. Salinas. 2006. Vertical and horizontal migrations by the jumbo squid *Dosidicus gigas* revealed by electronic tagging. Mar. Eco. Prog. Ser. 324: 1-17.

Hamel, O.S. and I.J. Stewart. 2009. Stock assessment of the Pacific hake, *Merluccius productus*, (a.k.a. whiting) in the U.S. and Canadian waters in 2009. Pacific Fishery Management Council, Portland, OR. 246 p.

Hannah, R.W. and S. Jones. 2009. 20th Annual pink shrimp review. Oregon Department of Fish and Wildlife, 2040 S.E. Marine Science Dr., Newport, OR 97365. 12 p.

Harvey, C.J., K. Gross, V.H. Simon, and J. Hastie. 2008. Trophic and fishery interactions between Pacific hake and rockfish: effect on rockfish population rebuilding times. Marine Ecology-Progress Series 365:165-176.

Helser, T.E, M.W. Dorn, M.W. Saunders, and R.D. Methot. 2001. Pacific whiting assessment update for 2000. In Pacific Fishery Management Council, Status of the Pacific Coast groundfish fishery through 2001 and recommended acceptable biological catches in 2002 (Document prepared for the Council and its advisory entities.) Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E. , M.W. Dorn, M.W. Saunders, C.D. Wilson, M.A. Guttormsen, K. Cooke and M.E. Wilkins. 2002. Stock assessment of Pacific whiting in U.S. and Canadian waters in 2001. In: Status of the Pacific Coast groundfish fishery through 2001 and recommended acceptable biological catches in 2002 (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E, R.D. Methot, and G.W. Fleischer. 2004. Stock assesment of Pacific hake (whiting) in U.S. and Canadian waters in 2003. In: Status of the Pacific Coast groundfish fishery through 2004 and stock assessment and fishery evaluation (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E., M.W. Fleisher, S. Martell and N. Taylor. 2005. Stock assessment of Pacific hake (whiting) in U.S. and Canadian waters in 2004. In: Status of the Pacific Coast Groundfish Fishery Through 2005, Stock Assessment and Fishery Evaluation: Stock Assessments and Rebuilding Analyses (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E, I. J. Stewart, G.W. Fleischer, and S. Martell. 2006. Stock assessment of Pacific hake (whiting) in U.S. and Canadian waters in 2006. In: Status of the Pacific Coast Groundfish Fishery Through 2005, Stock Assessment and Fishery Evaluation: Stock Assessments and Rebuilding Analyses (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E. and S. Martell. 2007. Stock assessment of Pacific hake (whiting) in U.S. and Canadian waters in 2007. In: Status of the Pacific Coast groundfish fishery through 200 and recommended acceptable biological catches in 2006 (Document prepared for the Council and its advisory entities). Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Helser, T.E., I.J. Stewart, and O.S. Hamel. 2008. Stock Assessment of Pacific Hake, *Merluccius productus*, (a.k.a Whiting) in U.S. and Canadian Waters in 2008. *In*: Status of the Pacific Coast groundfish fishery through 2008, Stock Assessment and Fishery evaluation: Stock Assessments, STAR Panel Reports, and Rebuilding Analyses. Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR.

Henderson, M.J., and J.K. Horne. 2007. Comparison of in situ, ex situ, and backscatter model estimates of Pacific hake (Merluccius productus) target strength. Can. J. Fish. Aquat. Sci. 64: 1781-1794.

Hilborn, R., and Walters, C.J. 1992. Quantitative Fisheries Stock Assessment Choice, Dynamics and Uncertainty. Routledge, Chapman and Hall.

Hoenig, J.M. 1982. A compilation of mortality and longevity estimates for fish, mollusks, and cetaceans, with a bibliography of comparative life history studies. Technical Report No. 82-2. Narragansett Marine Laboratory, University of Rhode Island.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82:898-903.

Hollowed, A.B., S.A. Adlerstein, R.C. Francis, M. Saunders, N.J. Williamson, and T.A. Dark. 1988a. Status of the Pacific whiting resource in 1987 and recommendations to management in 1988. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-138, 54 p.

Iwamoto, E., M. J. Ford, and R. G. Gustafson. 2004. Genetic population structure of Pacific hake, Merluccius productus, in the Pacific Northwest. Environmental Biology of Fishes 69:187-199.

Jolly, G.M., and I. Hampton. 1990. A stratified random transect design for acoustic surveys of fish stocks. Can. J. Fish. Aquat. Sci. 47:1282–1291.

Jow, T. 1973. Pacific hake length frequencies at California ports, 1963-1970. Marine Resources Technical Report No. 2. California Department of Fish and Game.

Keller, A. A., B.H. Horness, E.L. Fruh, V.H. Simon, V.J. Tuttle, K.L. Bosley, J.C. Buchanan, D. J. Kamikawa, and J.R. Wallace. 2008. The 2005 U.S. West Coast bottom trawl survey of groundfish resources off Washington, Oregon, and California: Estimates of distribution, abundance, and length composition., U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-93, 136 p.

King, J.R., MacFarlane, G.A., Jones, S.R.M., Gilmore, S.R., and Abbott, C.L. 2012. *Stock delineation of* migratory and resident Pacific hake in Canadian waters. Fisheries Research 114: 19-30.

Kurota, H., Hiramatsu, K., Takahashi, N., Shono, H., Itoh, T., and Tsuji, S. 2010. Developing a management procedure robust to uncertainty for southern bluefin tuna: a somewhat frustrating struggle to bridge the gap between ideals and reality. Popul. Ecol 52: 359-372.

Livingston, P.A. and K.M. Bailey. 1985. Trophic role of the Pacific whiting, Merluccius productus. Mar. Fish. Rev. 47(2):16-22-34.

Lo, N.C.H. 2007. Daily larval production of Pacific hake (*Merluccius productus*) off California in 1951-2006. CalCOFI rep. Vol. 48:147-164.

Martell, S. J. D. 2010. Assessment and management advice for Pacific hake in U.S. and Canadian waters in 2010. Pacific Fishery Management Council. Portland, Oregon. 80 p.

Martell, S. J. D. 2011. iSCAM User's Guide. Version 1.0. University of British Columbia, Vancouver. 34 pp. Available online at http://code.google.com/p/iscam-project/source/checkout.

Mello, L. G. S. and Rose, G. A. 2005. Using geostatistics to quantify seasonal distribution and aggregation patterns of fishes: an example of Atlantic cod (Gadus morhua). Can. J. Fish. Aquat. Sci. 62: 659–670.

Methot, R.D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. In E.F. Edwards and B.A. Megrey, (eds.), Mathematical Analysis of Fish Stock Dynamics: Reviews. Evaluations, and Current Applications, p. 66-82. Am. Fish. Soc. Symp. Ser. No. 6.

Myers, R.A, K.G. Bowen, and N.J. Barrowman. 1999. Maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. 56: 2404-2419.

Northwest Fisheries Science Center (NWFSC). 2009. Data report and summary analyses of the California and Oregon pink shrimp trawl fisheries. West Coast Groundfish Observer Program. NWFSC, 2725 Montlake Blvd E., Seattle, WA 98112. 33 p.

O'Driscoll, R. L. 2004. Estimating the uncertainty associated with acoustic surveys of spawning hoki (*Macruronus novaezelandiae*) in Cook Strait, New Zealand. ICES J. of Mar. Sci. 61:84–97.

Pennington, M., 1983. Efficient estimators of abundance for fish and plankton surveys. Biometrics 39, 281–286.

Petitgas, P., 1993. Geostatistics for fish stock assessments: a review and an acoustic application, ICES J. Mar. Sci. 50: 285:298.

Phillips, A.J., S. Ralston, R.D. Brodeur, T.D. Auth, R.L. Emmett, C. Johnson, and V.G. Wespestad. 2007. Recent pre-recruit Pacific hake (*Merluccius productus*) occurrences in the northern California current suggest a northward expansion of their spawning area. CalCOFI Reps. Vol. 48: 215-229.

Punt, A.E. and D.S. Butterworth. 1993. Variance estimates for fisheries assessment: their importance and how best to evaluate them. p. 145-162. *In*: S.J. Smith, J.J. Hunt and D. Rivard [Ed.] Risk evaluation and biological reference points for fisheries management. Can. J. Fish. Aquat. Sci. Spec. Publ. 120.

Punt, A.E., Dorn, M.W., and Haltuch, M.A. 2008. Evaluation of threshold management strategies for groundfish off the US West Coast. Fisheries Research 94: 251-266.

Punt, A.E. and R. Hilborn. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Rev. Fish. Biol. Fish. 7:35-63.

Punt, A.E., and Ralston, S. 2007. A Management Strategy Evaluation of Rebuilding Revision Rules for Overfished Rockfish Stocks. Biology, Assessment, and Management of North Pacific Rockfishes AK-SG-07-01: 329-351.

Punt, A.E., and Smith, A.D.M. 1999. Harvest strategy evaluation for the eastern stock of gemfish (*Rexea solandri*). ICES J. of Mar. Sci. 56: 860-875.

Punt, A. E., D. C. Smith, K. KrusicGolub, and S. Robertson. 2008. Quatifying age-reading error for use in fisheries stock assessments, with application to species in Australia's southern and eastern scalefish and shark fishery. Can. J. Fish. Aquat. Sc. 65:1991-2005.

Ralston, S. 2007. Coast-wide Pre-Recruit Indices from SWFSC and PWCC/NWFSC Midwater Trawl Surveys (2001-2006). Southwest Fisheries Science Center, Santa Cruz, California

Ralston, S., Punt, A.E., Hamel, O.S., DeVore, J.D., and Conser, R.J. 2011. A meta-analytic approach to quantifying scientific uncertainty in stock assessments. Fish. Bull. 109: 217-231.

Ressler, P.H., J.A. Holmes, G.W. Fleischer, R.E. Thomas, and K.C. Cooke. 2007. Pacific hake, *Merluccius productus*, autecology: a timely review. Mar. Fish. Rev. 69:1-24.

Richards, L. J., J. T. Schnute, and N. Olsen. 1997. Visualizing catch-age analysis: a case study. Can. J. Fish. Aquat. Sci. 54:1646-1658.

Richards, L. J. and J. T. Schnute. 1998. Model complexity and catch-age analysis. Can. J. Fish. Aquat. Sci. 55:949-957.

Rivoirard, J., E.J. Simmonds, K. Foote, P.G. Fernandes, and N. Bez, 2000. Geostatistics for Estimating Fish Abundance. Blackwell Science Ltd, Oxford.

Sakuma, K.M., S. Ralston, and V.G. Wespestad. 2006. Interannual and spatial variation in the distribution of young-of-the-year rockfish (*Sebastes* spp.): expanding and coordinating the survey sampling frame. Calif. Coop. Oceanic Fish. Invest. Rep. 47:127–139.

Saunders, M.W. and G.A. McFarlane. 1997. Observation on the spawning distribution and biology of offshore Pacific hake. Calif. Coop. Oceanic Fish. Invest. Rep. 38:147:160.

Simmonds, J. and D. MacLennan, 2005. Fisheries Acoustics: Theory and practice. 2nd ed. Blackwell Science Ltd, Oxford, 437p.

Spiegelhalter, D.J., Thomas, A., and Best, N.G. 1999. WinBUGS Version 1.2 User Manual. Medical Research Council Biostatistics Unit, Institute of Public Health, Cambridge, U.K.

Stefánsson, G., 1996. Analysis of groundfish survey abundance data: combining the GLM and delta approaches. ICES J. Mar. Sci. 53, 577–588.

Stewart, I. J. and O. S. Hamel. 2010. Stock Assessment of Pacific Hake, Merluccius productus, (a.k.a. Whiting) in U.S. and Canadian Waters in 2010. Pacific Fishery Management Council. Portland, Oregon. 290 p.

Stewart, I. J., R. E. Forrest, C.J. Grandin, O.S. Hamel, A.C. Hicks, S.J.D. Martell and I.G. Taylor. 2011. Status of the Pacific hake (whiting) stock in U.S. and Canadian waters in 2011, *In* Status of the Pacific Coast Groundfish Fishery through 2011, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and rebuilding analyses. Pacific Fishery Management Council, Portland, Oregon. 217 p.

Thomas, A., Spiegelhalter, D.J, and Gilks, W.R. 1992. BUGS: a program to perform Bayesian statistical inference using Gibbs sampling. *In* Bayesian statistics 4. Edited by J.M. Bernardo, J.O. Berger, A.P. Dawid, and A.F.M. Smith. Oxford University Press, Oxford, U.K. pp. 837-842.

Traynor, J.J. 1996. Target-strength measurements of walleye pollock (*Theragra chalcogramma*) and Pacific whiting (*Merluccius productus*). ICES J. of Mar. Sci. 53:253-258.

Utter, F.M. 1971. Biochemical polymorphisms in Pacific hake (*Merluccius productus*). Cons. Perm. Int. Explor. Mer Rapp. P.-V. Reun. 161:87-89.

Vrooman, A.M. and P.A. Paloma. 1977. Dwarf hake off the coast of Baja California, Mexico. Calif. Coop. Oceanic Fish. Invest. Rep. 19:67-72.

Walters, C.J. 1986. Adaptive management of renewable resources. Macmillian Publishing Co., New York.

Walters, C.J., and Hilborn, R. 1978. Ecological optimization and adaptive management. Ann. Rev. Ecol.Syst. 9: 157-188.

Walters, C. J. and D. Ludwig. 1994. Calculation of Bayes posterior probability distributions for key population parameters. Canadian Journal of Fisheries and Aquatic Sciences 51: 713-722.

Walters, C.J., and Martell, S.J.D. 2004. Fisheries Ecology and Management. Princeton University Press, Princeton, New Jersey.

Wilkins, M.E. 1998. The 1995 Pacific west coast bottom trawl survey of groundfish resources: estimates of distribution, abundance, and length and age composition. NOAA Tech. Memo. NMFS-AFSC-89.

6. Tables

Table 1. Annual catches of Pacific hake (1000s mt) in U.S. and Canadian waters by sector, 1966-2011. Tribal catches are included in the sector totals.

	U.S					Canada				
Year	Foreign	JV	At-sea	Shore -based	Total U.S.	Foreign	JV	Domestic	Total Canada	Total
1966	137.00	0.00	0.00	0.00	137.00	0.70	0.00	0.00	0.70	137.70
1967	168.70	0.00	0.00	8.96	177.66	36.71	0.00	0.00	36.71	214.37
1968	60.66	0.00	0.00	0.16	60.82	61.36	0.00	0.00	61.36	122.18
1969	86.19	0.00	0.00	0.09	86.28	93.85	0.00	0.00	93.85	180.13
1970	159.51	0.00	0.00	0.07	159.58	75.01	0.00	0.00	75.01	234.59
1971	126.49	0.00	0.00	1.43	127.92	26.70	0.00	0.00	26.70	154.62
1972	74.09	0.00	0.00	0.04	74.13	43.41	0.00	0.00	43.41	117.54
1973	147.44	0.00	0.00	0.07	147.51	15.13	0.00	0.00	15.13	162.64
1974	194.11	0.00	0.00	0.00	194.11	17.15	0.00	0.00	17.15	211.26
1975	205.65	0.00	0.00	0.00	205.65	15.70	0.00	0.00	15.70	221.35
1976	231.33	0.00	0.00	0.22	231.55	5.97	0.00	0.00	5.97	237.52
1977	127.01	0.00	0.00	0.49	127.50	5.19	0.00	0.00	5.19	132.69
1978	96.83	0.86	0.00	0.69	98.38	3.45	1.81	0.00	5.26	103.64
1979	114.91	8.83	0.00	0.94	124.68	7.90	4.23	0.30	12.43	137.11
1980	44.02	27.54	0.00	0.79	72.35	5.27	12.21	0.10	17.58	89.93
1981	70.36	43.56	0.00	0.88	114.80	3.92	17.16	3.28	24.36	139.16
1982	7.09	67.46	0.00	1.03	75.58	12.48	19.68	0.00	32.16	107.74
1983	0.00	72.10	0.00	1.05	73.15	13.12	27.66	0.00	40.78	113.93
1984	14.77	78.89	0.00	2.72	96.38	13.20	28.91	0.00	42.11	138.49
1985	49.85	31.69	0.00	3.89	85.44	10.53	13.24	1.19	24.96	110.40
1986	69.86	81.64	0.00	3.47	154.97	23.74	30.14	1.77	55.65	210.62
1987	49.66	106.00	0.00	4.80	160.45	21.45	48.08	4.17	73.70	234.15
1988	18.04	135.78	0.00	6.87	160.69	38.08	49.24	0.83	88.15	248.84
1989	0.00	195.64	0.00	7.41	203.05	29.75	62.72	2.56	95.03	298.08
1990	0.00	170.97	4.54	9.63	185.14	3.81	68.31	4.02	76.14	261.29
1991	0.00	0.00	205.82	23.97	229.79	5.61	68.13	16.17	89.92	319.71
1992	0.00	0.00	154.74	56.13	210.87	0.00	68.78	20.04	88.82	299.69
1993	0.00	0.00	98.04	42.11	140.15	0.00	46.42	12.35	58.77	198.92
1994	0.00	0.00	179.87	73.62	253.48	0.00	85.16	23.78	108.94	362.42
1995	0.00	0.00	102.31	74.96	177.27	0.00	26.19	46.18	72.37	249.64
1996	0.00	0.00	128.11	85.13	213.24	0.00	66.78	26.36	93.14	306.38
1997	0.00	0.00	146.05	87.42	233.47	0.00	42.57	49.23	91.79	325.26
1998	0.00	0.00	145.16	87.86	233.01	0.00	39.73	48.07	87.80	320.81
1999	0.00	0.00	141.02	83.47	224.49	0.00	17.20	70.16	87.36	311.84
2000	0.00	0.00	120.92	85.85	206.77	0.00	15.06	6.38	21.44	228.21
2001	0.00	0.00	100.53	73.41	173.94	0.00	21.65	31.94	53.59	227.53
2002	0.00	0.00	84.75	45.71	130.46	0.00	0.00	50.24	50.24	180.70
2003	0.00	0.00	86.61	55.34	141.95	0.00	0.00	63.23	63.23	205.18
2004	0.00	0.00	117.07	96.50	213.57	0.00	58.89	66.19	125.08	338.65
2005	0.00	0.00	151.07	109.05	260.12	0.00	15.69	87.34	103.04	363.16
2006	0.00	0.00	139.79	127.17	266.96	0.00	14.32	80.49	94.80	361.76
2007	0.00	0.00	126.24	91.44	217.68	0.00	6.78	66.67	73.45	291.13
2008	0.00	0.00	180.64	67.76	248.40	0.00	3.59	70.16	73.75	322.14
2009	0.00	0.00	72.35	49.22	121.57	0.00	0.00	55.88	55.88	177.46
2010	0.00	0.00	106.31	63.79	170.10	0.00	8.08	48.01	56.09	226.20
2011	0.00	0.00	128.07	102.35	230.42	0.00	9.72	45.91	55.63	286.05
Average:					165.92				56.30	222.22

Table 2. Recent trend in Pacific hake landings and management.

Year	Total landings (mt)	Coast-wide (U.S. + Canada) catch target (mt)
2001	227,531	238,000
2002	180,698	162,000
2003	205,177	228,000
2004	338,654	501,073
2005	363,157	364,197
2006	361,761	364,842
2007	291,129	328,358
2008	322,145	364,842
2009	177,459	184,000
2010	226,202	262,500
2011	286,055	393,751

Table 3. Annual summary of U.S. and Canadian fishery sampling included in this stock assessment. Foreign, joint-venture and at-sea sectors are in number of hauls sampled for age-composition, the shore-based sector is in number of trips.

	U.S.				Canada		
Year	Foreign	Joint-venture	At-sea	Shore-based	Foreign	Joint-venture	Domestic
1975	13	—	—	—	—	—	—
1976	142	—	—	—	—	—	—
1977	320	—	—	—	—	—	—
1978	336	5	—	—	—	—	—
1979	99	17	—	—	—	—	—
1980	191	30	—	—	—	—	—
1981	113	41	—	—	—	—	—
1982	52	118	—	—	—	—	—
1983	0	117	—	—	—	—	—
1984	49	74	—	—	—	—	—
1985	37	19	—	—	—	—	—
1986	88	32	—	—	—	—	—
1987	22	34	—	—	—	—	—
1988	39	42	—	—	—	—	—
1989	—	77	—	—	—	—	—
1990	—	143	—	15	—	5	—
1991	—	—	116	26	—	18	—
1992	—	—	164	46	—	33	—
1993	—	—	108	36	—	25	—
1994	—	—	143	50	—	41	—
1995	—	—	61	51	—	35	—
1996	—	—	123	35	—	28	—
1997	—	—	127	65	—	27	3
1998	—	—	149	64	—	21	9
1999	—	—	389	80	—	14	31
2000	—	—	413	91	—	25	—
2001	—	—	429	82	—	28	2
2002	—	—	342	71	—	—	37
2003	—	—	358	78	—	—	21
2004	—	—	381	72	—	20	28
2005	—	—	499	58	—	11	45
2006	—	—	549	83	—	21	67
2007	—	—	524	68	—	1	36
2008	—	—	680	63	—	—	51
2009	—	—	594	66	—	—	26
2010	—	—	774	75	—	—	24
2011	—	—	708	81	—	13	

Table 4. Acoustic survey summary, 1995-2011.

Year	Start date	End date	Vessels	Biomass index (million mt)	Sampling CV[1]	Number of hauls with bio. samples
1995	1 July	1 Sept.	Miller Freeman, Ricker	1.518	0.067	69
1998	6 July	27 Aug.	Miller Freeman, Ricker	1.343	0.049	84
2001	15 June	18 Aug	Miller Freeman, Ricker	0.919	0.082	49
2003	29 June	1 Sept.	Ricker	2.521	0.071	71
2005	20 June	19 Aug.	Miller Freeman	1.755	0.085	49
2007	20 June	21 Aug.	Miller Freeman	1.123	0.075	130
2009	30 June	7 Sept.	Miller Freeman, Ricker	1.612	0.137[2]	61
2011	26 June	10 Sept	Bell Shimada, Ricker	0.521	0.1015	59

[1]Sampling CV includes only error associated with kriging of transect-based observations.
[2]Also includes bootstrapped estimates of uncertainty associated with delineation of Humboltd squid from hake.

Table 5. Informative prior probability distributions used in this stock assessment. Note "CCAM - est" refers to the CCAM sensitivity case with survey selectivity parameters estimated. "CCAM - fix" refers to the CCAM sensitivity case with survey selectivity parameters fixed. It was not possible to achieve convergence in both cases with the same standard deviation on the prior for natural mortality, see text.

Model Parameter prior Justification

Model	Parameter	prior	Justification
Base case	Steepness (*h*)	~Beta(mean=0.777, SD=0.113)	Myers et al. 1999 meta-analysis results for Gadids.
CCAM	Steepness (*h*)	~Beta(α=0.977, β=2.80)	Myers et al. 1999 meta-analysis results for Gadids.
Base case	Natural mortality (*M*)	~log(N)(mean=0.2, σ=0.1)	Hoenig's method and maximum age = 22
CCAM – est CCAM - fix	Natural mortality (*M*)	~log(N)(mean=0.2, σ=0.05) ~log(N)(mean=0.2, σ=0.2)	Hoenig's method and maximum age = 22
CCAM	Variance ratio (ρ)	~Beta(α=3.0, β=12.0)	Used in previous TINSS assessments to help achieve convergence
CCAM	Inverse total standard deviation (φ^{-1})	~Gamma(7.5,5.8)	Used in previous TINSS assessments to help achieve convergence
CCAM	Acoustic survey catchability (*q*)	~log(N)(mean=1.0, SD=0.1)	Used in previous TINSS assessments to help achieve convergence

Table 6. Summary of estimated model parameters in the base-case model.

Parameter	Number estimated	Bounds (low, high)	Prior (Mean, SD) (single value = fixed)
Stock dynamics			
Ln(R_0)	1	(13,17)	uniform
Steepness (h)	1	(0.2,1.0)	~Beta(0.777,0.113)
Recruitment variability (σ_R)	-	NA	1.40
Ln(Rec. deviations): 1946-2011	66	(-6, 6)	~Ln(N(0, σ_r))
Natural mortality (M)	1	(0.05,0.4)	~Ln(N(0.2,0.1))
Catchability and selectivity (double normal)			
Acoustic survey:			
Catchability (q)	1	NA	Analytic solution
Additional value for acoustic survey log(SE)	1	(0.0, 1.2)	uniform
Non parametric age-based selectivity: ages 3–6	4	(-5,9)	Uniform in scaled logistic space
Fishery:			
Non parametric age-based selectivity: ages 2–6	5	(-5,9)	Uniform in scaled logistic space
Total: 14 + 66 recruitment deviations = 90 estimated parameters. See Appendix A for all parameter estimates.			

Table 7. Summary of estimated model parameters in the CCAM model with survey selectivity parameters estimated.

Parameter	Number estimated	Bounds (low,high)	Prior (Mean, SD) (single value=fixed)
Log recruitment (log_ro)	1	[-1,4]	Uniform
Steepness (h)	1	[0.2,1]	~Beta(α=9.77,β=2.80)
Log natural mortality (log_m)	1	[-5,0]	~Normal(ln(0.2),0.05)
Log mean recruitment (log_avgrec)	1	[-5,15]	Uniform
Log initial recruitment (log_recinit)	1	[-5,15]	Uniform
Variance ratio (ρ)	1	[0.01,0.999]	~Beta(α=3.0, β=12.0)
Inverse total standard deviation (φ^{-1})	1	[0.01,150]	~Gamma(7.5,5.8)
Survey age at 50% vulnerability (ahat_surv)	1	[0,1]	Uniform
Fishery age at 50% vulnerability (ahat_comm)	1	[0,1]	Uniform
Survey SD of logistic selectivity (ghat_surv)	1	[0,Inf)	None
Fishery SD of logistic selectivity (ghat_comm)	1	[0,Inf)	None
Survey catchability (q)	1	None	~Normal(0,0.1)
Log fishing mortality values	46	None	[-30,3]
Log recruitment deviations	59	[-5,5]	~Normal(0,τ[1])

[1]τ = standard deviation of recruitment residuals

Table 8. Time-series of median posterior population estimates from the base-case model.

Year	Female spawning biomass (millions mt)	Depletion	Age-0 recruits (billions)	1-SPR / 1-SPR40%	Exploitation fraction
1966	0.960	NA	1.264	47.8%	6.9%
1967	0.887	47.2%	3.117	68.2%	11.8%
1968	0.835	44.0%	1.820	50.9%	7.1%
1969	0.887	47.3%	0.761	65.2%	10.2%
1970	0.940	50.2%	7.002	74.7%	11.5%
1971	0.928	49.8%	0.616	56.6%	7.5%
1972	1.107	59.0%	0.391	44.9%	6.1%
1973	1.262	67.9%	3.828	48.9%	5.4%
1974	1.279	68.6%	0.344	54.2%	7.5%
1975	1.274	68.0%	1.201	49.2%	7.2%
1976	1.248	66.4%	0.303	45.8%	6.1%
1977	1.180	62.7%	4.527	32.7%	4.2%
1978	1.092	58.1%	0.257	30.4%	3.7%
1979	1.126	59.9%	0.814	36.0%	5.2%
1980	1.134	60.2%	15.137	28.9%	3.1%
1981	1.114	59.1%	0.263	41.6%	5.5%
1982	1.499	80.1%	0.238	36.7%	5.2%
1983	1.882	100.9%	0.394	30.0%	2.6%
1984	2.007	107.7%	12.263	29.6%	3.2%
1985	1.920	102.8%	0.172	24.3%	2.8%
1986	2.141	114.1%	0.190	39.8%	6.2%
1987	2.261	121.3%	5.199	43.0%	4.7%
1988	2.174	116.6%	1.845	42.6%	5.5%
1989	2.097	112.2%	0.174	55.1%	8.5%
1990	1.978	105.9%	4.278	47.8%	6.6%
1991	1.806	96.4%	0.500	57.6%	8.7%
1992	1.661	88.6%	0.177	62.2%	10.5%
1993	1.502	80.0%	3.181	55.9%	7.8%
1994	1.321	70.0%	2.343	79.8%	15.5%
1995	1.105	58.7%	1.330	71.1%	13.2%
1996	1.049	55.7%	1.500	83.9%	15.7%
1997	0.956	50.9%	1.223	88.6%	16.6%
1998	0.854	45.2%	1.718	93.4%	19.4%
1999	0.742	39.4%	10.387	97.6%	22.1%
2000	0.648	34.5%	0.347	82.2%	15.3%
2001	0.924	49.2%	0.792	76.4%	13.9%
2002	1.179	62.9%	0.064	51.0%	4.8%
2003	1.288	68.7%	1.266	52.0%	6.6%
2004	1.219	65.1%	0.064	76.5%	13.3%
2005	1.020	54.6%	1.964	84.8%	19.5%
2006	0.774	41.6%	1.579	97.2%	23.7%
2007	0.580	31.3%	0.070	102.0%	29.1%
2008	0.491	26.4%	5.248	113.2%	31.4%
2009	0.384	20.4%	1.736	99.6%	20.3%
2010	0.483	25.4%	0.932	109.8%	34.3%
2011	0.587	31.3%	0.763	111.6%	23.3%
2012	0.616	32.6%	0.762	NA	NA

Table 9. Time-series of ~95% posterior credibility intervals for female spawning biomass, relative depletion estimates, age-0 recruits, relative spawning potential ratio (1-SPR/1-$SPR_{Target=0.4}$) and exploitation fraction from the base-case model.

Year	Female spawning Biomass (millions mt)	Depletion	Age-0 recruits (billions)	(1-SPR) / (1-SPR_{target})	Exploitation fraction
1966	0.52-1.81	NA	0.06-6.72	0.27-0.74	0.04-0.13
1967	0.49-1.71	0.27-0.87	0.13-10.74	0.40-0.98	0.06-0.22
1968	0.45-1.58	0.24-0.82	0.10-7.76	0.28-0.80	0.04-0.14
1969	0.53-1.67	0.28-0.85	0.05-4.39	0.37-0.93	0.05-0.20
1970	0.60-1.83	0.31-0.89	3.40-17.14	0.43-0.99	0.06-0.20
1971	0.59-1.89	0.31-0.88	0.05-2.68	0.30-0.81	0.04-0.12
1972	0.72-2.16	0.37-1.04	0.05-1.63	0.22-0.67	0.03-0.10
1973	0.82-2.39	0.42-1.16	1.92-8.88	0.25-0.72	0.03-0.09
1974	0.81-2.45	0.42-1.14	0.04-1.51	0.29-0.79	0.04-0.12
1975	0.79-2.52	0.41-1.15	0.40-3.11	0.26-0.72	0.04-0.12
1976	0.77-2.44	0.40-1.13	0.03-1.33	0.23-0.70	0.03-0.10
1977	0.72-2.29	0.38-1.06	2.25-10.37	0.16-0.53	0.02-0.07
1978	0.67-2.10	0.35-0.96	0.03-1.36	0.15-0.50	0.02-0.06
1979	0.69-2.08	0.37-0.98	0.12-2.87	0.18-0.57	0.03-0.08
1980	0.69-2.14	0.36-0.98	8.92-30.18	0.14-0.48	0.02-0.05
1981	0.67-2.01	0.35-0.95	0.03-1.32	0.22-0.65	0.03-0.09
1982	0.97-2.63	0.50-1.24	0.03-1.14	0.19-0.57	0.03-0.09
1983	1.27-3.21	0.64-1.50	0.04-1.48	0.16-0.47	0.02-0.04
1984	1.38-3.35	0.69-1.58	7.90-21.74	0.16-0.45	0.02-0.05
1985	1.33-3.10	0.67-1.49	0.02-0.86	0.13-0.38	0.02-0.04
1986	1.56-3.27	0.77-1.62	0.03-0.95	0.24-0.57	0.04-0.09
1987	1.70-3.34	0.84-1.69	3.29-8.92	0.27-0.60	0.03-0.06
1988	1.66-3.13	0.82-1.60	0.67-3.80	0.27-0.59	0.04-0.07
1989	1.63-2.92	0.79-1.53	0.02-0.75	0.37-0.72	0.06-0.11
1990	1.57-2.69	0.76-1.43	2.84-6.71	0.32-0.63	0.05-0.08
1991	1.46-2.42	0.70-1.28	0.07-1.33	0.40-0.74	0.06-0.11
1992	1.37-2.20	0.65-1.16	0.02-0.64	0.45-0.77	0.08-0.13
1993	1.24-1.96	0.60-1.05	2.22-4.93	0.40-0.70	0.06-0.09
1994	1.11-1.68	0.54-0.91	1.52-3.62	0.61-0.96	0.12-0.18
1995	0.93-1.42	0.45-0.77	0.79-2.32	0.53-0.86	0.10-0.16
1996	0.88-1.33	0.43-0.73	0.97-2.40	0.65-0.99	0.12-0.19
1997	0.80-1.21	0.39-0.66	0.68-2.10	0.70-1.03	0.13-0.20
1998	0.72-1.08	0.35-0.58	1.09-2.89	0.75-1.07	0.15-0.23
1999	0.61-0.95	0.30-0.51	7.91-15.50	0.79-1.12	0.17-0.27
2000	0.52-0.84	0.26-0.45	0.08-0.80	0.63-0.99	0.12-0.19
2001	0.75-1.21	0.37-0.63	0.48-1.28	0.58-0.93	0.11-0.17
2002	0.98-1.54	0.48-0.80	0.01-0.23	0.37-0.65	0.04-0.06
2003	1.10-1.64	0.53-0.87	0.87-2.02	0.38-0.66	0.05-0.08
2004	1.06-1.52	0.51-0.82	0.01-0.21	0.59-0.91	0.11-0.15
2005	0.89-1.29	0.43-0.68	1.32-3.70	0.67-0.99	0.15-0.22
2006	0.67-1.02	0.33-0.53	0.89-3.69	0.79-1.10	0.18-0.28
2007	0.48-0.86	0.24-0.41	0.01-0.29	0.83-1.16	0.20-0.35
2008	0.38-0.83	0.19-0.40	2.04-17.58	0.90-1.27	0.19-0.40
2009	0.26-0.77	0.13-0.36	0.51-6.48	0.69-1.18	0.10-0.30
2010	0.26-1.24	0.14-0.58	0.06-10.26	0.73-1.30	0.15-0.58
2011	0.23-1.86	0.13-0.87	0.05-10.26	0.64-1.37	0.07-0.50
2012	0.17-2.23	0.09-1.02	0.04-10.73	NA	NA

Table 10. Estimated numbers at age at the beginning of the year from the base model (MLE; millions).

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
1966	1.14	1.03	0.58	0.40	0.30	0.24	0.19	0.16	0.14	0.11	0.10	0.08	0.07	0.06	0.05	0.22
1967	2.80	0.94	0.84	0.48	0.32	0.23	0.18	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.19
1968	1.60	2.30	0.77	0.68	0.36	0.22	0.16	0.11	0.09	0.08	0.06	0.05	0.05	0.04	0.03	0.15
1969	0.76	1.31	1.89	0.62	0.53	0.27	0.16	0.11	0.08	0.06	0.05	0.05	0.04	0.03	0.03	0.13
1970	5.03	0.63	1.08	1.52	0.47	0.38	0.19	0.11	0.07	0.05	0.04	0.04	0.03	0.03	0.02	0.10
1971	0.64	4.13	0.51	0.87	1.13	0.33	0.25	0.12	0.07	0.05	0.03	0.03	0.02	0.02	0.02	0.08
1972	0.38	0.52	3.39	0.42	0.67	0.84	0.24	0.18	0.08	0.05	0.03	0.02	0.02	0.02	0.01	0.07
1973	2.71	0.31	0.43	2.76	0.33	0.51	0.63	0.17	0.13	0.06	0.04	0.02	0.02	0.01	0.01	0.06
1974	0.34	2.23	0.26	0.35	2.16	0.25	0.38	0.46	0.13	0.09	0.04	0.03	0.02	0.01	0.01	0.05
1975	0.89	0.28	1.83	0.21	0.27	1.61	0.18	0.27	0.33	0.09	0.07	0.03	0.02	0.01	0.01	0.04
1976	0.28	0.73	0.23	1.49	0.16	0.20	1.20	0.13	0.20	0.24	0.07	0.05	0.02	0.01	0.01	0.04
1977	3.42	0.23	0.60	0.19	1.17	0.12	0.15	0.88	0.10	0.14	0.17	0.05	0.04	0.02	0.01	0.03
1978	0.25	2.81	0.19	0.49	0.15	0.92	0.10	0.12	0.67	0.07	0.11	0.13	0.04	0.03	0.01	0.03
1979	0.76	0.21	2.31	0.15	0.39	0.12	0.71	0.07	0.09	0.52	0.06	0.08	0.10	0.03	0.02	0.04
1980	11.60	0.62	0.17	1.88	0.12	0.31	0.09	0.54	0.06	0.07	0.39	0.04	0.06	0.08	0.02	0.04
1981	0.28	9.53	0.51	0.14	1.51	0.10	0.24	0.07	0.42	0.04	0.05	0.31	0.03	0.05	0.06	0.05
1982	0.23	0.23	7.82	0.42	0.11	1.17	0.07	0.18	0.05	0.31	0.03	0.04	0.23	0.03	0.04	0.08
1983	0.38	0.19	0.19	6.38	0.33	0.09	0.90	0.06	0.14	0.04	0.24	0.02	0.03	0.17	0.02	0.09
1984	9.74	0.32	0.15	0.16	5.12	0.26	0.07	0.70	0.04	0.11	0.03	0.19	0.02	0.02	0.13	0.09
1985	0.19	8.00	0.26	0.13	0.13	4.05	0.21	0.05	0.54	0.03	0.08	0.02	0.14	0.02	0.02	0.17
1986	0.20	0.16	6.57	0.21	0.10	0.10	3.21	0.16	0.04	0.42	0.03	0.06	0.02	0.11	0.01	0.15
1987	4.17	0.17	0.13	5.36	0.17	0.08	0.08	2.43	0.12	0.03	0.32	0.02	0.05	0.01	0.09	0.12
1988	1.64	3.42	0.14	0.10	4.25	0.13	0.06	0.06	1.82	0.09	0.02	0.24	0.02	0.04	0.01	0.16
1989	0.17	1.35	2.81	0.11	0.08	3.29	0.10	0.05	0.04	1.37	0.07	0.02	0.18	0.01	0.03	0.12
1990	3.51	0.14	1.11	2.28	0.09	0.06	2.44	0.07	0.03	0.03	0.99	0.05	0.01	0.13	0.01	0.11
1991	0.51	2.88	0.11	0.90	1.80	0.07	0.05	1.81	0.05	0.02	0.02	0.74	0.04	0.01	0.10	0.09
1992	0.18	0.42	2.36	0.09	0.70	1.35	0.05	0.03	1.30	0.04	0.02	0.02	0.53	0.03	0.01	0.13
1993	2.66	0.15	0.34	1.92	0.07	0.52	0.99	0.03	0.02	0.92	0.03	0.01	0.01	0.37	0.02	0.10
1994	1.99	2.18	0.12	0.28	1.50	0.05	0.39	0.71	0.03	0.02	0.66	0.02	0.01	0.01	0.27	0.08
1995	1.12	1.63	1.79	0.10	0.21	1.05	0.04	0.25	0.46	0.02	0.01	0.43	0.01	0.01	0.01	0.23
1996	1.25	0.92	1.34	1.45	0.07	0.15	0.74	0.02	0.17	0.31	0.01	0.01	0.29	0.01	0.00	0.16
1997	1.04	1.02	0.75	1.08	1.08	0.05	0.10	0.47	0.02	0.11	0.20	0.01	0.00	0.18	0.01	0.10
1998	1.43	0.85	0.84	0.61	0.79	0.72	0.03	0.06	0.28	0.01	0.06	0.12	0.00	0.00	0.11	0.06
1999	8.61	1.18	0.70	0.67	0.44	0.52	0.45	0.02	0.03	0.16	0.01	0.04	0.07	0.00	0.00	0.10
2000	0.33	7.07	0.97	0.56	0.48	0.28	0.31	0.25	0.01	0.02	0.09	0.00	0.02	0.04	0.00	0.06
2001	0.66	0.27	5.80	0.78	0.41	0.33	0.18	0.20	0.16	0.01	0.01	0.06	0.00	0.01	0.02	0.04
2002	0.07	0.55	0.22	4.68	0.59	0.29	0.23	0.12	0.13	0.10	0.00	0.01	0.04	0.00	0.01	0.04
2003	1.04	0.05	0.45	0.18	3.68	0.45	0.22	0.17	0.09	0.09	0.07	0.00	0.01	0.03	0.00	0.03
2004	0.06	0.86	0.04	0.36	0.14	2.80	0.34	0.16	0.12	0.07	0.07	0.05	0.00	0.00	0.02	0.03
2005	1.57	0.05	0.70	0.04	0.28	0.10	1.94	0.22	0.11	0.08	0.04	0.05	0.04	0.00	0.00	0.03
2006	1.19	1.29	0.04	0.56	0.03	0.19	0.07	1.21	0.14	0.07	0.05	0.03	0.03	0.02	0.00	0.02
2007	0.06	0.98	1.06	0.03	0.40	0.02	0.11	0.04	0.67	0.08	0.04	0.03	0.01	0.02	0.01	0.01
2008	3.46	0.05	0.80	0.84	0.02	0.25	0.01	0.06	0.02	0.34	0.04	0.02	0.01	0.01	0.01	0.01
2009	1.11	2.84	0.04	0.63	0.54	0.01	0.12	0.00	0.02	0.01	0.13	0.02	0.01	0.01	0.00	0.01
2010	0.95	0.91	2.33	0.03	0.44	0.33	0.01	0.06	0.00	0.01	0.00	0.07	0.01	0.00	0.00	0.01
2011	0.69	0.78	0.74	1.82	0.02	0.23	0.16	0.00	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.00

Table 11. Summary of Pacific hake reference points from the base-case model.

Quantity	2.5th percentile	Median	97.5th percentile
Unfished female spawning biomass (SB_0, millions mt)	1.489	1.888	2.529
Unfished recruitment (R_0, billions)	1.540	2.326	3.976
Reference points based on $SB_{40\%}$			
Female spawning biomass ($SB_{40\%}$ million mt)	0.595	0.755	1.011
$SPR_{SB40\%}$	40.6%	43.5%	52.1%
Exploitation fraction resulting in $SB_{40\%}$	13.5%	18.6%	23.2%
Yield at $SB_{40\%}$ (million mt)	0.207	0.290	0.433
Reference points based on $F_{40\%}$			
Female spawning biomass ($SB_{F40\%}$ million mt)	0.501	0.670	0.902
$SPR_{MSY\text{-}proxy}$	0.40	0.40	0.40
Exploitation fraction corresponding to SPR	18.1%	21.4%	25.7%
Yield at $SB_{F40\%}$ (million mt)	0.210	0.299	0.443
Reference points based on estimated MSY			
Female spawning biomass (SB_{MSY} million mt)	0.291	0.460	0.781
SPR_{MSY}	18.3%	28.9%	47.9%
Exploitation fraction corresponding to SPR_{MSY}	15.9%	33.0%	56.9%
MSY (million mt)	0.215	0.317	0.482

Table 12.1. Posterior distribution quantiles for Pacific hake relative **depletion** (at the beginning of the year before fishing takes place) from the base model. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g).

Within model quantile			5%	25%	50%	75%	95%
Management Action							
	Year	Catch (mt)	**Beginning of year depletion**				
a	2012	0	11%	22%	33%	51%	86%
	2013	0	14%	28%	40%	60%	104%
	2014	0	18%	32%	47%	67%	120%
b	2012	50,000	11%	22%	33%	51%	86%
	2013	50,000	13%	27%	39%	59%	103%
	2014	50,000	15%	30%	44%	65%	117%
c	2012	100,000	11%	22%	33%	51%	86%
	2013	100,000	12%	25%	38%	58%	102%
	2014	100,000	13%	27%	41%	63%	115%
d	2012	150,000	11%	22%	33%	51%	86%
	2013	150,000	10%	24%	37%	57%	101%
	2014	150,000	10%	25%	39%	60%	113%
e	2012	200,000	11%	22%	33%	51%	86%
	2013	200,000	9%	23%	36%	56%	99%
	2014	200,000	8%	22%	37%	58%	111%
f	2012	251,809	11%	22%	33%	51%	86%
	2013	267,146	8%	21%	34%	54%	98%
	2014	277,887	6%	19%	34%	55%	109%
g	2012	393,751	11%	22%	33%	51%	86%
	2013	393,751	7%	18%	30%	51%	95%
	2014	393,751	5%	13%	27%	49%	102%

Table 12.2. Posterior distribution quantiles for Pacific hake **fishing intensity (**spawning potential ratio; 1-SPR/1-$SPR_{40\%}$; values greater than 100% denote fishing in excess of the $F_{40\%}$ default harvest rate) from the base model. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g).

Within model quantile			5%	25%	50%	75%	95%
Management Action							
	Year	Catch (mt)	**Fishing intensity**				
	2012	0	0%	0%	0%	0%	0%
a	2013	0	0%	0%	0%	0%	0%
	2014	0	0%	0%	0%	0%	0%
	2012	50,000	13%	24%	36%	52%	79%
b	2013	50,000	11%	21%	31%	44%	71%
	2014	50,000	10%	18%	26%	38%	63%
	2012	100,000	25%	42%	59%	79%	107%
c	2013	100,000	22%	38%	53%	72%	104%
	2014	100,000	19%	33%	48%	66%	100%
	2012	150,000	35%	56%	76%	95%	121%
d	2013	150,000	31%	52%	71%	91%	122%
	2014	150,000	27%	47%	65%	87%	123%
	2012	200,000	43%	67%	87%	106%	129%
e	2013	200,000	39%	64%	84%	105%	132%
	2014	200,000	35%	59%	80%	104%	133%
	2012	251,809	51%	77%	97%	115%	133%
f	2013	267,146	49%	76%	97%	118%	135%
	2014	277,887	46%	74%	97%	120%	136%
	2012	393,751	68%	95%	113%	128%	137%
g	2013	393,751	65%	95%	116%	131%	138%
	2014	393,751	61%	94%	119%	132%	138%

Table 12.3. Median of the posterior distribution for Pacific hake relative **depletion** (at the beginning of the year before fishing takes place) from alternate modeling approaches. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g). See main text for descriptions of alternative models.

Alternate models			CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Management action							
	Year	Catch (mt)	**Beginning of year depletion**				
a	2012	0	19%	27%	33%	40%	39%
	2013	0	25%	35%	40%	49%	48%
	2014	0	30%	40%	47%	55%	53%
b	2012	50,000	19%	27%	33%	40%	39%
	2013	50,000	24%	33%	39%	47%	47%
	2014	50,000	27%	37%	44%	52%	50%
c	2012	100,000	19%	27%	33%	40%	39%
	2013	100,000	23%	32%	38%	46%	45%
	2014	100,000	25%	35%	41%	50%	48%
d	2012	150,000	19%	27%	33%	40%	39%
	2013	150,000	21%	31%	37%	45%	44%
	2014	150,000	22%	32%	39%	47%	45%
e	2012	200,000	19%	27%	33%	40%	39%
	2013	200,000	20%	30%	36%	44%	43%
	2014	200,000	19%	30%	37%	45%	43%
f	2012	251,809	19%	27%	33%	40%	39%
	2013	267,146	19%	28%	34%	43%	42%
	2014	277,887	16%	27%	34%	42%	39%
g	2012	393,751	19%	27%	33%	40%	39%
	2013	393,751	15%	25%	30%	39%	38%
	2014	393,751	12%	21%	27%	35%	33%

Table 12.4. Median of the posterior distribution for Pacific hake **fishing intensity** (spawning potential ratio; 1-SPR/1-$SPR_{40\%}$; values greater than 100% denote fishing in excess of the $F_{40\%}$ default harvest rate) from alternate modeling approaches. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt (rows a–e), 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case (row f), and the status quo catch target (row g). See main text for descriptions of alternative models.

Alternate models			CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Management action							
	Year	Catch (mt)	**Fishing intensity**				
a	2012	0	0%	0%	0%	0%	0%
	2013	0	0%	0%	0%	0%	0%
	2014	0	0%	0%	0%	0%	0%
b	2012	50,000	58%	41%	36%	31%	34%
	2013	50,000	47%	33%	31%	26%	26%
	2014	50,000	40%	30%	26%	24%	22%
c	2012	100,000	86%	67%	59%	52%	57%
	2013	100,000	75%	57%	53%	46%	46%
	2014	100,000	69%	54%	48%	44%	41%
d	2012	150,000	102%	83%	76%	67%	72%
	2013	150,000	95%	75%	71%	62%	62%
	2014	150,000	91%	73%	65%	60%	57%
e	2012	200,000	113%	96%	87%	78%	84%
	2013	200,000	109%	89%	84%	74%	74%
	2014	200,000	108%	89%	80%	74%	71%
f	2012	251,809	121%	105%	97%	88%	93%
	2013	267,146	122%	103%	97%	87%	87%
	2014	277,887	126%	107%	97%	90%	88%
g	2012	393,751	132%	120%	113%	105%	110%
	2013	393,751	134%	122%	116%	106%	107%
	2014	393,751	135%	126%	119%	110%	110%

Table 12.5. Probabilities of various management metrics given different catch alternatives. Catch alternatives are based on: 1) arbitrary constant catch levels of 0, 50,000, 100,000, 150,000, and 200,000 mt, 2) the median values estimated via the default harvest control rule (the $F_{40\%}$ default harvest rate and *SB* 40:10 reduction) for the base case, and the *status quo* catch target.

Catch	$P(SB_{2013}>SB_{2012})$	$P(SB_{2013}>SB_{40\%})$	$P(SB_{2013}>SB_{25\%})$	$P(SB_{2013}>SB_{10\%})$	P(Fishing intensity in 2012 > 40% Target)
0	>99%	51%	80%	99%	0%
50,000	99%	49%	78%	98%	<1%
100,000	88%	46%	76%	96%	7%
150,000	74%	44%	73%	95%	17%
200,000	58%	42%	70%	94%	31%
251,809	47%	40%	68%	93%	47%
393,751	28%	35%	61%	91%	70%

Table 13. Select parameters, derived quantities, and reference point estimates for the alternate sensitivity models. Note that recruits are estimated as age-0 fish in SS and as age-1 fish in CCAM.

	CCAM Fixed survey selectivity	SS Selectivity est. to age-5	Base case	SS Selectivity est. to age-7	CCAM est. survey selectivity
Parameters					
R_0 (billions)	1.631	2.367	2.326	2.367	1.776
Steepness (*h*)	0.848	0.808	0.812	0.804	0.851
Natural mortality (*M*)	0.205	0.219	0.219	0.220	0.209
Acoustic catchability (*Q*)	1.015	NA	NA	NA	1.210
Additional acoustic survey SD	NA	0.504	0.464	0.478	NA
Derived Quantities					
2008 recruitment (billions)	1.922	4.624	5.248	6.412	3.443
SB_0 (million mt)	1.905	1.912	1.888	1.909	1.963
2012 Depletion	19.2%	27.5%	32.6%	40.3%	38.8%
2011 Fishing intensity (1-SPR/1-SPR40%)	131.7%	117.0%	111.6%	105.3%	113.6%
Reference points based on $SB_{40\%}$					
Female spawning biomass ($SB_{40\%}$ million mt)	0.762	0.765	0.755	0.764	0.785
$SPR_{SB40\%}$	42.7%	43.6%	43.5%	43.7%	42.6%
Exploitation fraction resulting in $SB_{40\%}$	16.5%	18.5%	18.6%	18.8%	17.0%
Yield at $SB_{40\%}$ (million mt)	0.264	0.293	0.290	0.295	0.285
Reference points based on $F_{40\%}$					
Female spawning biomass ($SB_{F40\%}$ million mt)	0.697	0.680	0.670	0.676	0.724
$SPR_{MSY\text{-}proxy}$	40%	40%	40%	40%	40%
Exploitation fraction corresponding to SPR	18.4%	21.3%	21.4%	21.5%	18.7%
Yield at $SB_{F40\%}$ (million mt)	0.271	0.302	0.299	0.302	0.292
Reference points based on estimated MSY					
Female spawning biomass (SB_{MSY} million mt)	0.441	0.470	0.460	0.471	0.449
SPR_{MSY}	26.2%	28.9%	28.9%	29.4%	26.2%
Exploitation fraction corresponding to SPR_{MSY}	31.2%	32.6%	33.0%	32.5%	32.4%
MSY (million mt)	0.293	0.320	0.317	0.318	0.319

Table 14. Select parameters, derived quantities, and reference point estimates for the base case MLE and posterior medians.

	MLE	Posterior median
Parameters		
R_0 (billions)	2.018	2.326
Steepness (h)	0.847	0.812
Natural mortality (M)	0.209	0.219
Acoustic catchability (Q)	1.211	
Additional acoustic survey SD	0.378	0.464
Derived Quantities		
2008 recruitment	4.059	
SB_0 (million mt)	1.766	1.888
2012 Depletion	27.4%	32.6%
2011 Fishing intensity (1-SPR/1-SPR40%)	121.5%	111.6%
Reference points based on $SB_{40\%}$		
Female spawning biomass ($SB_{40\%}$ million mt)	0.706	0.755
$SPR_{SB40\%}$	42.7%	43.5%
Exploitation fraction resulting in $SB_{40\%}$	18.5%	18.6%
Yield at $SB_{40\%}$ (million mt)	0.274	0.290
Reference points based on $F_{40\%}$		
Female spawning biomass ($SB_{F40\%}$ million mt)	0.656	0.670
$SPR_{MSY\text{-}proxy}$		40%
Exploitation fraction corresponding to SPR	20.4%	21.4%
Yield at $SB_{F40\%}$ (million mt)	0.281	0.299
Reference points based on estimated MSY		
Female spawning biomass (SB_{MSY} million mt)	0.407	0.460
SPR_{MSY}	26.5%	28.9%
Exploitation fraction corresponding to SPR_{MSY}	34.8%	33.0%
MSY (million mt)	0.301	0.317

Table 15. Select parameters, derived quantities, and reference point estimates for sensitivity analyses to priors on natural mortality (*M*) and the degree of recruitment variability (σ_r) for the base case. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

	Base case	*M* prior SD=0.2	*M* prior SD=0.3	σ_r est. with prior ~N (1.4,0.1)
Parameters				
R_0 (billions)	2.369	3.408	4.159	2.484
Steepness (*h*)	0.803	0.800	0.800	0.812
Natural mortality (*M*)	0.219	0.256	0.272	0.220
Acoustic catchability (*Q*)	NA	NA	NA	NA
Additional acoustic survey SD	0.463	0.477	0.472	0.463
Derived Quantities				
2008 recruitment	5.499	8.223	10.345	5.327
SB_0 (million mt)	1.906	2.089	2.230	1.998
2012 Depletion	34.6%	44.9%	50.1%	30.6%
2011 Fishing intensity (1-SPR/1-SPR40%)	110.1%	93.6%	83.3%	111.6%
Reference points based on $SB_{40\%}$				
Female spawning biomass ($SB_{40\%}$ million mt)	1.525	1.672	1.784	1.598
$SPR_{SB40\%}$	43.7%	43.8%	43.8%	43.5%
Exploitation fraction resulting in $SB_{40\%}$	18.6%	21.2%	22.5%	18.7%
Yield at $SB_{40\%}$ (million mt)	0.293	0.368	0.414	0.305
Reference points based on $F_{40\%}$				
Female spawning biomass ($SB_{F40\%}$ million mt)	1.361	1.472	1.550	1.402
$SPR_{MSY\text{-}proxy}$	40%	40%	40%	40%
Exploitation fraction corresponding to SPR	21.4%	24.8%	26.5%	21.5%
Yield at $SB_{F40\%}$ (million mt)	0.301	0.380	0.424	0.314
Reference points based on estimated MSY				
Female spawning biomass (SB_{MSY} million mt)	0.934	1.044	1.125	0.976
SPR_{MSY}	29.4%	29.3%	29.2%	28.8%
Exploitation fraction corresponding to SPR_{MSY}	32.3%	37.6%	40.5%	33.1%
MSY (million mt)	0.316	0.404	0.449	0.332

Table 16. Select parameters, derived quantities, and reference point estimates for CCAM sensitivity analyses to the prior for steepness. Note that recruits are age-1 and not directly comparable with the SS base-case model. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

	CCAM base case	*Gadids (no P. hake) Mean =0.717 SD =0.072*	*Merluccius (no P. hake) Mean =0.673 SD =0.067*	*Merluccius (w/ P. hake) Mean =0.585 SD =0.059*
Parameters				
R_0 (billions)	3.871	3.048	3.022	3.494
Steepness (*h*)	0.842	0.732	0.694	0.614
Natural mortality (*M*)	0.294	0.269	0.271	0.272
Acoustic catchability (*Q*)	1.085	1.157	1.124	1.124
Additional acoustic survey SD	NA	NA	NA	NA
Derived Quantities				
2008 recruitment	5.925	4.575	4.711	6.296
SB_0 (million mt)	2.345	2.176	2.120	2.449
2012 Depletion	44.7%	35.8%	40.7%	43.9%
2011 Fishing intensity (1-SPR/1-SPR40%)	86.1%	99.4%	95.5%	92.4%
Reference points based on $SB_{40\%}$				
Female spawning biomass ($SB_{40\%}$ million mt)	0.938	0.870	0.848	0.980
$SPR_{SB40\%}$	42.8%	45.5%	46.6%	49.5%
Exploitation fraction resulting in $SB_{40\%}$	23.8%	19.8%	19.2%	17.4%
Yield at $SB_{40\%}$ (million mt)	0.483	0.374	0.356	36.3%
Reference points based on $F_{40\%}$				
Female spawning biomass ($SB_{F40\%}$ million mt)	0.858	0.731	0.688	0.683
$SPR_{MSY\text{-}proxy}$	40%	40%	40%	40%
Exploitation fraction corresponding to SPR	26.9%	24.3%	24.6%	24.6%
Yield at $SB_{F40\%}$ (million mt)	0.498	0.390	0.371	0.367
Reference points based on estimated MSY				
Female spawning biomass (SB_{MSY} million mt)	0.539	0.582	0.595	0.768
SPR_{MSY}	26.8%	33.6%	36.2%	42.0%
Exploitation fraction corresponding to SPR_{MSY}	44.8%	30.9%	28.2%	22.9%
MSY (million mt)	0.541	0.399	0.377	0.374

Table 17. Select parameters, derived quantities, and reference point estimates for CCAM sensitivity analyses to the standard deviation of the prior for natural mortality. Note that recruits are age 1 and not directly comparable with SS. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

	CCAM est. survey selectivity	*M prior Mean =0.2 SD=0.05*	*M prior Mean =0.2 SD=0.1*	*M prior Mean =0.2 SD=0.175*
Parameters				
R_0 (billions)	3.871	1.779	2.395	2.439
Steepness (h)	0.842	0.865	0.857	0.852
Natural mortality (M)	0.294	0.210	0.245	0.243
Acoustic catchability (Q)	1.085	1.206	1.153	1.169
Additional acoustic survey SD	NA	NA	NA	NA
Derived Quantities				
2008 recruitment	5.925	3.808	4.615	4.499
SB_0 (million mt)	2.345	1.971	2.054	2.005
2012 Depletion	44.7%	40.4%	43.9%	43.3%
2011 Fishing intensity (1-SPR/1-SPR40%)	86.1%	111.4%	101.0%	101.6%
Reference points based on $SB_{40\%}$				
Female spawning biomass ($SB_{40\%}$ million mt)	0.938	0.788	0.821	0.802
$SPR_{SB40\%}$	42.8%	42.3%	42.5%	42.6%
Exploitation fraction resulting in $SB_{40\%}$	23.8%	17.3%	19.9%	20.1%
Yield at $SB_{40\%}$ (million mt)	0.483	0.289	0.347	0.351
Reference points based on $F_{40\%}$				
Female spawning biomass ($SB_{F40\%}$ million mt)	0.858	0.732	0.757	0.739
$SPR_{MSY\text{-}proxy}$	40%	40%	40%	40%
Exploitation fraction corresponding to SPR	26.9%	18.9%	22.0%	21.9%
Yield at $SB_{F40\%}$ (million mt)	0.498	0.296	0.357	0.360
Reference points based on estimated MSY				
Female spawning biomass (SB_{MSY} million mt)	0.539	0.440	0.460	0.452
SPR_{MSY}	26.8%	25.0%	25.5%	25.9%
Exploitation fraction corresponding to SPR_{MSY}	44.8%	34.6%	38.6%	39.3%
MSY (million mt)	0.541	0.325	0.391	0.392

Table 18. Select parameters, derived quantities, and reference point estimates for CCAM sensitivity analyses to the mean of the prior for natural mortality. Note that recruits are age 1 and not directly comparable with SS. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

	CCAM est. survey selectivity	*M prior Mean =0.175 SD=0.2*	*M prior Mean =0.225 SD=0.2*
Parameters			
R_0 (billions)	3.871	2.806	3.380
Steepness (h)	0.842	0.850	0.855
Natural mortality (M)	0.294	0.261	0.282
Acoustic catchability (Q)	1.085	1.143	1.075
Additional acoustic survey SD	NA	NA	NA
Derived Quantities			
2008 recruitment	5.925	4.813	5.464
SB_0 (million mt)	2.345	2.094	2.201
2012 Depletion	44.7%	43.1%	46.6%
2011 Fishing intensity (1-SPR/1-SPR40%)	86.1%	97.0%	91.5%
Reference points based on $SB_{40\%}$			
Female spawning biomass ($SB_{40\%}$ million mt)	0.938	0.837	0.880
$SPR_{SB40\%}$	42.8%	42.6%	42.5%
Exploitation fraction resulting in $SB_{40\%}$	23.8%	21.2%	23.2%
Yield at $SB_{40\%}$ (million mt)	0.483	0.384	0.446
Reference points based on $F_{40\%}$			
Female spawning biomass ($SB_{F40\%}$ million mt)	0.858	0.773	0.811
$SPR_{MSY\text{-}proxy}$	40%	40%	40%
Exploitation fraction corresponding to SPR	26.9%	23.6%	25.6%
Yield at $SB_{F40\%}$ (million mt)	0.498	0.396	0.459
Reference points based on estimated MSY			
Female spawning biomass (SB_{MSY} million mt)	0.539	0.478	0.491
SPR_{MSY}	26.8%	26.0%	25.8%
Exploitation fraction corresponding to SPR_{MSY}	44.8%	40.6%	44.8%
MSY (million mt)	0.541	0.429	0.498

Table 19. Select parameters, derived quantities, and reference point estimates for CCAM sensitivity analyses to the standard deviation of the prior for survey catchability. Note that recruits are age 1 and not directly comparable with SS. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

	CCAM est. survey selectivity	*Q prior SD=0.15*	*Q prior SD=0.25*	*Q prior SD=0.3*
Parameters				
R_0 (billions)	3.871	2.475	2.165	2.164
Steepness (*h*)	0.842	0.856	0.850	0.852
Natural mortality (*M*)	0.294	0.255	0.243	0.233
Acoustic catchability (*Q*)	1.085	1.279	1.544	1.579
Additional acoustic survey SD	NA	NA	NA	NA
Derived Quantities				
2008 recruitment	5.925	4.075	3.201	3.248
SB_0 (million mt)	2.345	2.016	1.908	1.937
2012 Depletion	44.7%	38.1%	29.9%	29.8%
2011 Fishing intensity (1-SPR/1-SPR40%)	86.1%	105.1%	115.3%	117.1%
Reference points based on $SB_{40\%}$				
Female spawning biomass ($SB_{40\%}$ million mt)	0.938	0.806	0.764	0.775
$SPR_{SB40\%}$	42.8%	42.5%	42.7%	42.6%
Exploitation fraction resulting in $SB_{40\%}$	23.8%	20.6%	19.6%	18.9%
Yield at $SB_{40\%}$ (million mt)	0.483	0.349	0.319	0.322
Reference points based on $F_{40\%}$				
Female spawning biomass ($SB_{F40\%}$ million mt)	0.858	0.741	0.703	0.715
$SPR_{MSY\text{-}proxy}$	40%	40%	40%	40%
Exploitation fraction corresponding to SPR	26.9%	23.0%	21.9%	21.0%
Yield at $SB_{F40\%}$ (million mt)	0.498	0.359	0.326	0.331
Reference points based on estimated MSY				
Female spawning biomass (SB_{MSY} million mt)	0.539	0.455	0.438	0.442
SPR_{MSY}	26.8%	25.7%	26.2%	26.0%
Exploitation fraction corresponding to SPR_{MSY}	44.8%	40.1%	37.1%	36.7%
MSY (million mt)	0.541	0.394	0.357	0.358

Table 20. Select parameters, derived quantities, and reference point estimates for retrospective analyses using the base case. Values in italics are implied by the removals after the ending year of the respective retrospective analysis. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

	Base case	-1 year	-2 years	-3 years	-4 years	-5 years
Parameters						
R_0 (billions)	2.369	2.921	2.956	2.869	2.886	2.724
Steepness (*h*)	0.8031	0.8112	0.8118	0.8088	0.8072	0.8107
Natural mortality (*M*)	0.2193	0.2253	0.2242	0.2240	0.2226	0.2226
Acoustic catchability (*Q*)	NA	NA	NA	NA	NA	NA
Additional acoustic survey SD	0.4630	0.2917	0.2998	0.3188	0.3222	0.3633
Derived Quantities						
2008 recruitment	5.499	15.134	1.237	0.923	*0.975*	*0.901*
SB_0 (million mt)	1.906	2.220	2.301	2.263	2.240	2.162
2012 Depletion	34.56%	*91.55%*	*48.71%*	*36.69%*	*34.35%*	*23.73%*
2011 Fishing intensity (1-SPR/1-SPR40%)	110.14%	NA	NA	NA	NA	NA
Reference points based on $SB_{40\%}$						
Female spawning biomass ($SB_{40\%}$ million mt)	1.525	1.776	1.841	1.811	1.792	1.729
$SPR_{SB40\%}$	43.68%	43.49%	43.48%	43.55%	43.58%	43.50%
Exploitation fraction resulting in $SB_{40\%}$	18.58%	19.04%	18.99%	19.01%	18.91%	18.92%
Yield at $SB_{40\%}$ (million mt)	0.293	0.351	0.362	0.354	0.349	0.336
Reference points based on $F_{40\%}$						
Female spawning biomass ($SB_{F40\%}$ million mt)	1.361	1.587	1.619	1.608	1.586	1.518
$SPR_{MSY\text{-}proxy}$						
Exploitation fraction corresponding to SPR	21.37%	21.97%	21.85%	21.81%	21.70%	21.69%
Yield at $SB_{F40\%}$ (million mt)	0.301	0.361	0.372	0.364	0.359	0.346
Reference points based on estimated MSY						
Female spawning biomass (SB_{MSY} million mt)	0.934	1.088	1.127	1.113	1.107	1.060
SPR_{MSY}	29.36%	28.70%	28.80%	29.00%	29.04%	28.91%
Exploitation fraction corresponding to SPR_{MSY}	32.34%	34.07%	33.50%	33.35%	33.44%	33.07%
MSY (million mt)	0.316	0.383	0.393	0.385	0.379	0.362

7. Figures

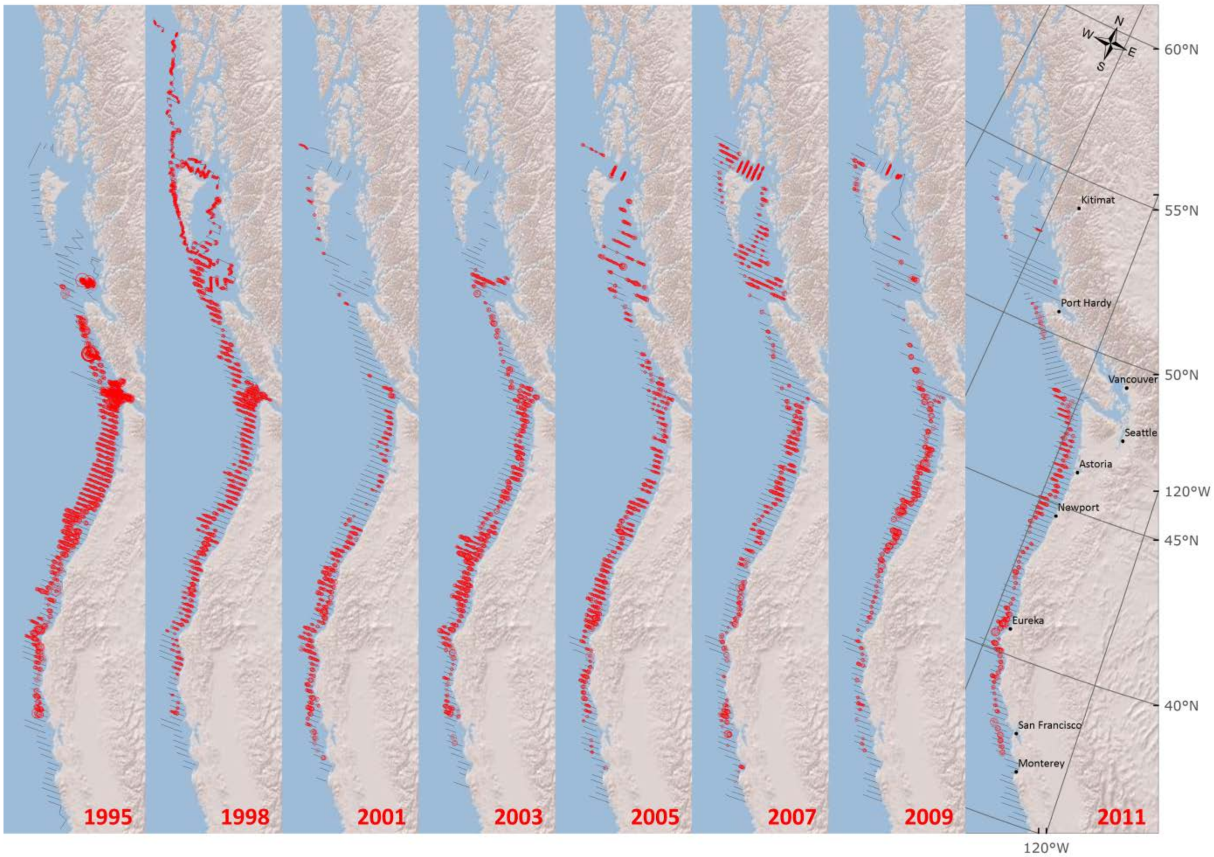


Figure 1. Spatial distribution of acoustic backscatter attributable to Pacific hake from joint US-Canada acoustic surveys 1995-2011. Area of the circles is roughly proportional to observed backscatter.

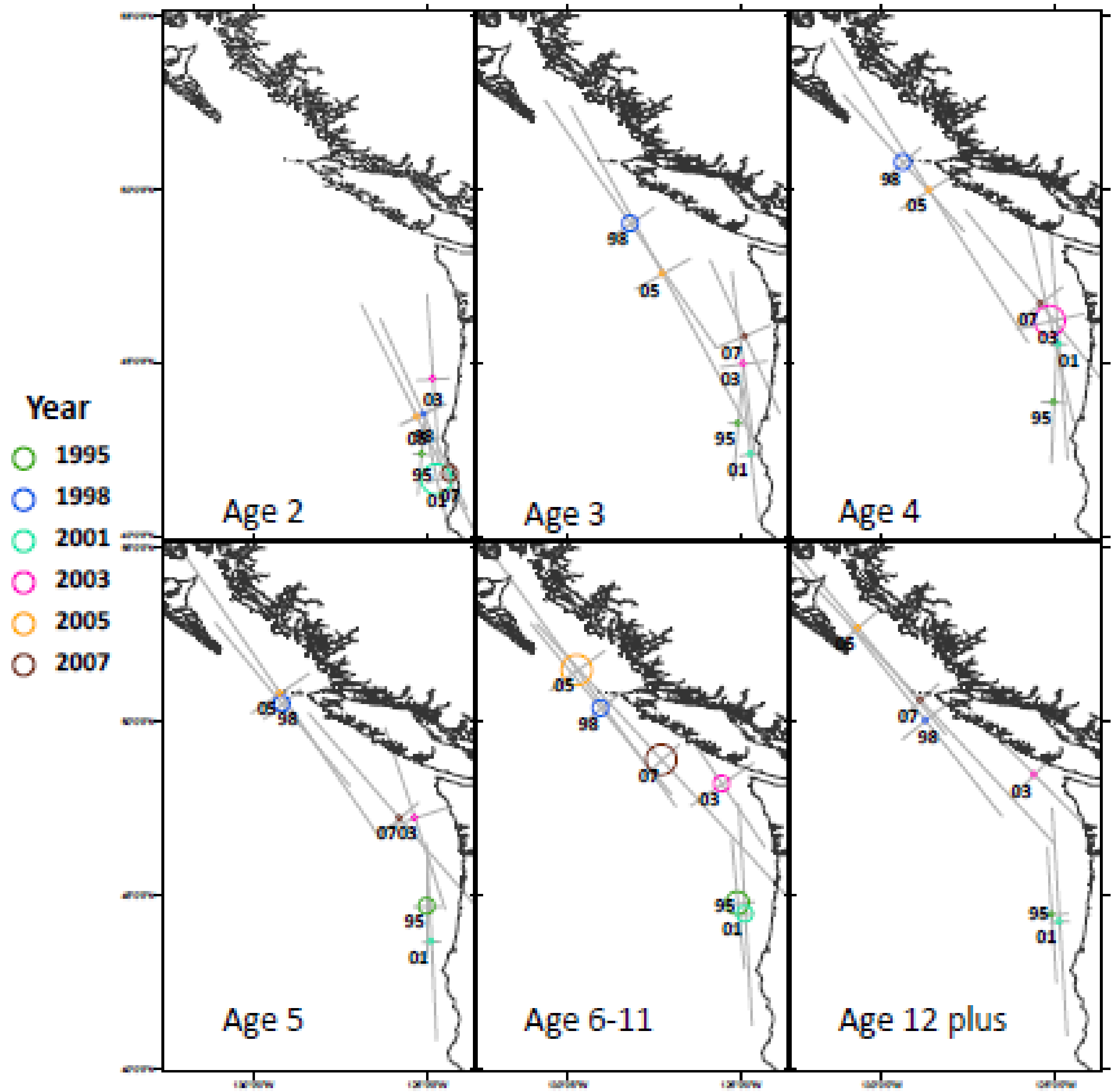


Figure 2. The mean spatial location of the hake stock (circles are proportional to biomass) and variance (grey lines) by age group and year based on acoustic survey observations 1995-2007 (Figure courtesy of O'Conner and Haltuch's ongoing Fisheries And The Environment project investigating the links between ocean conditions and Pacific hake distribution).

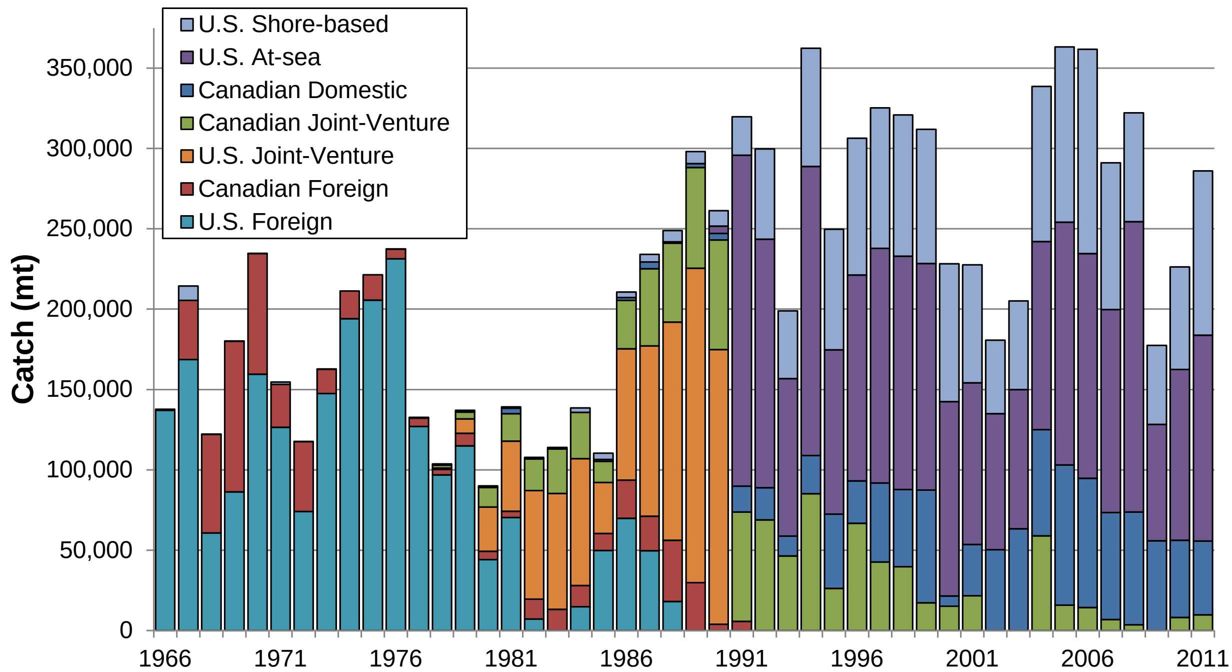


Figure 3. Total Pacific hake landings used in the assessment by sector, 1966-2011.

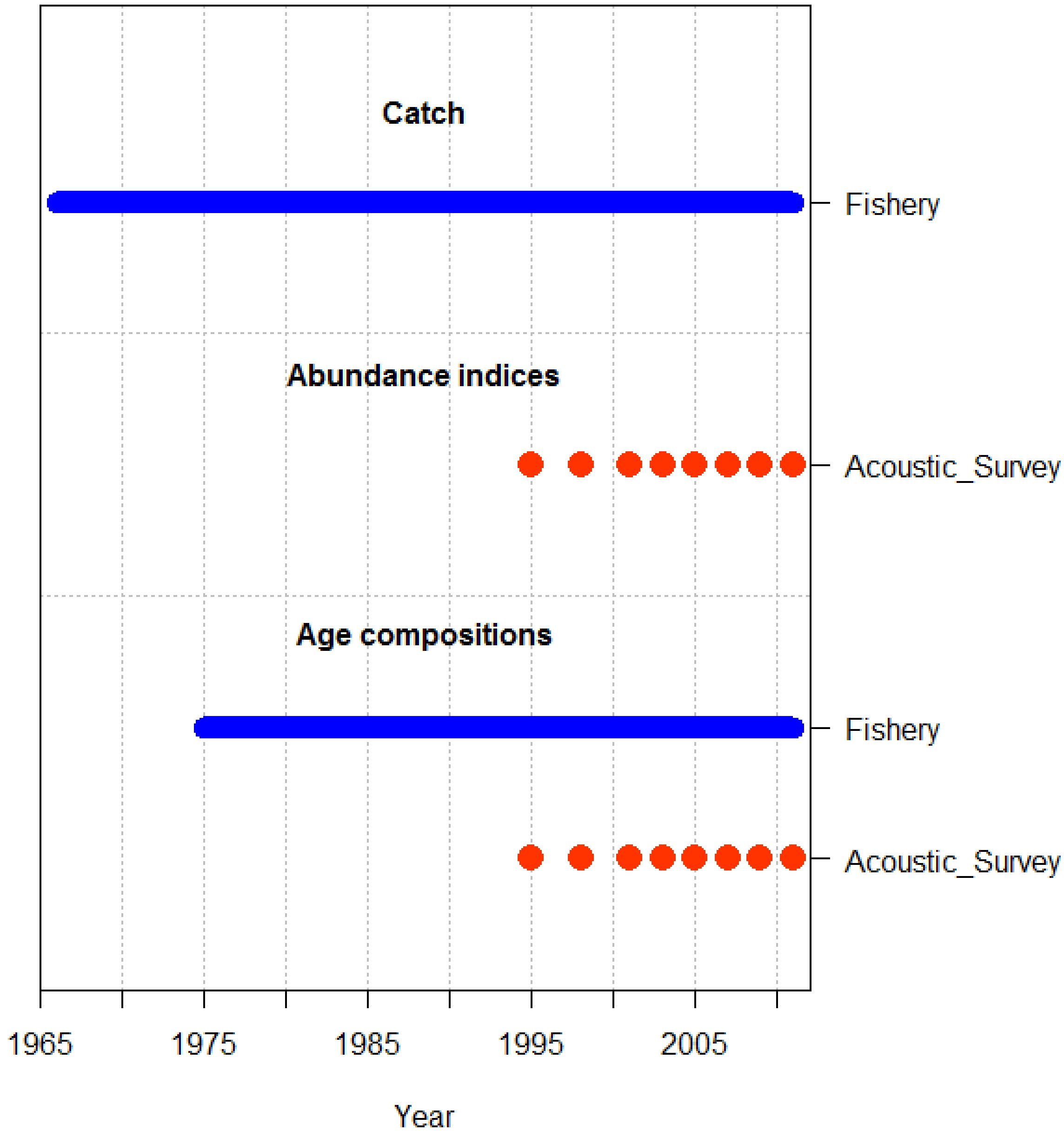


Figure 4. Overview of data used in this assessment, 1966-2011.

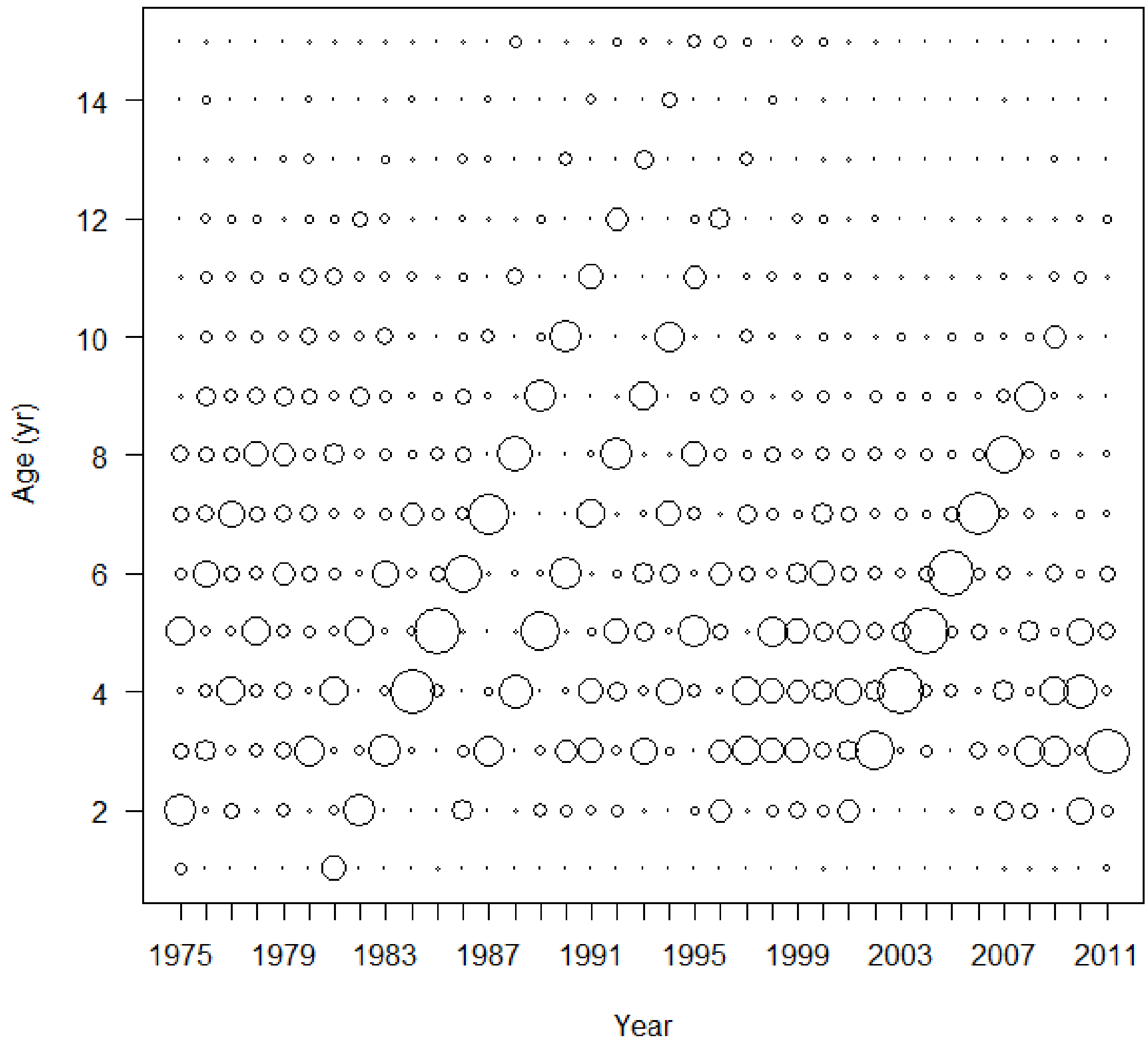


Figure 5. Aggregate fishery (all sectors combined) age compositions, 1975-2011. Proportions in each year sum to 1.0, maximum bubble size represents a value of 0.68.

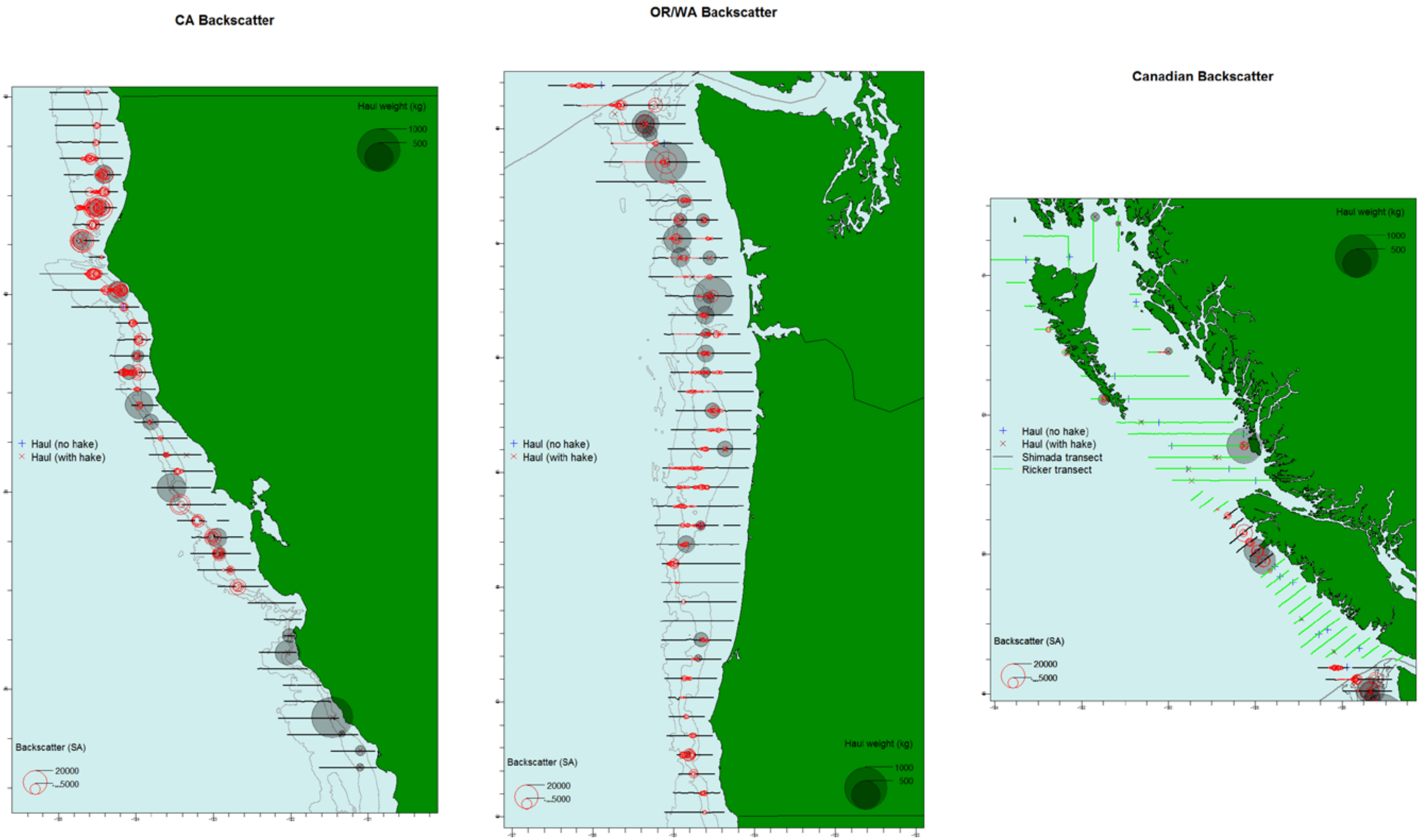


Figure 6. Acoustic survey transects surveyed in 2011, distribution of backscatter and magnitude of trawl catches of Pacific hake.

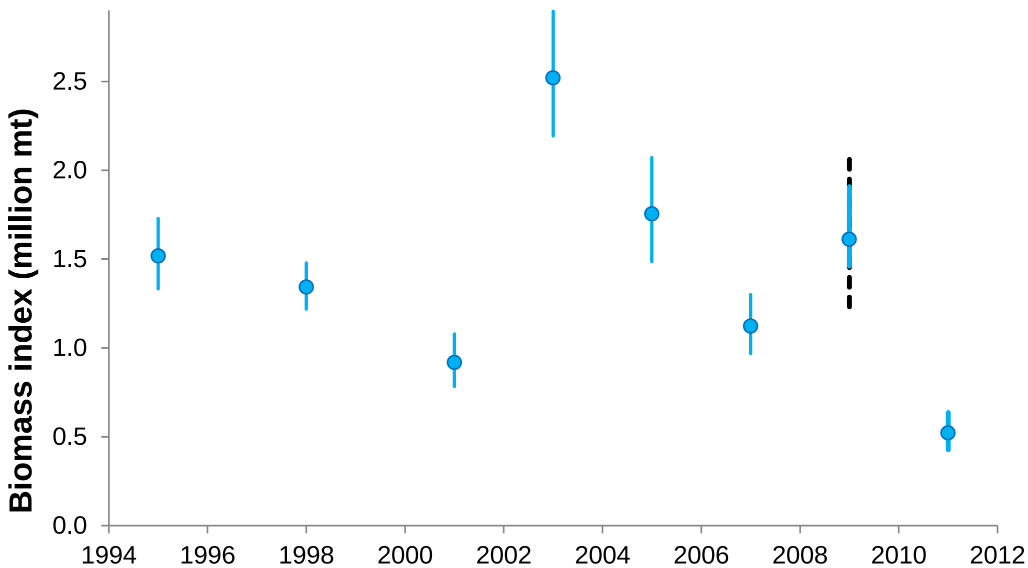


Figure 7. Acoustic survey biomass indices (millions of metric tons). Approximate 95% confidence intervals are based on only sampling variability (1995-2007, 2011) and sampling variability as well as squid/hake apportionment uncertainty (2009).

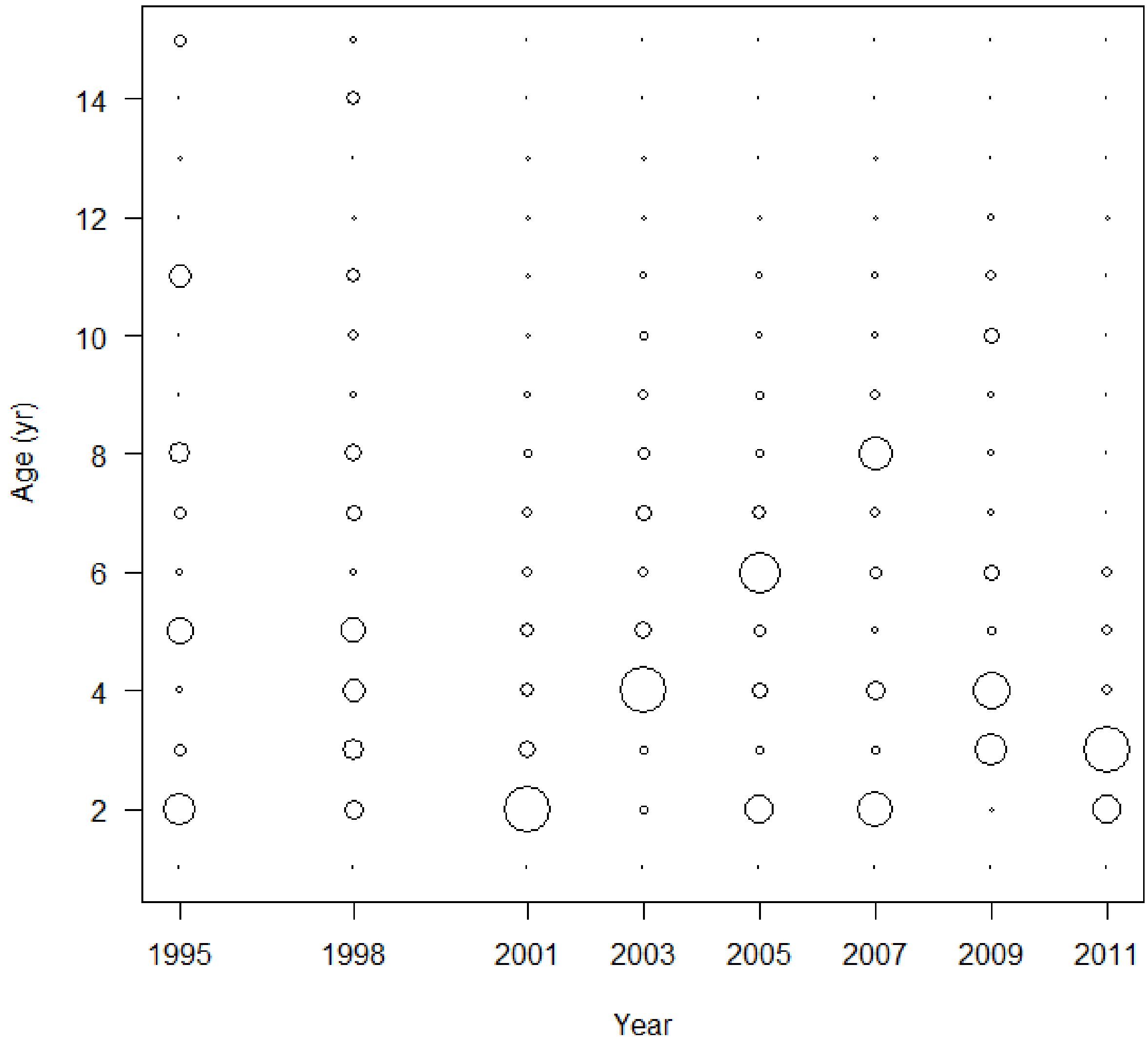


Figure 8. Acoustic survey age compositions, 1995-2009. Proportions in each year sum to 1.0, maximum bubble size represents a value of 0.63.

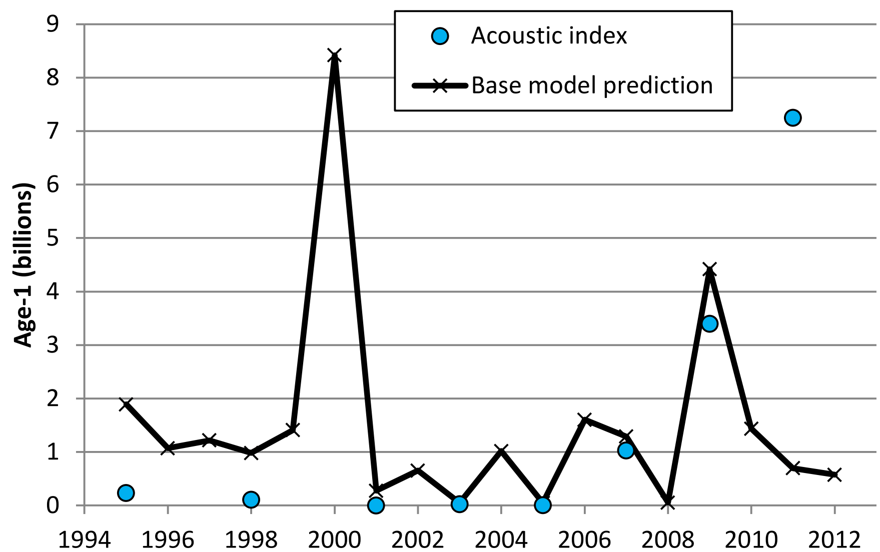


Figure 9. Preliminary acoustic survey age-1 index and base-case model predicted posterior median numbers at age-1. This figure represents a comparison with, not a fit to the preliminary data. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

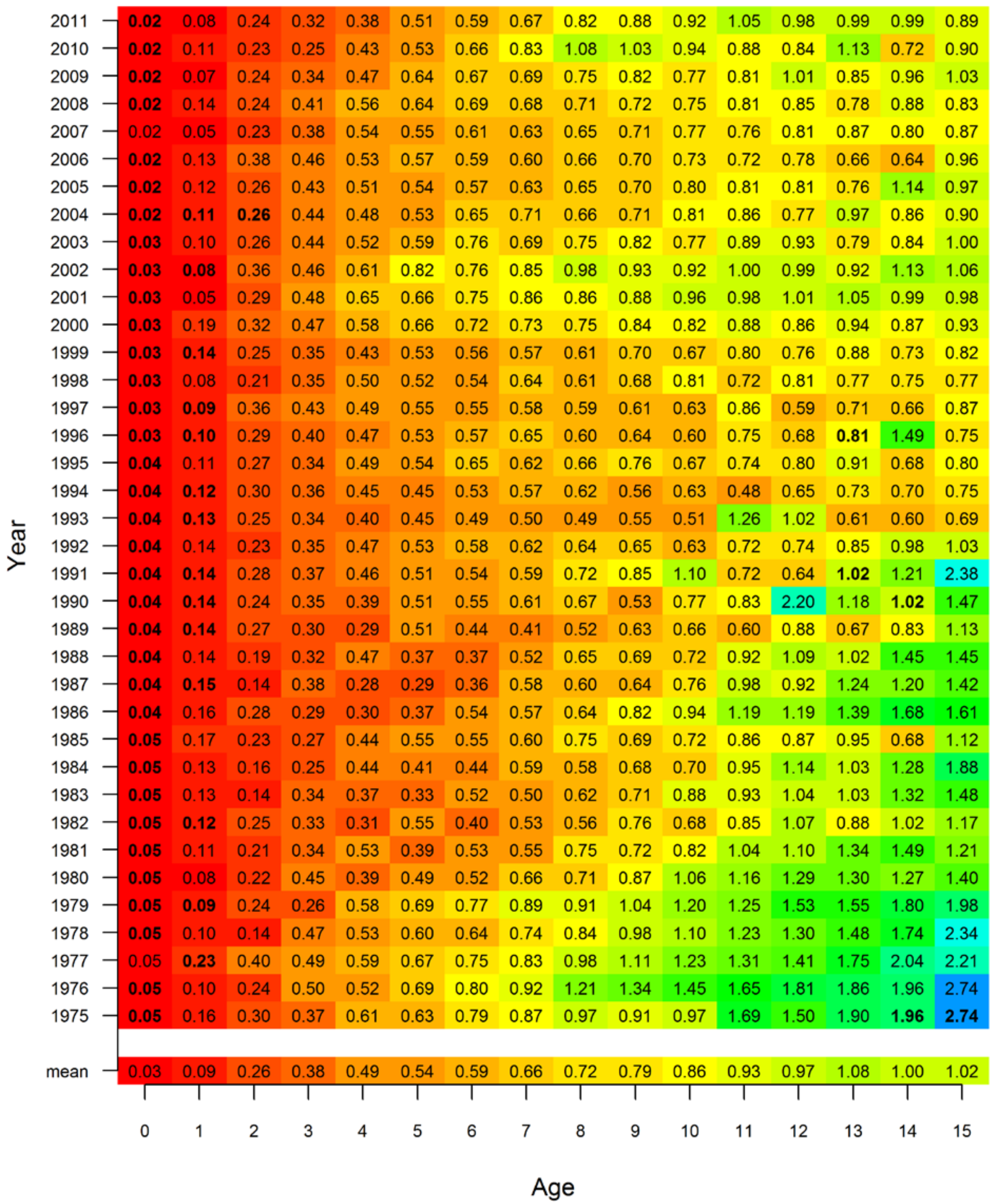


Figure 10. Interpolated matrix of weight at age (kg) used in both models.

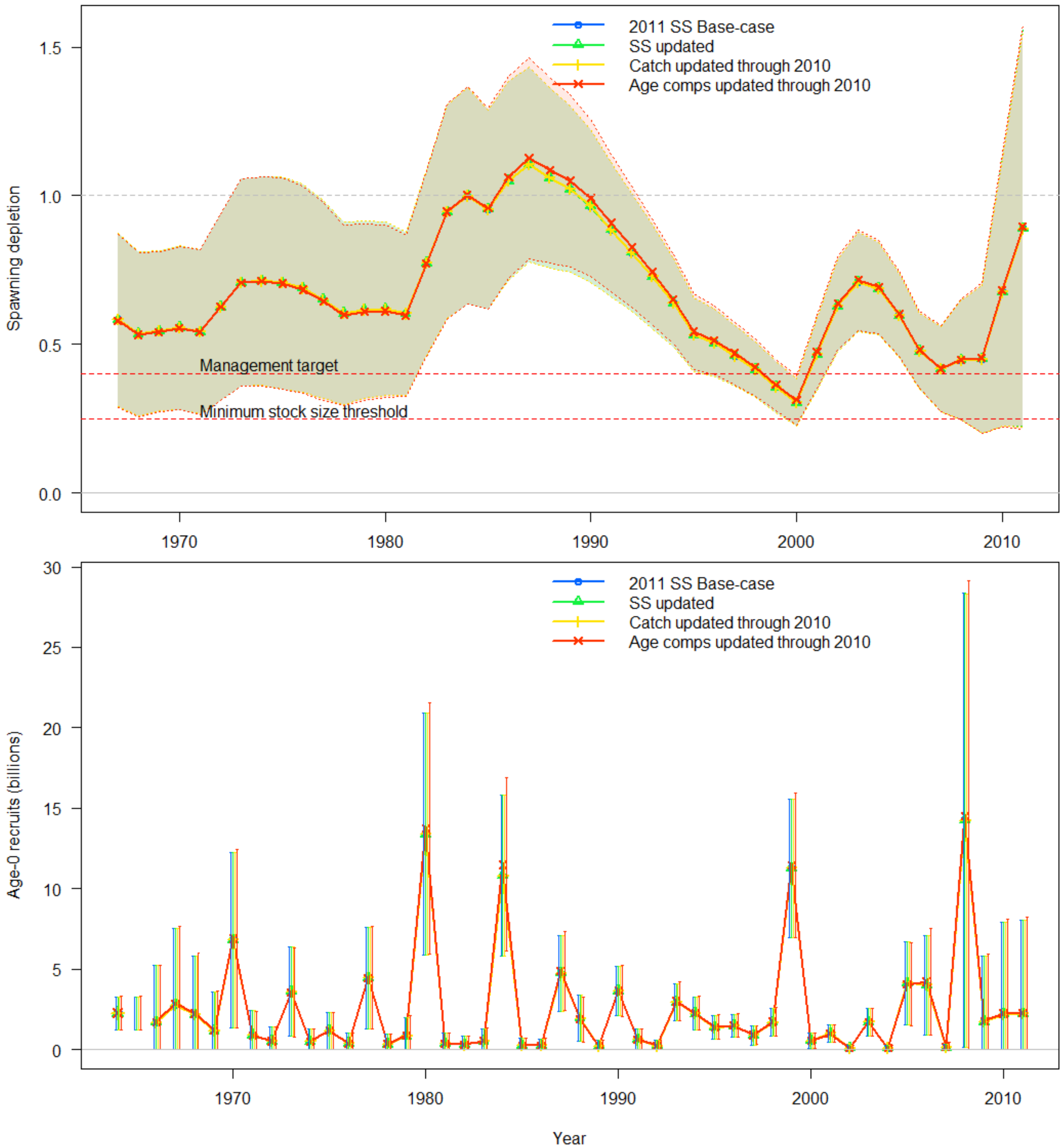


Figure 11. Results of bridging analyses updating the Stock Synthesis software, historical catch estimates (<=2010) and adding additional historical ages unavailable in 2011. Upper panel displays maximum likelihood depletion estimates, lower panel recruitment estimates, with ~95% confidence intervals.

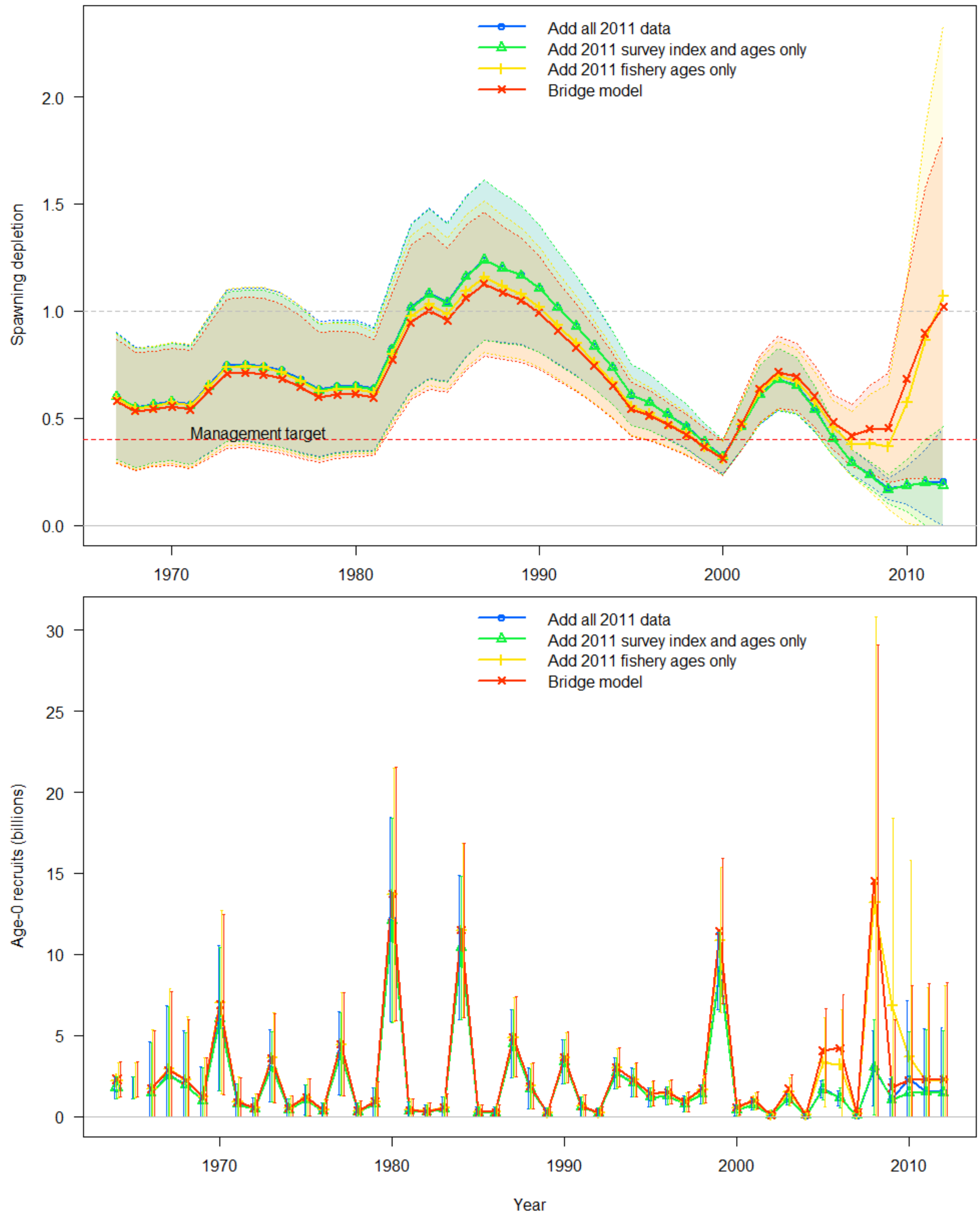


Figure 12. Results of bridging analyses adding 2011 data sources. Upper panel displays maximum likelihood depletion estimates, lower panel recruitment estimates, with ~95% confidence intervals. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

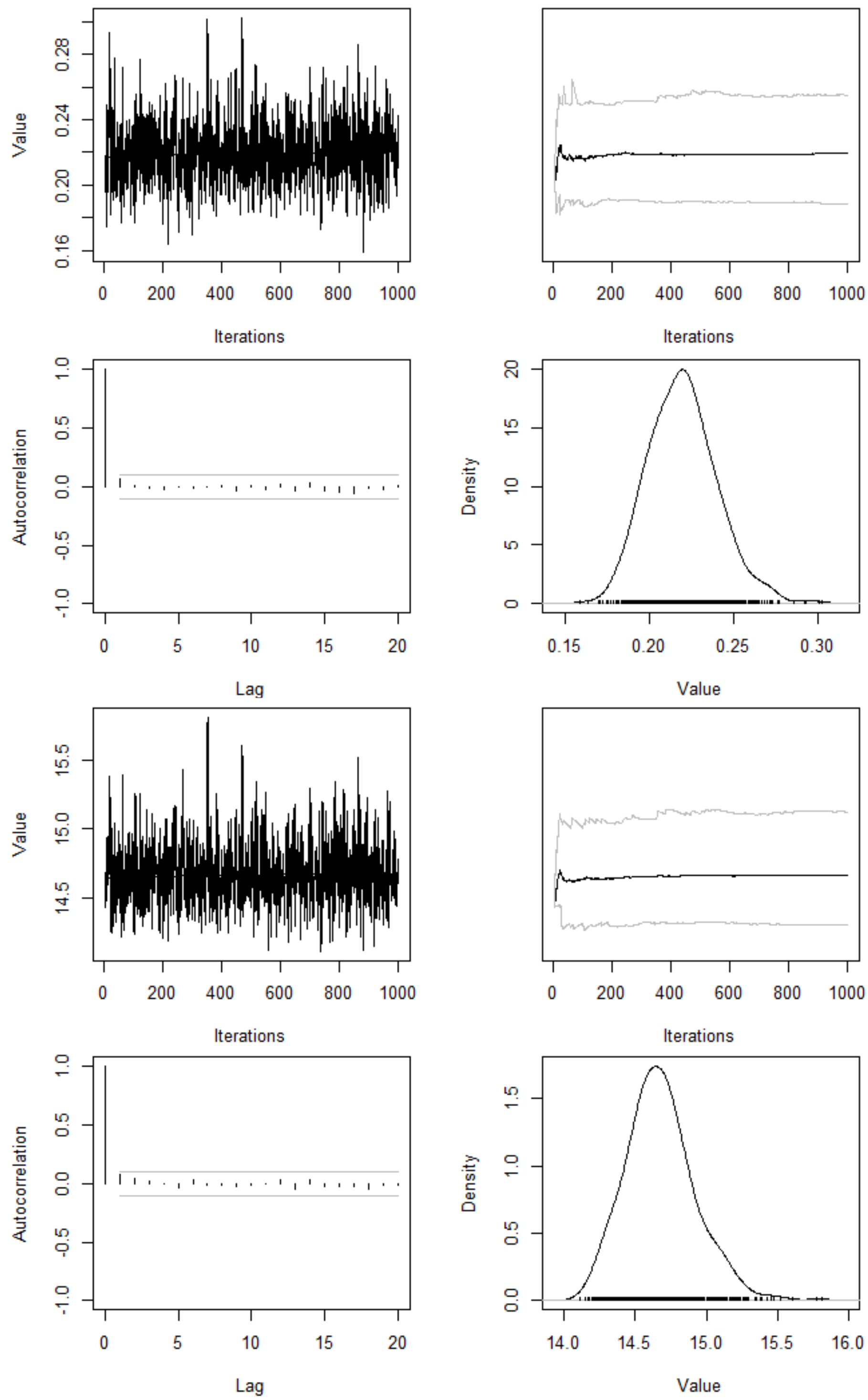


Figure 13. Summary of MCMC diagnostics for natural mortality (upper panels) and log(R_0) (lower panels) in the base-case model.

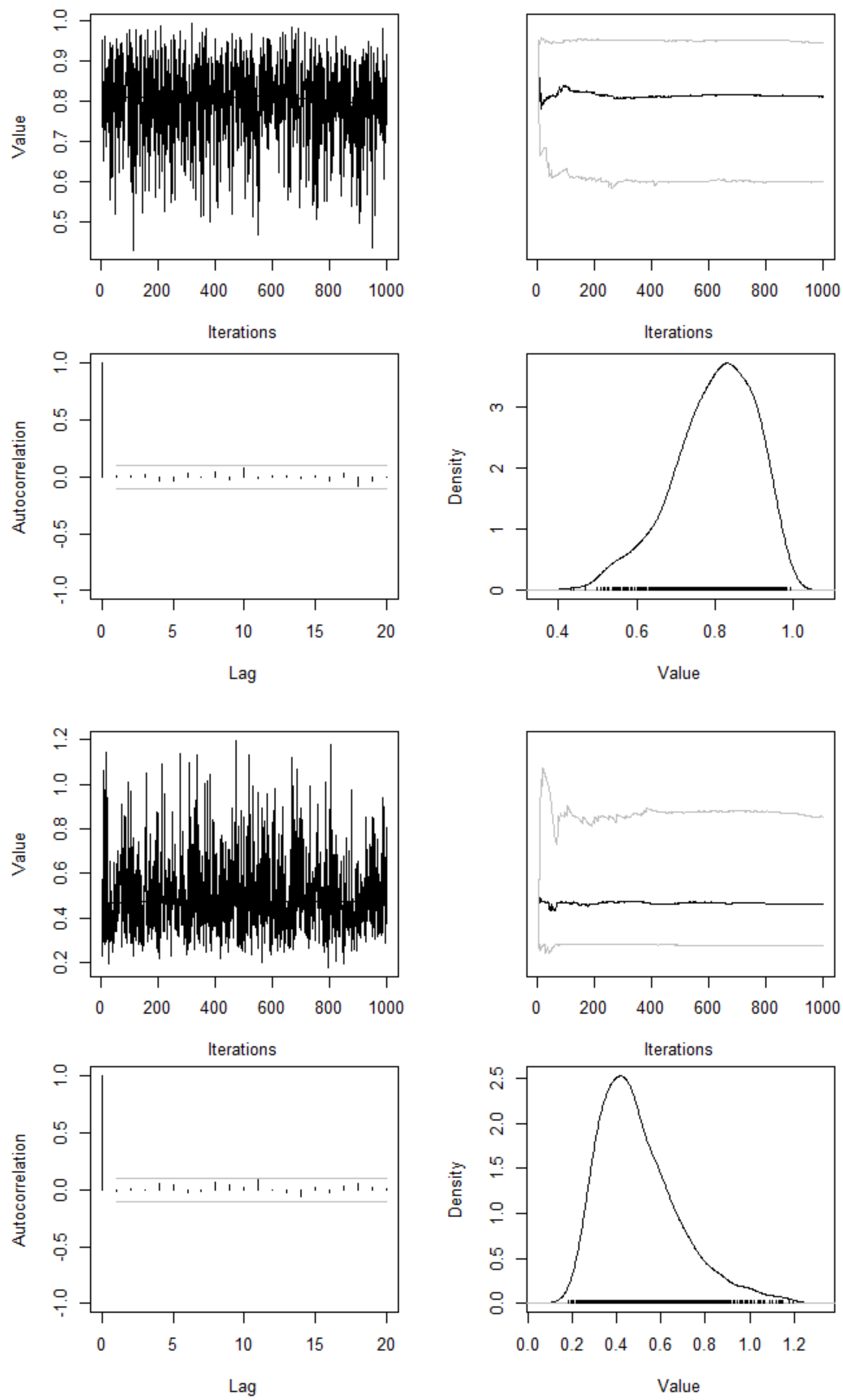


Figure 14. Summary of MCMC diagnostics for steepness (upper panels) and the additional SD for the acoustic survey index (lower panels) in the base-case model.

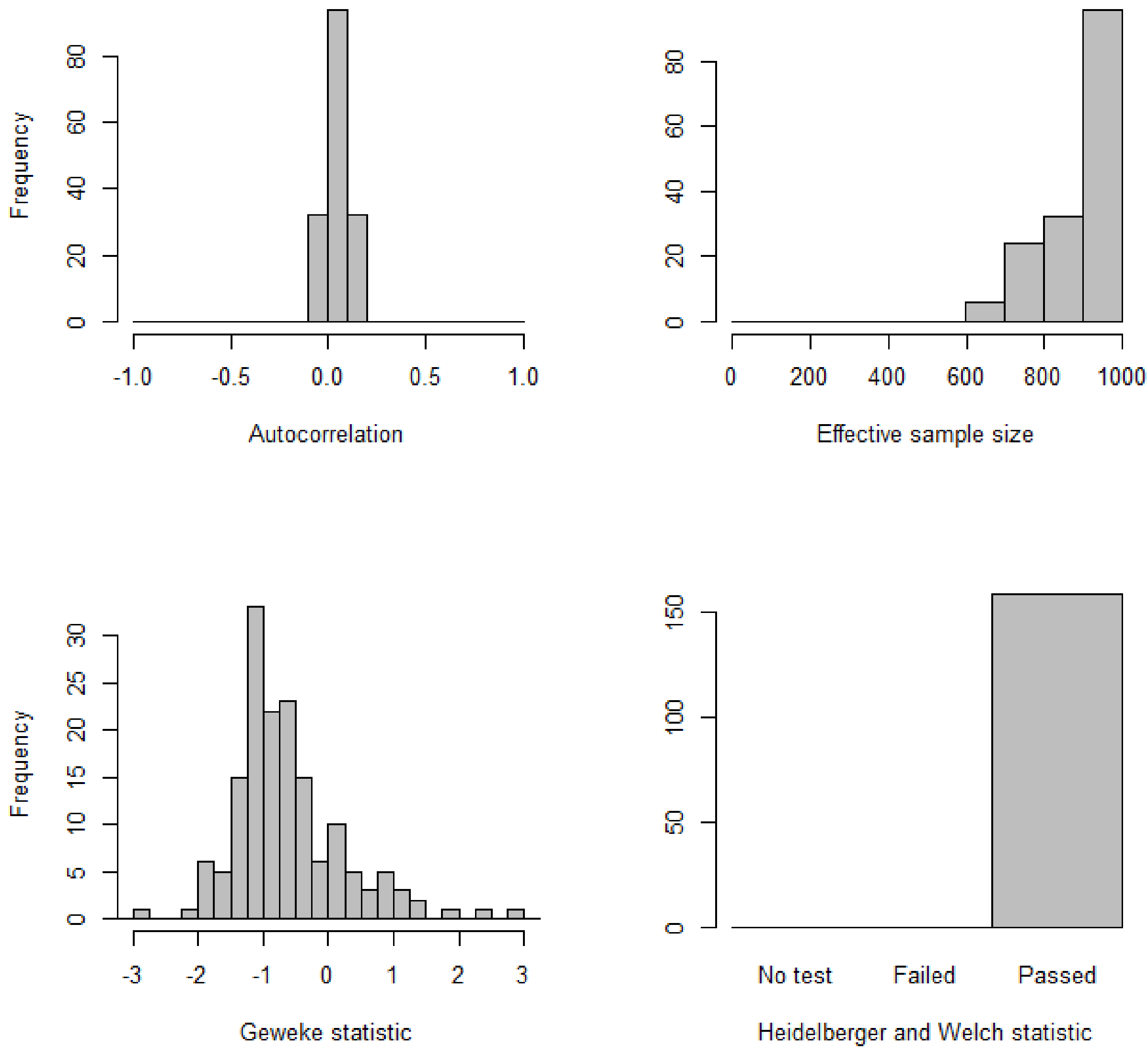


Figure 15. Summary histograms of MCMC diagnostics for all base-case model parameters and derived quantities including the recruitment, spawning biomass, and depletion time-series'.

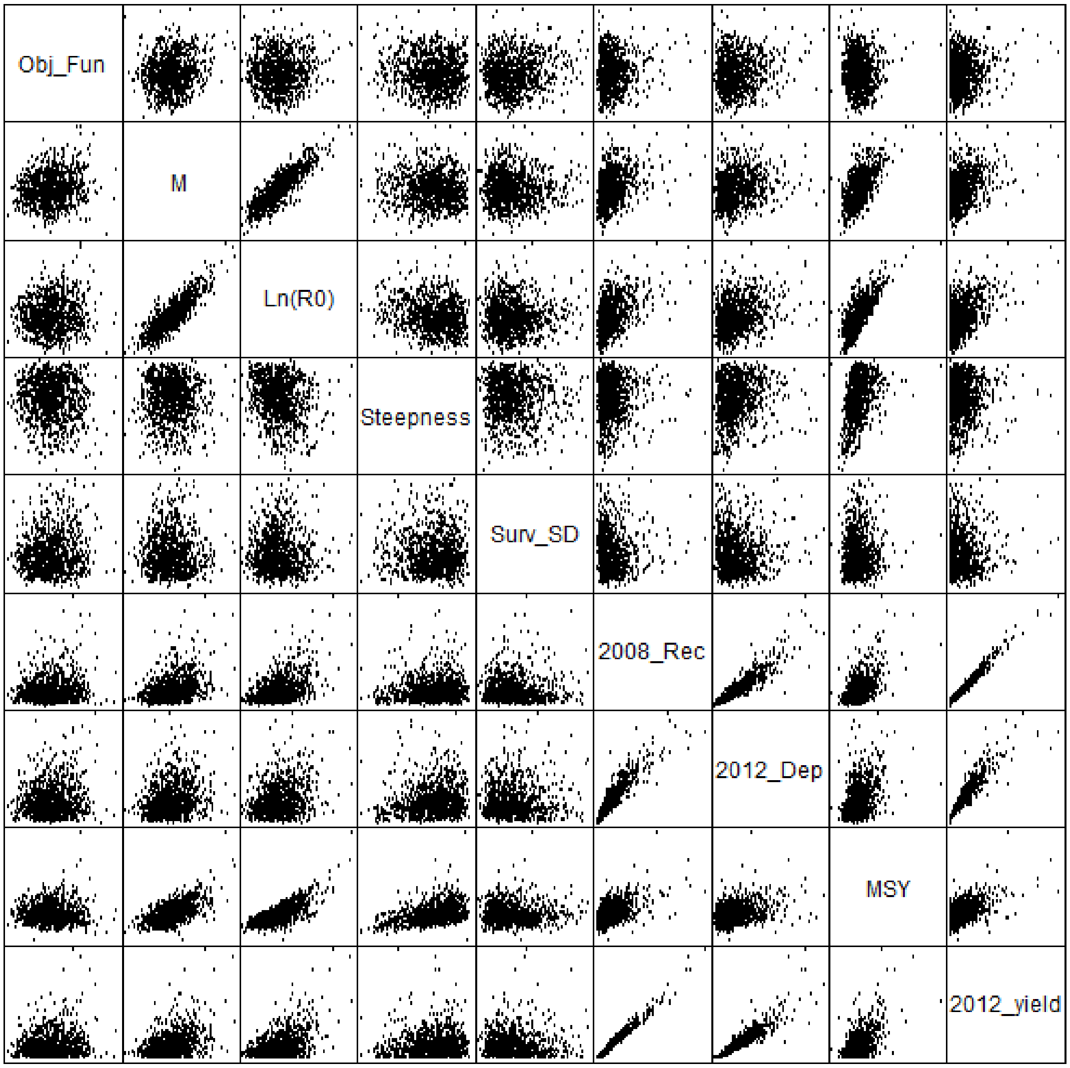


Figure 16. Posterior correlations among key base-case model parameters and derived quantities. From the top left the posteriors plotted are: objective function, natural mortality, ln(R_0), steepness, the process-error SD for the acoustic survey, the 2008 recruitment deviation, the depletion level in 2012, the estimate of MSY and the default harvest rate yield for 2012.

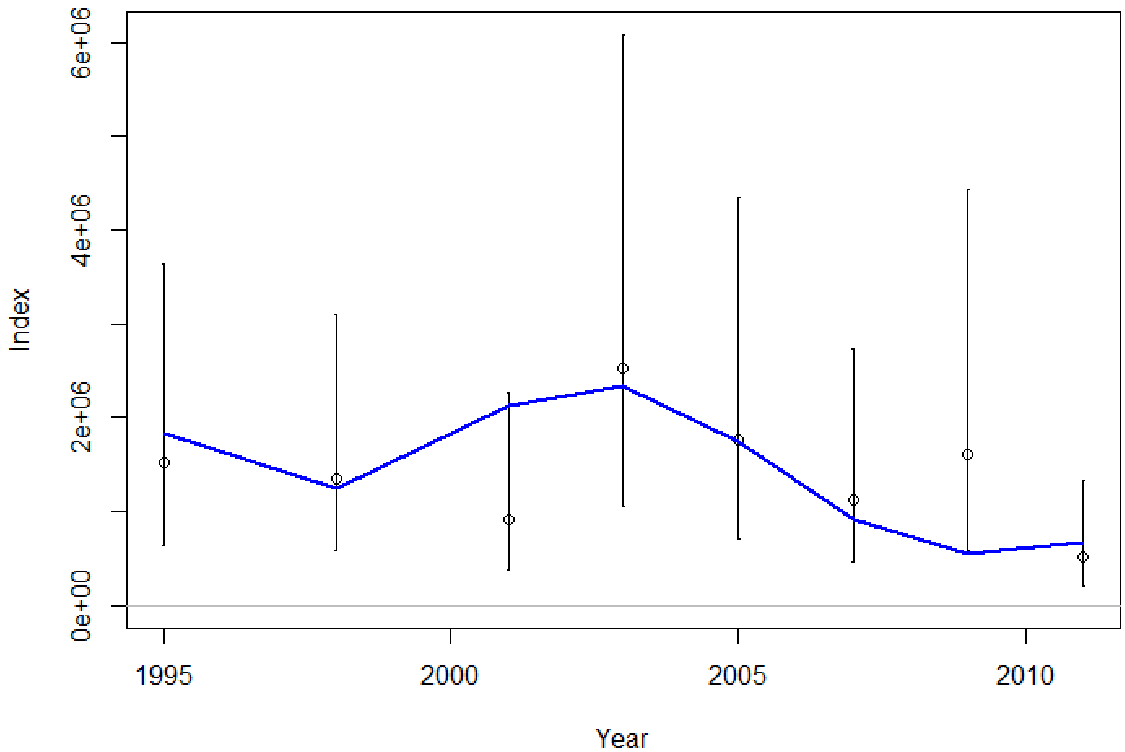


Figure 17. Predicted MLE fit to the acoustic survey biomass index.

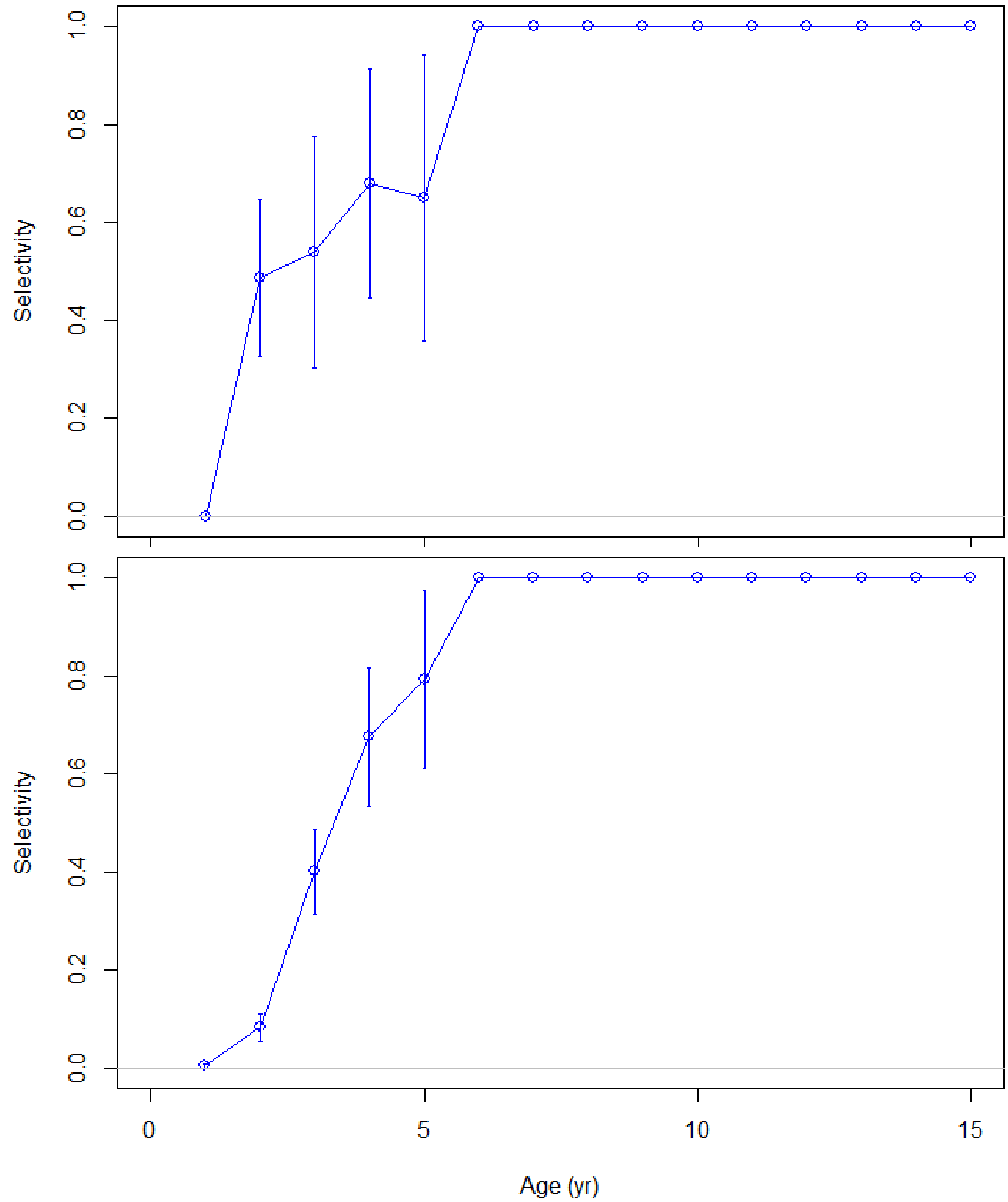


Figure 18. Estimated selectivity curves for the acoustic survey (upper panel) and fishery (lower panel) from the base-case model. Vertical bars represent 95% confidence intervals about the MLE.

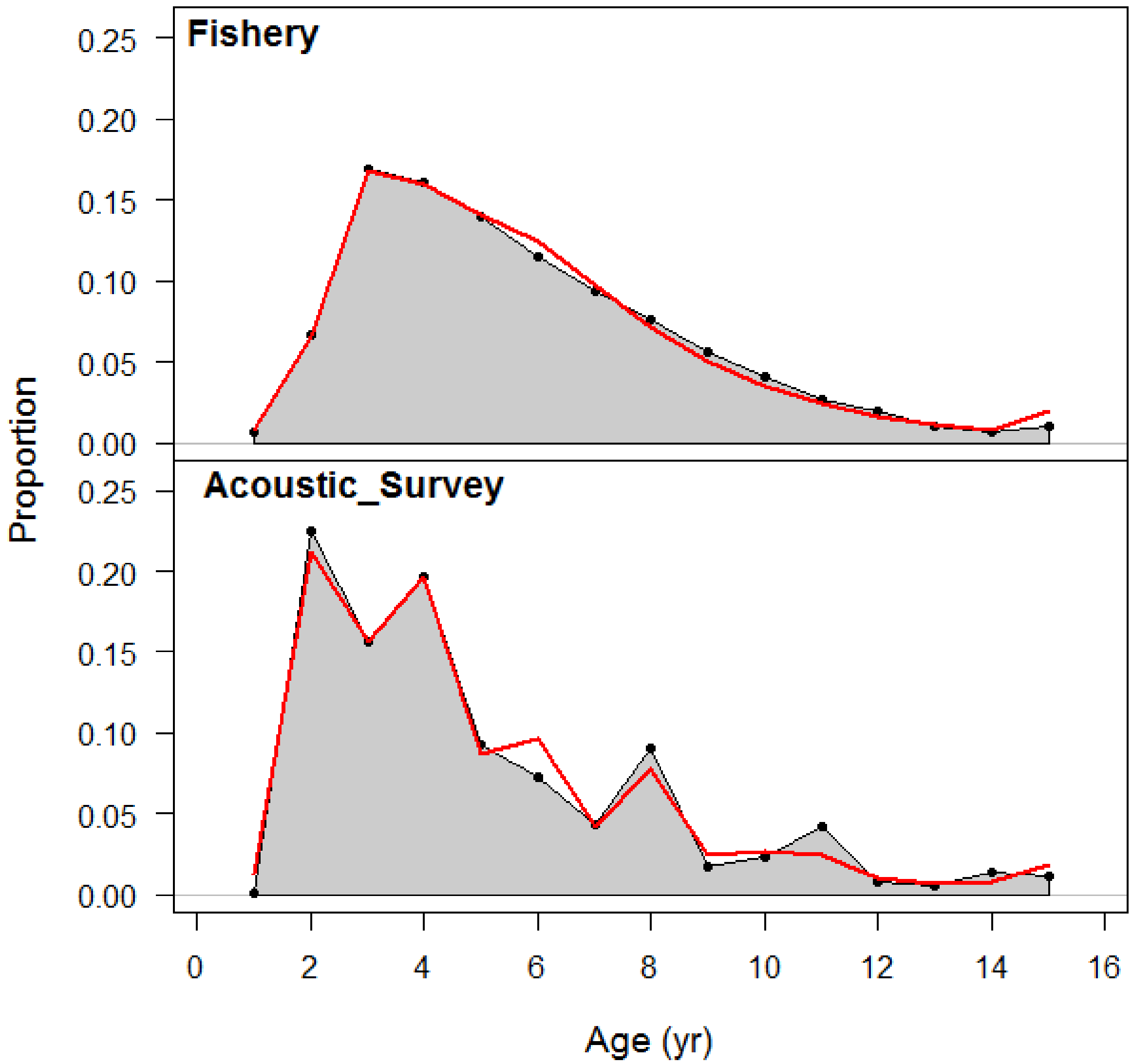


Figure 19. Base-case model fit to the aggregate fishery and acoustic age composition data.

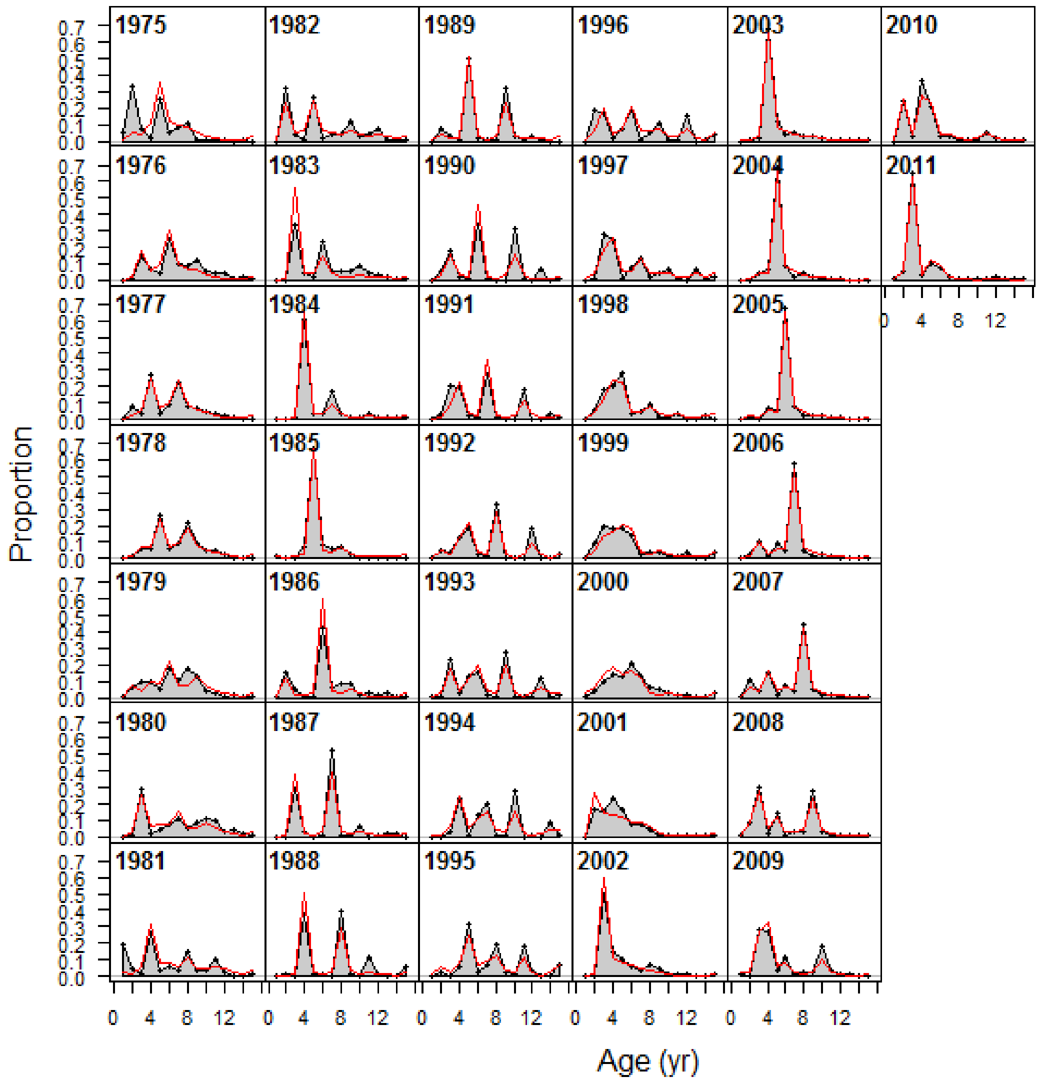


Figure 20. Base-case model fit to the observed fishery age composition data.

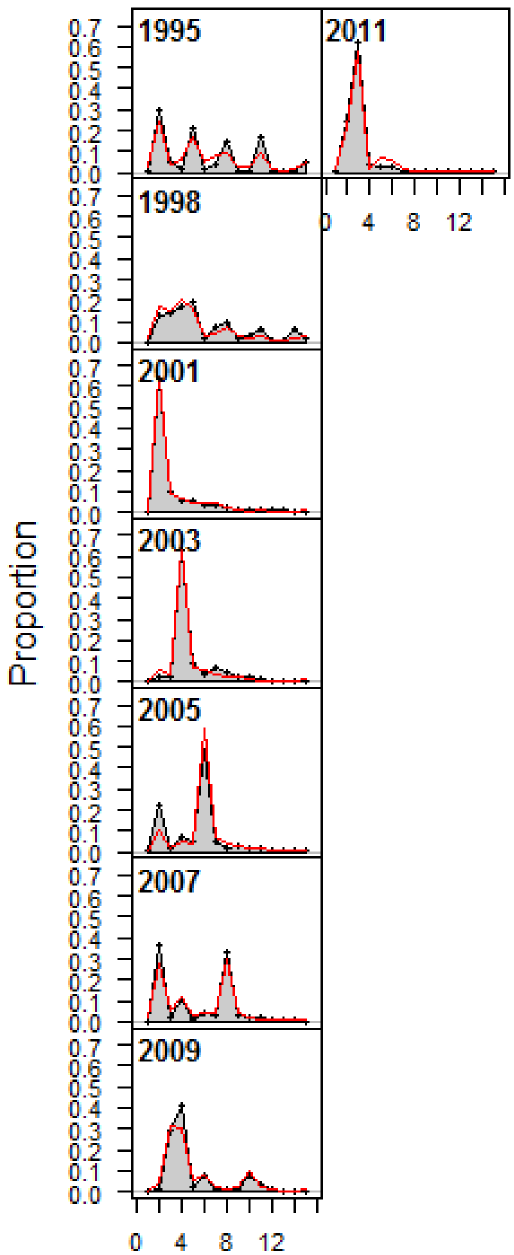


Figure 21. Base-case model fit to the observed acoustic survey age composition data.

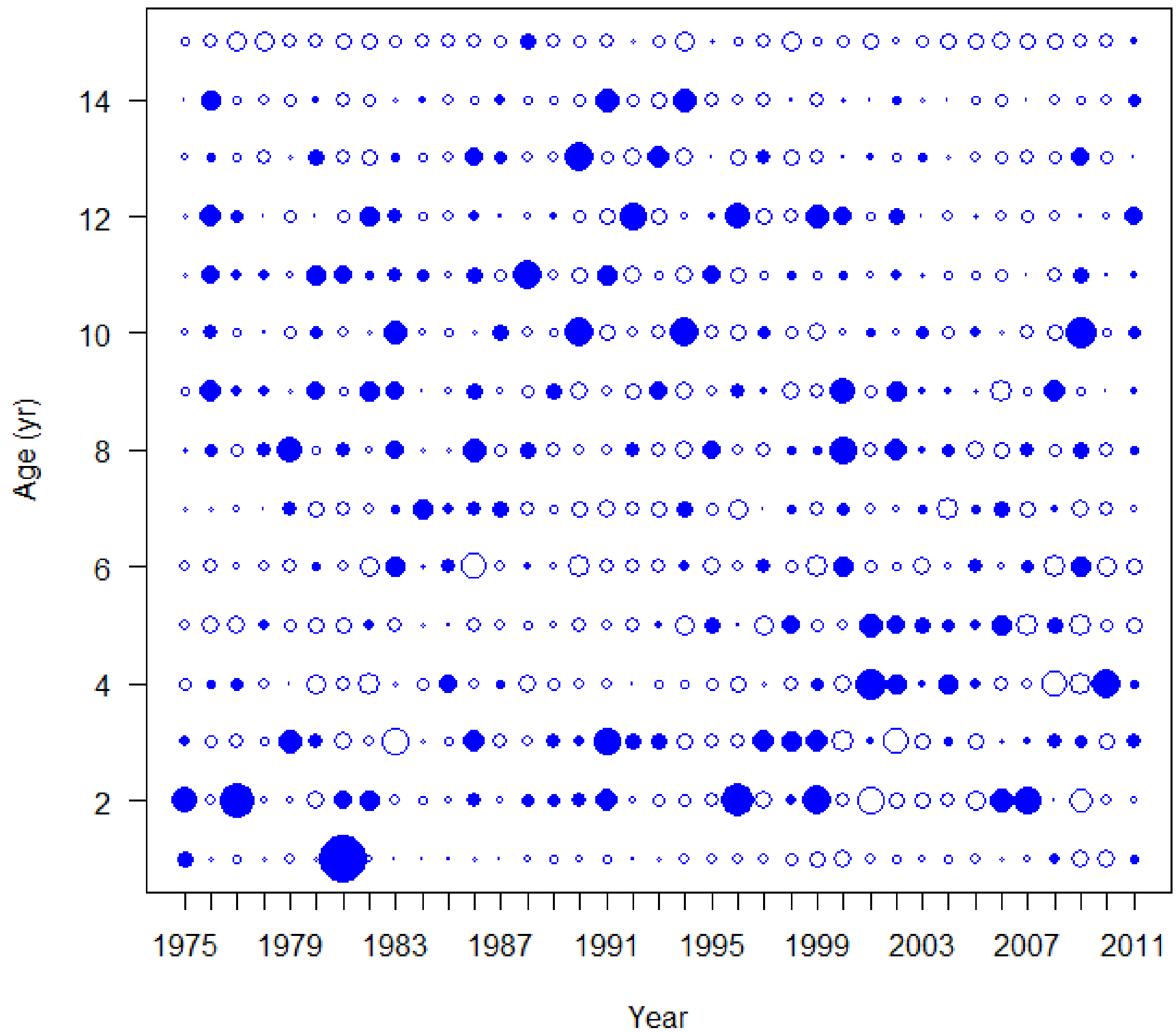


Figure 22. Pearson standardized residuals (observed - predicted) for base-case model fits to the fishery age composition data. Maximum bubble size = 5.15; filled circles represent positive values.

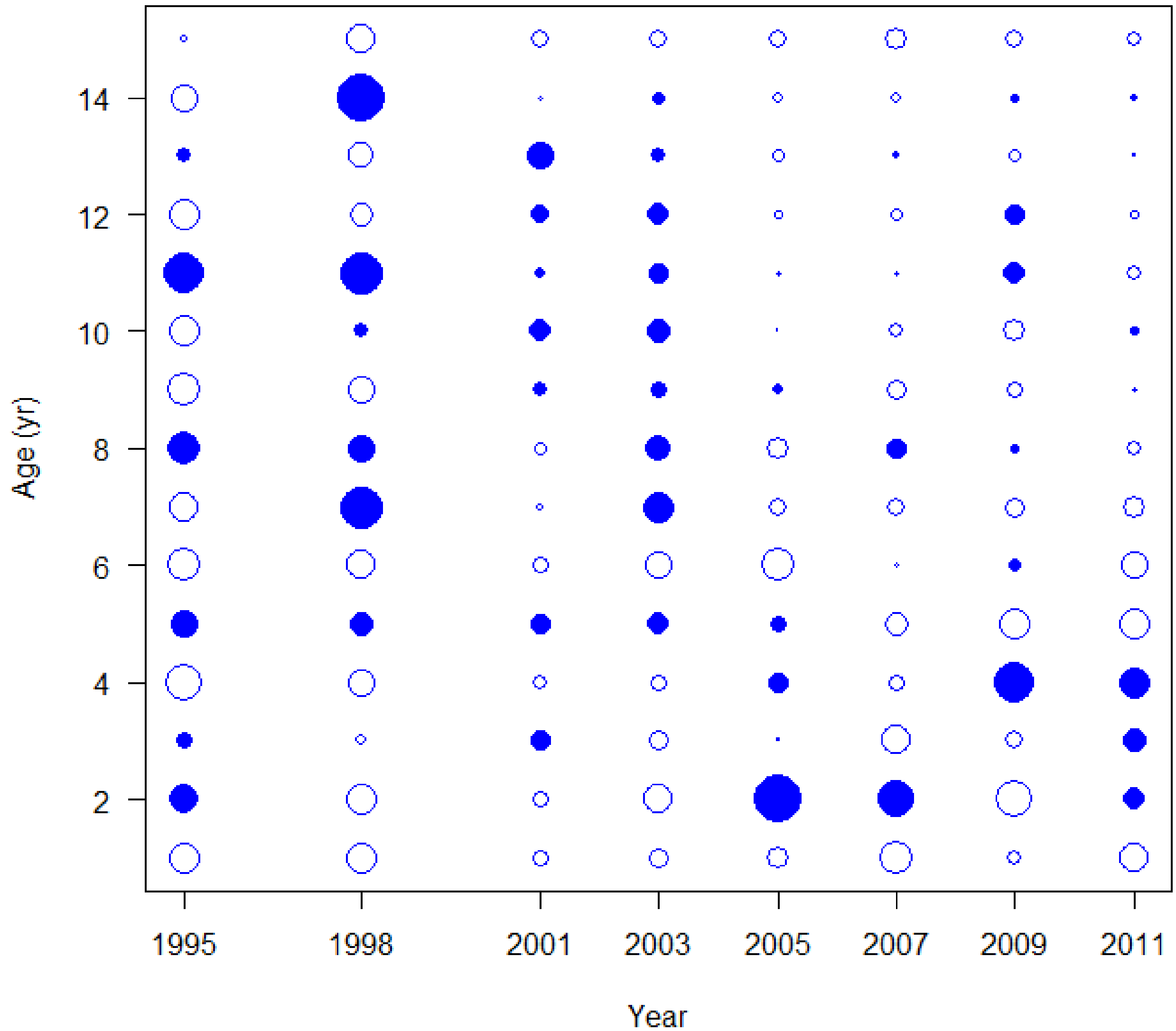


Figure 23. Pearson standardized residuals (observed - predicted) for base-case model fits to the acoustic survey age composition data. Maximum bubble size = 2.64; filled circles represent positive values.

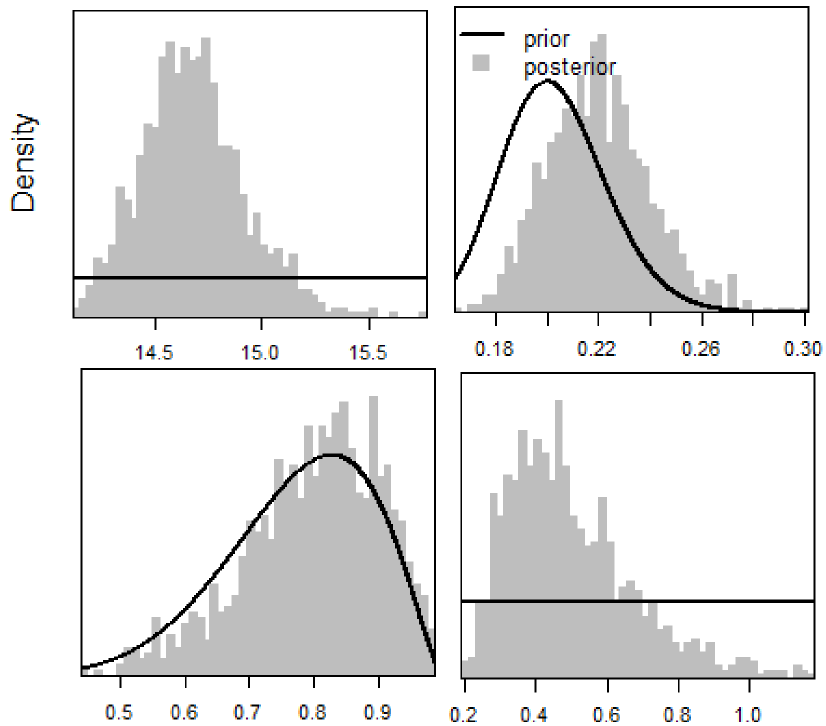


Figure 24. Prior and posterior probability distributions for key parameters in the base-case model. From the top left, the parameters are: ln(R_0), Natural mortality (M), steepness (h), and the additional process-error SD for the acoustic survey.

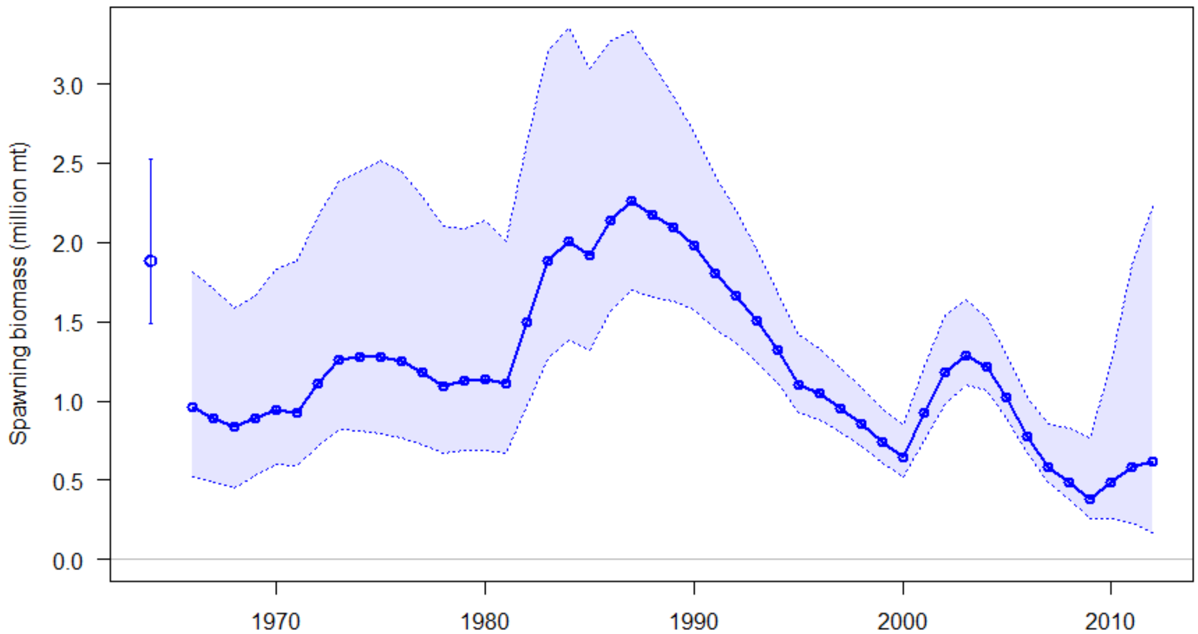


Figure 25. Posterior female spawning biomass time-series with 95% posterior credibility intervals.

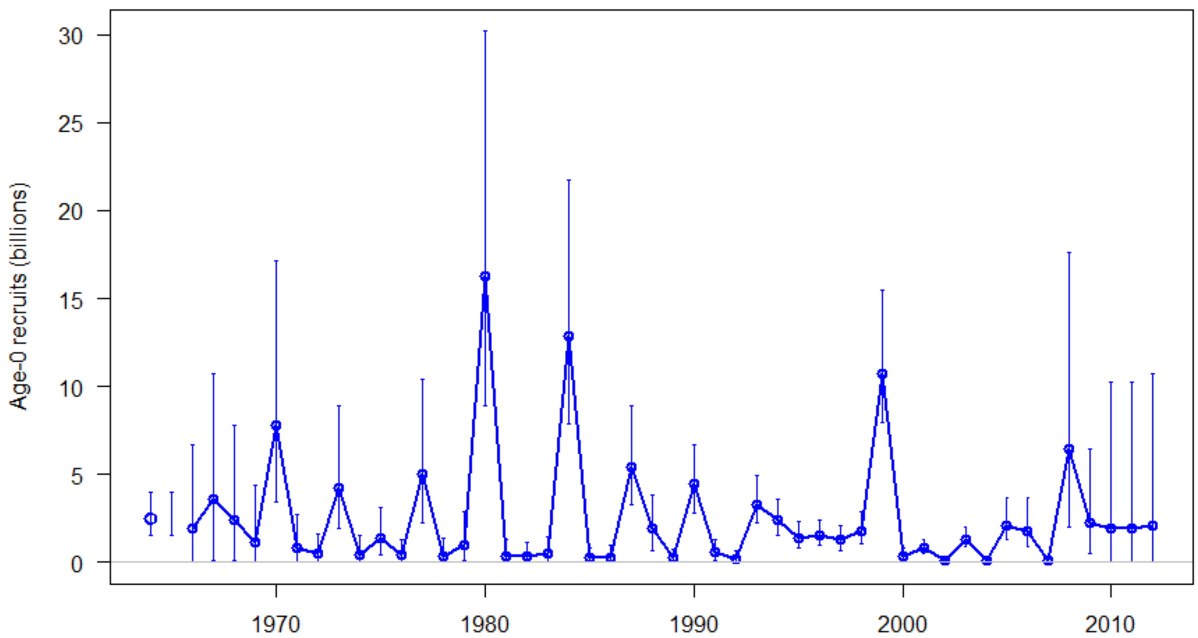


Figure 26. Posterior age-0 recruitment time-series for the base-case model with ~95% posterior credibility intervals.

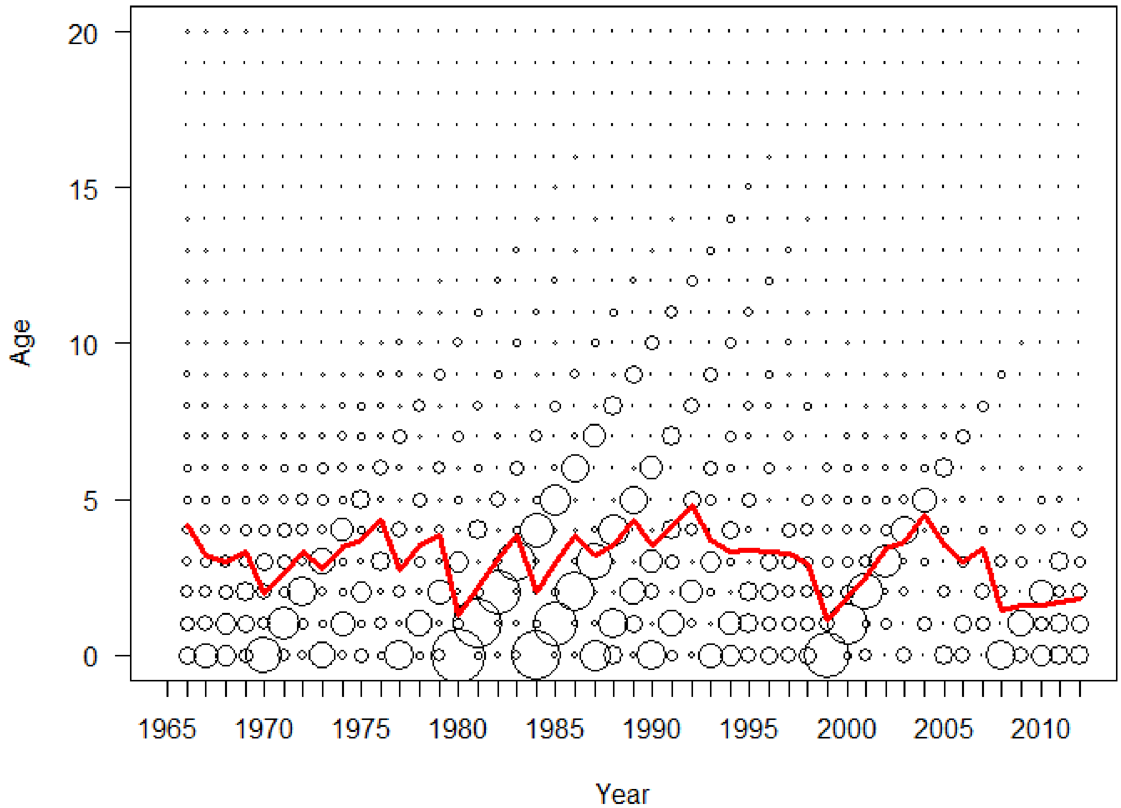


Figure 27. Estimated numbers at age (MLE) from the base-case model. Solid line indicates the average age during the time-series.

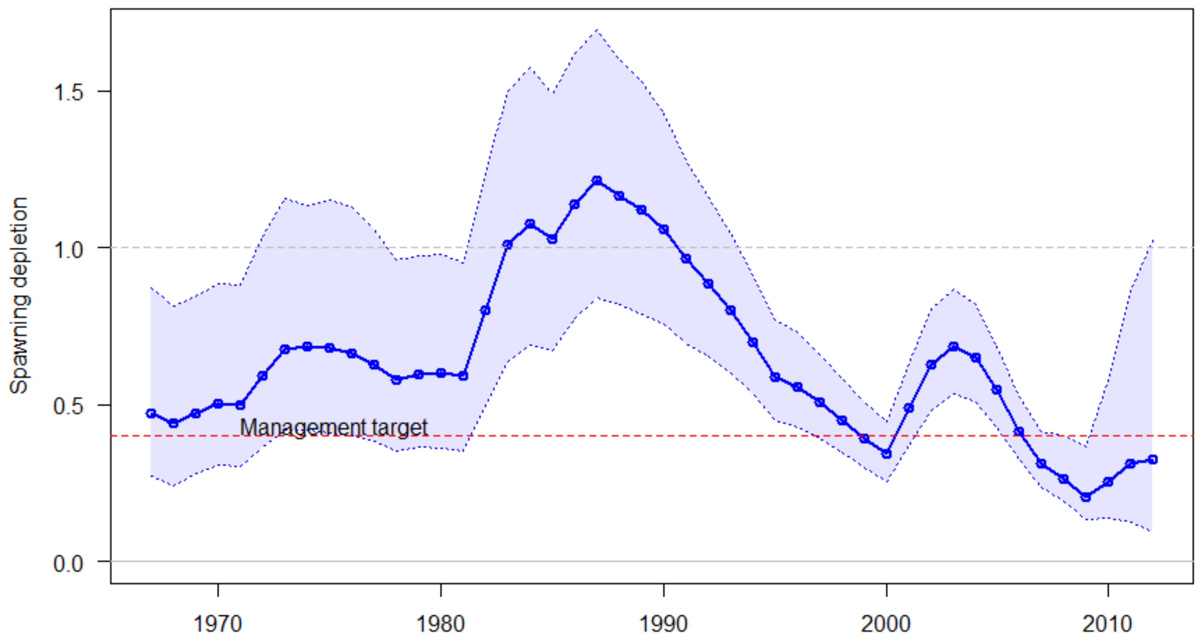


Figure 28. Time-series of posterior relative depletion for the base-case model.

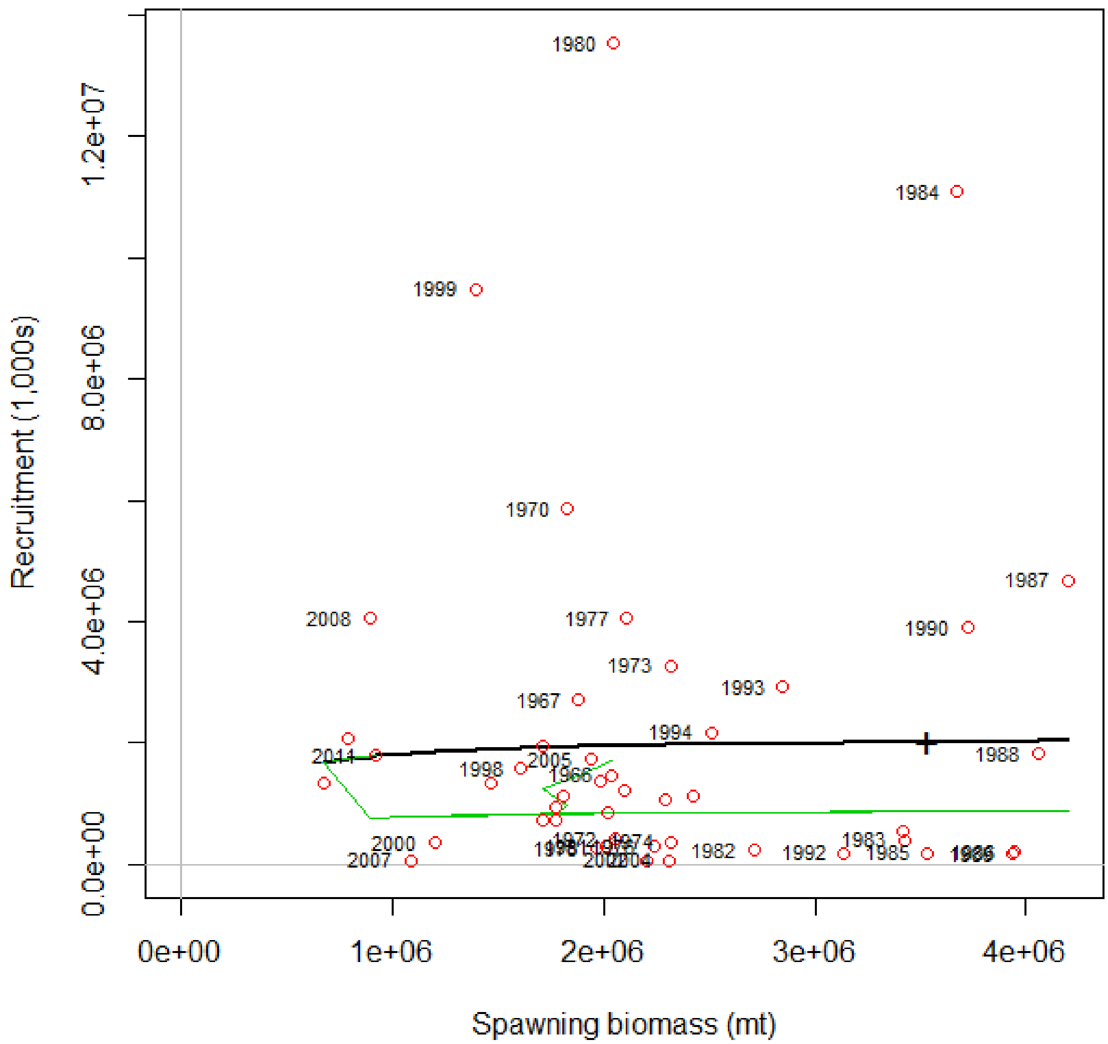


Figure 29. Estimated (MLE) stock-recruit relationship for the base-case model. The thick solid line indicates the central tendency, the thinner line the central tendency after bias correcting for the log-normal distribution.

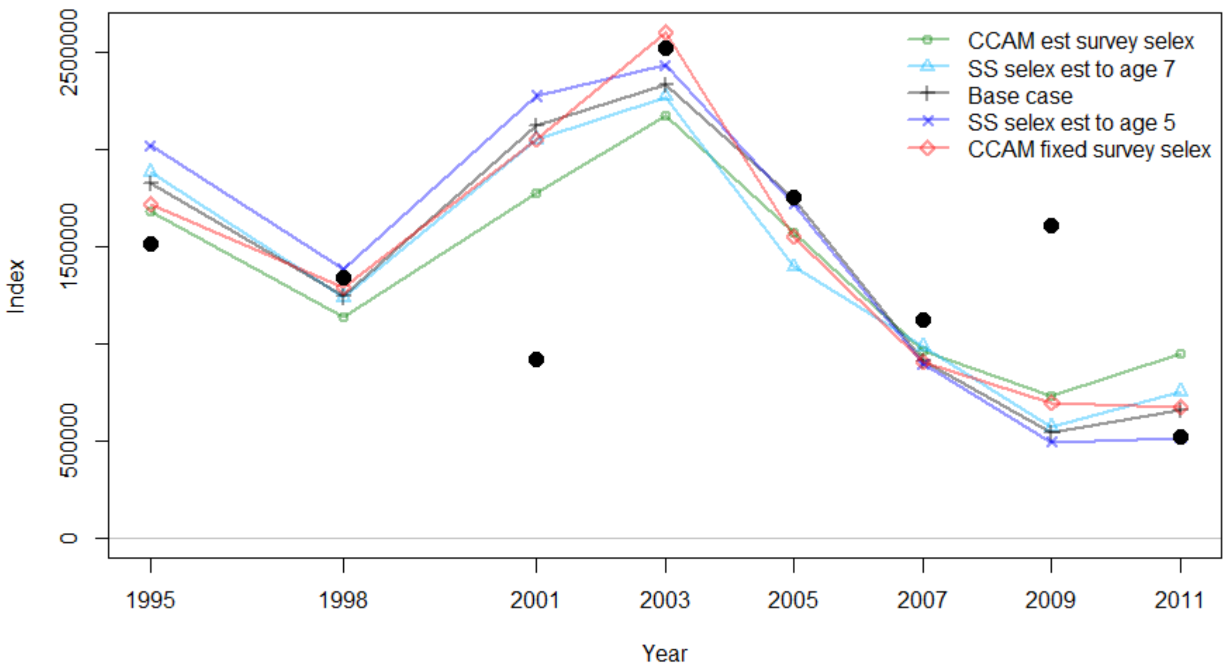


Figure 30. Comparison of fits to the acoustic survey index for alternate sensitivity models (based on MLE).

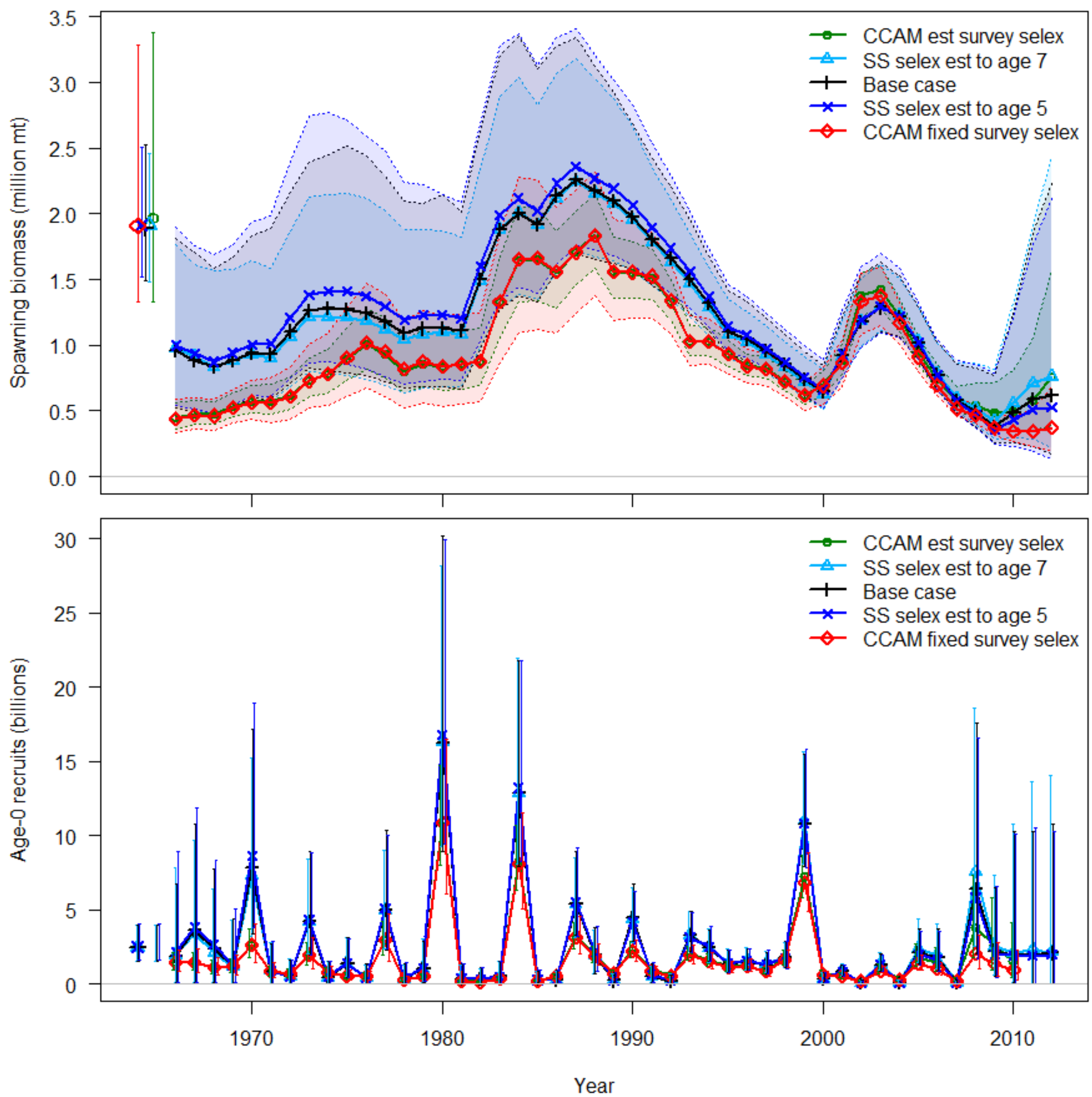


Figure 31. Comparison of results of alternate sensitivity models for spawning biomass (upper panel) and recruitment (lower panel).

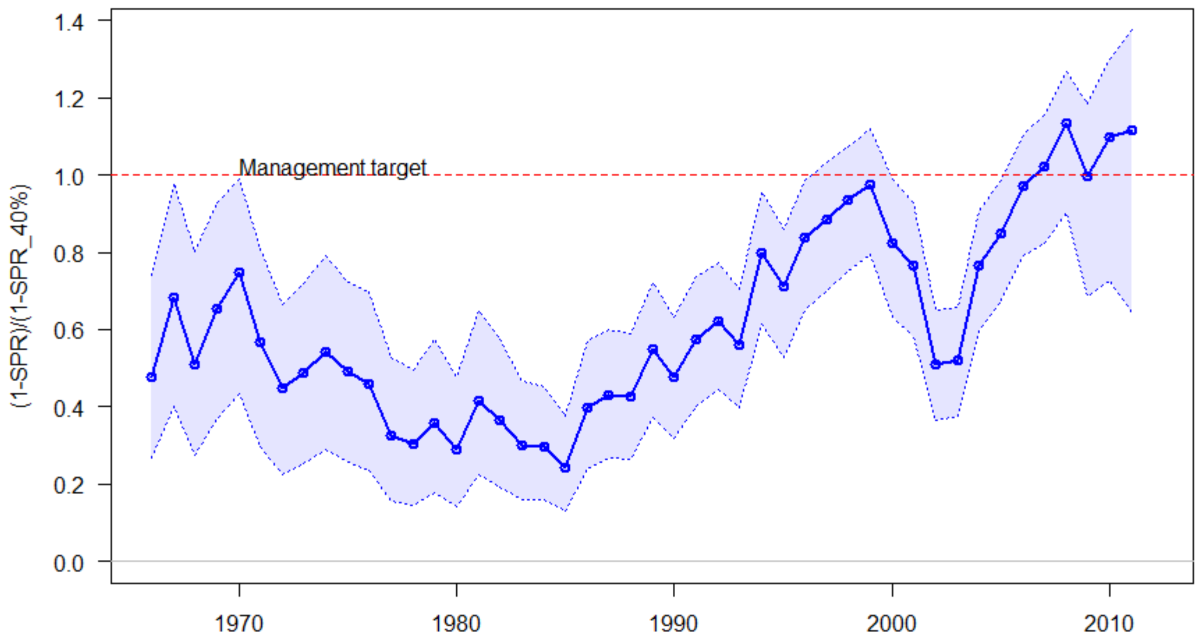


Figure 32. Trend in fishing intensity (relative SPR) through 2011.

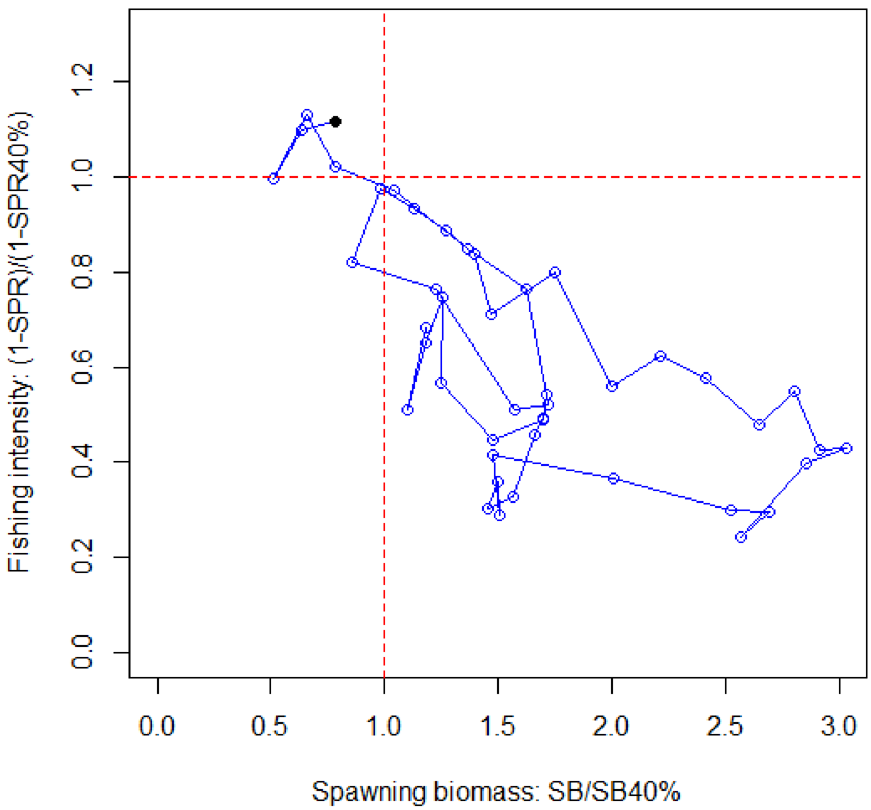


Figure 33. Temporal pattern (phase plot) of fishing intensity vs. relative spawning through 2011 for the base-case model. The filled circle denotes 2011 and the line connects years through the time-series.

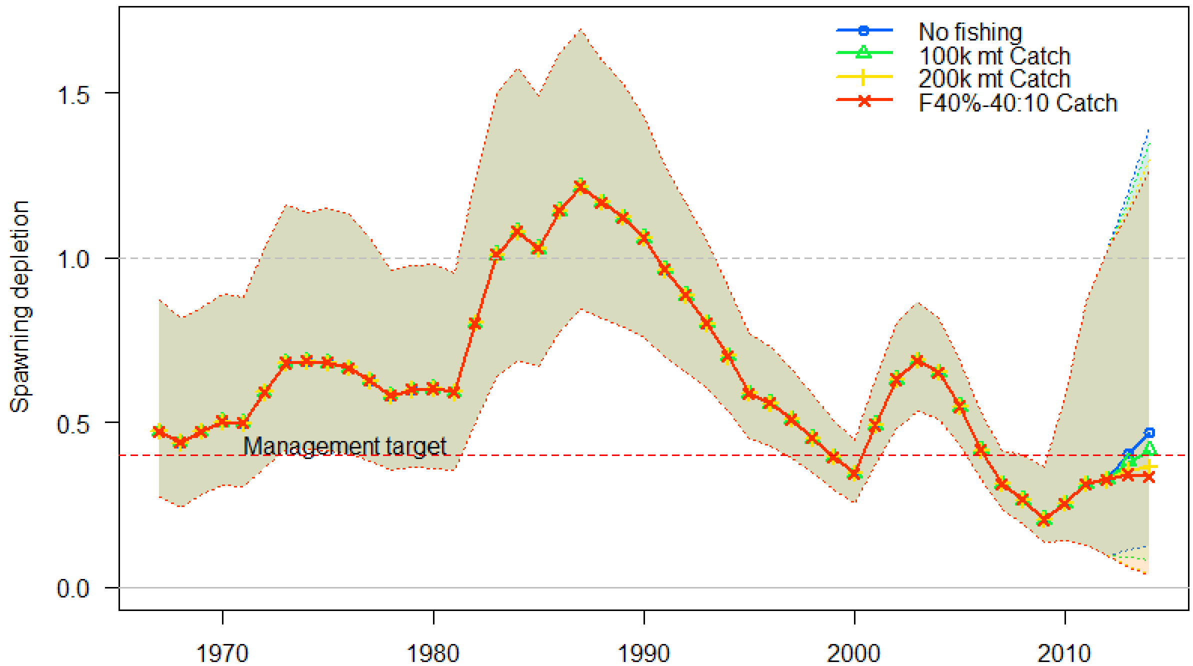


Figure 34. Time-series of estimated spawning depletion through 2012 from the base-case model, and forecast trajectories or several arbitrary management options from the decision table, with 95% posterior credibility intervals.

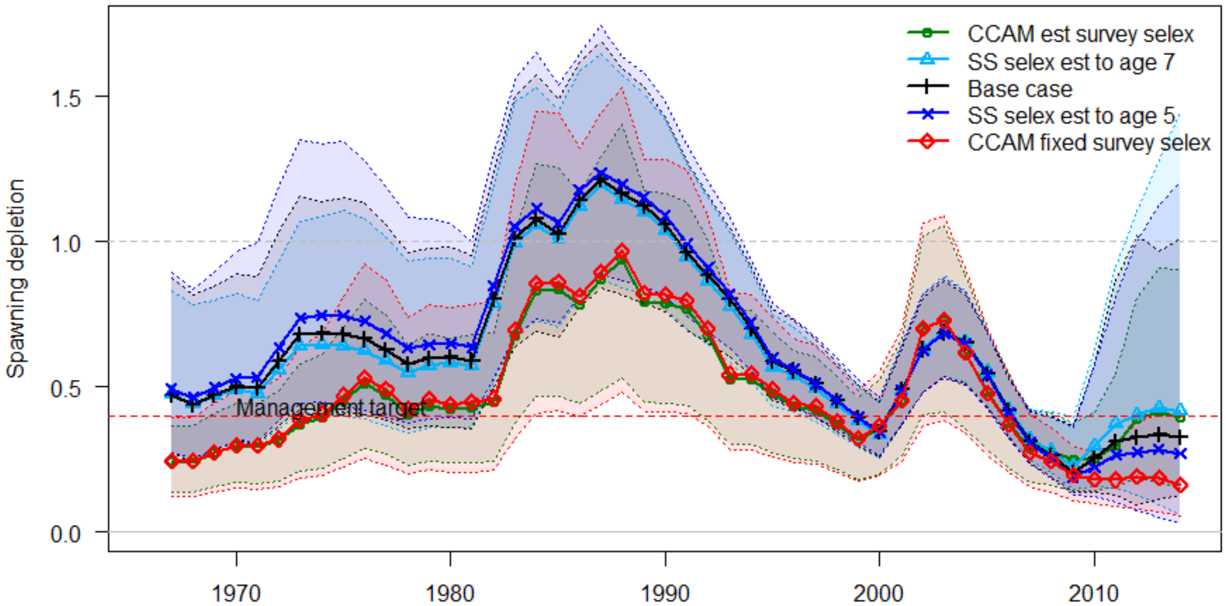


Figure 35. Time-series of estimated spawning depletion through 2012 from the base-case model, with 95% posterior credibility intervals, and among alternate sensitivity models, with forecast trajectories for the $F_{40\%}$-40:10 default harvest rate catch level from the base-case model.

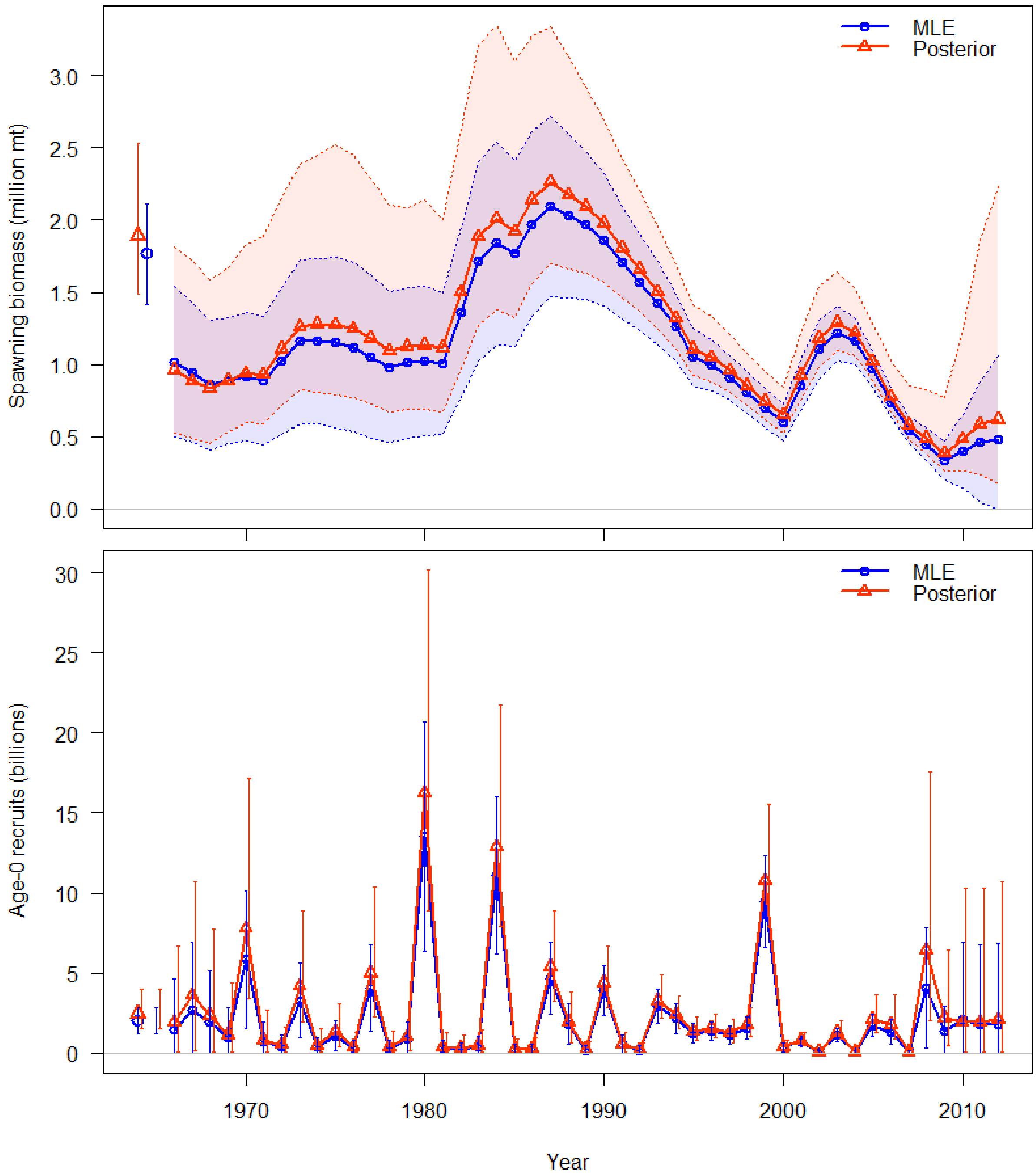


Figure 36. Comparison of maximum likelihood estimates and Bayesian posterior median results for spawning biomass (upper panel) and recruitment (lower panel) from the base-case model.

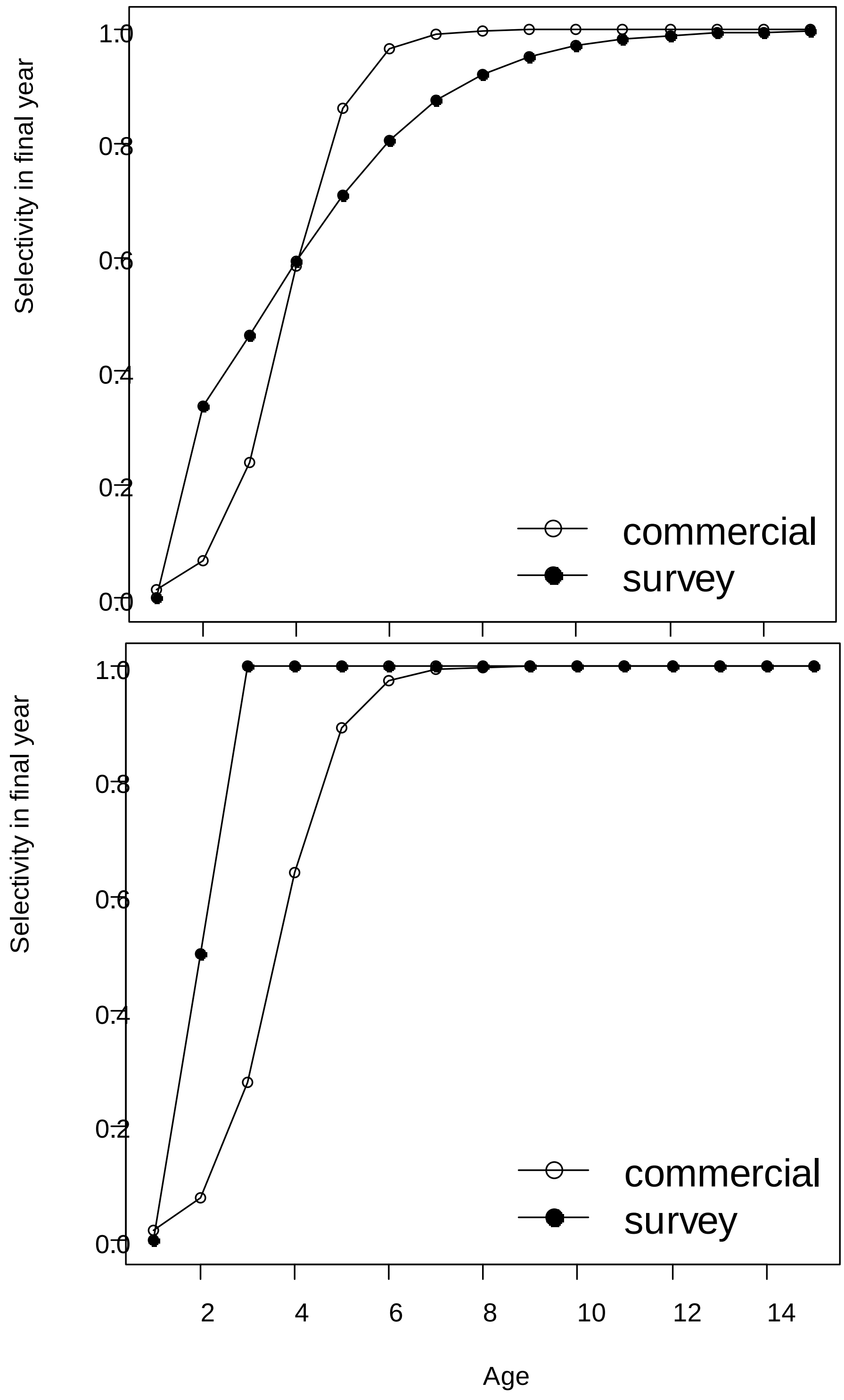


Figure 37. Selectivity curves for the alternate sensitivity models using CCAM showing: CCAM 'base case' (with survey selectivity parameters estimated; upper panel), and CCAM with survey selectivity parameters fixed (lower panel).

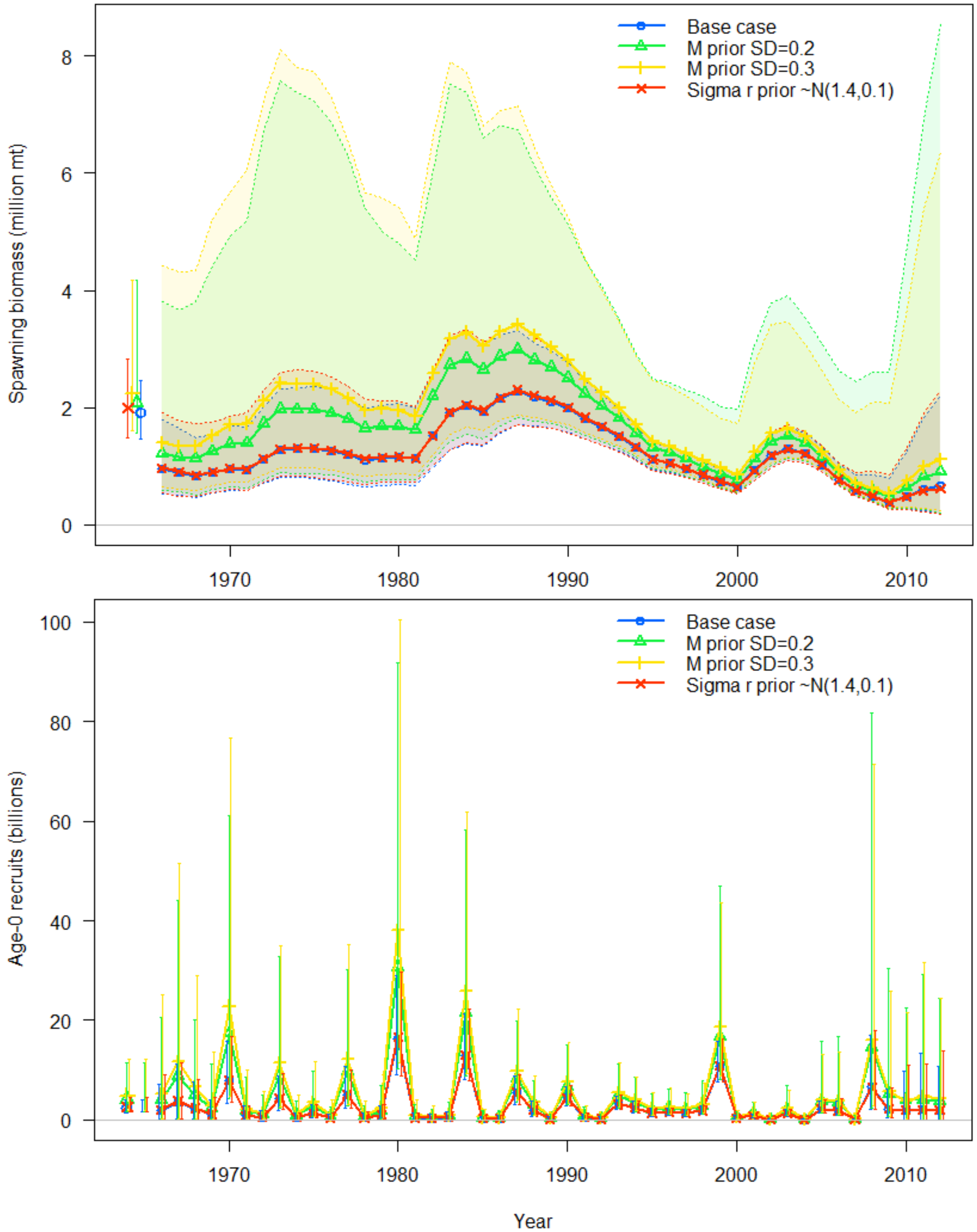


Figure 38. Results of sensitivity analysis to priors on natural mortality (*M*) and the degree of recruitment variability (σ_r). Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

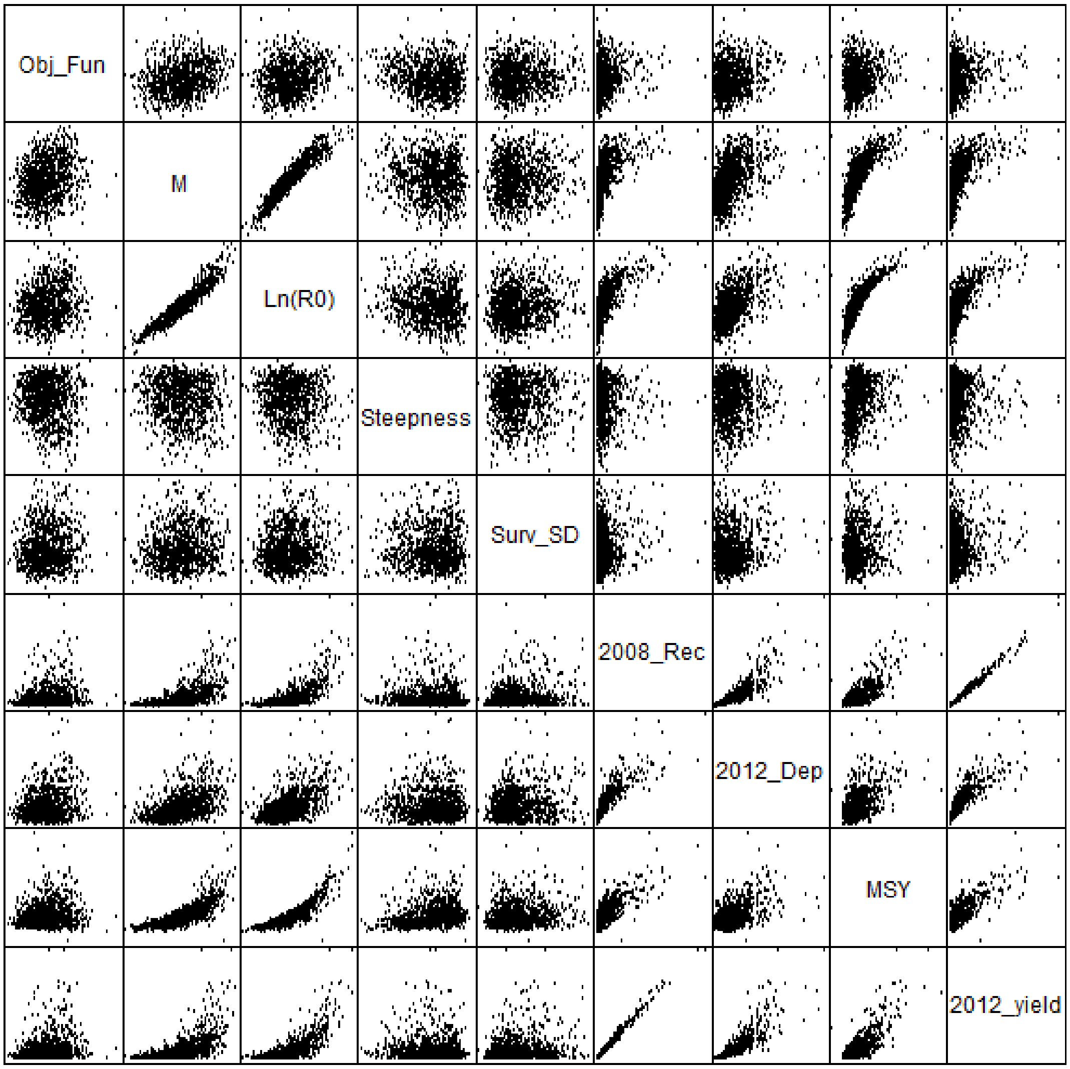


Figure 39. Posterior correlations among key model parameters and derived quantities for the sensitivity model with a weak prior (SD=0.3) on natural mortality. From the top left the posteriors plotted are: objective function, natural mortality, ln(R_0), steepness, the process-error SD for the acoustic survey, the 2008 recruitment deviation, the depletion level in 2012, the estimate of MSY and the default harvest rate yield for 2012. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

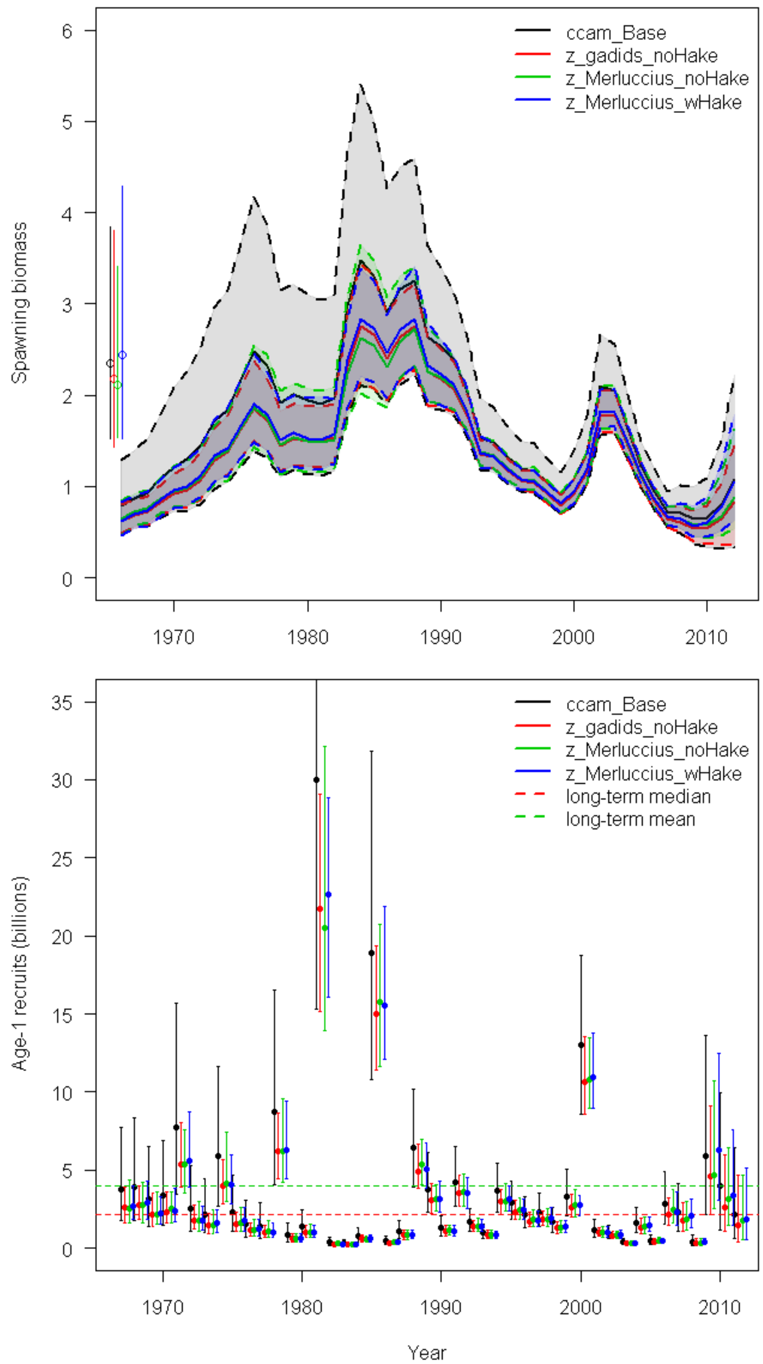


Figure 40. Results of sensitivity analysis for the CCAM model to the prior on steepness. For ccam_Base the prior was β(9.76,2.803); for z_gadids_noHake the prior was normal with mean=0.717, sd=0.0717; for z_Merluccius_NoHake the prior was normal with mean=0.673, sd=0.0673; for z_Merluccius wHake the prior was normal with mean=0.585, sd=0.0585. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

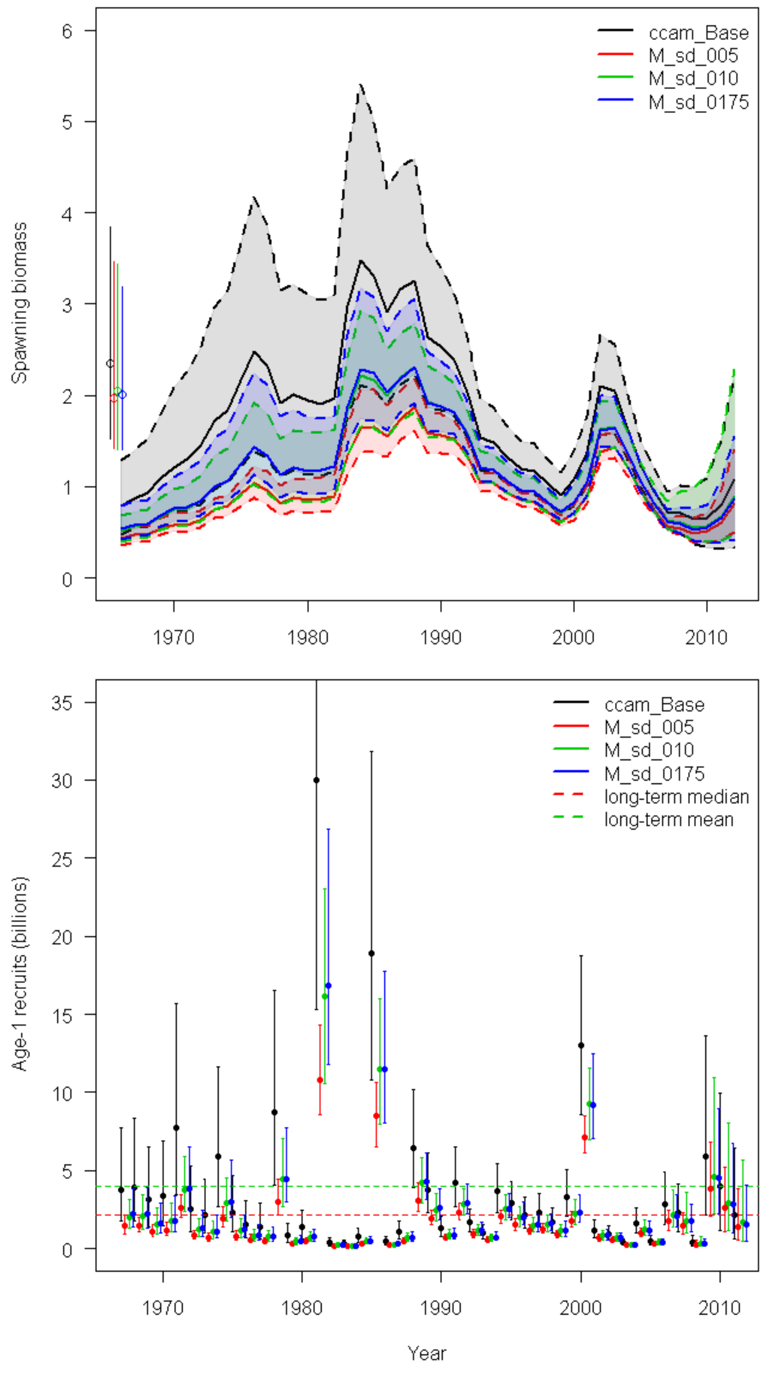


Figure 41. Results of sensitivity analysis for the CCAM model to the standard deviation of the prior on log(M) where the standard deviation on the prior for M was: 0.2 for the CCAM base case (ccam_Base), 0.05 for M_sd_005, 0.10 for M_sd_0.10 and 0.175 for M_sd_0.175. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

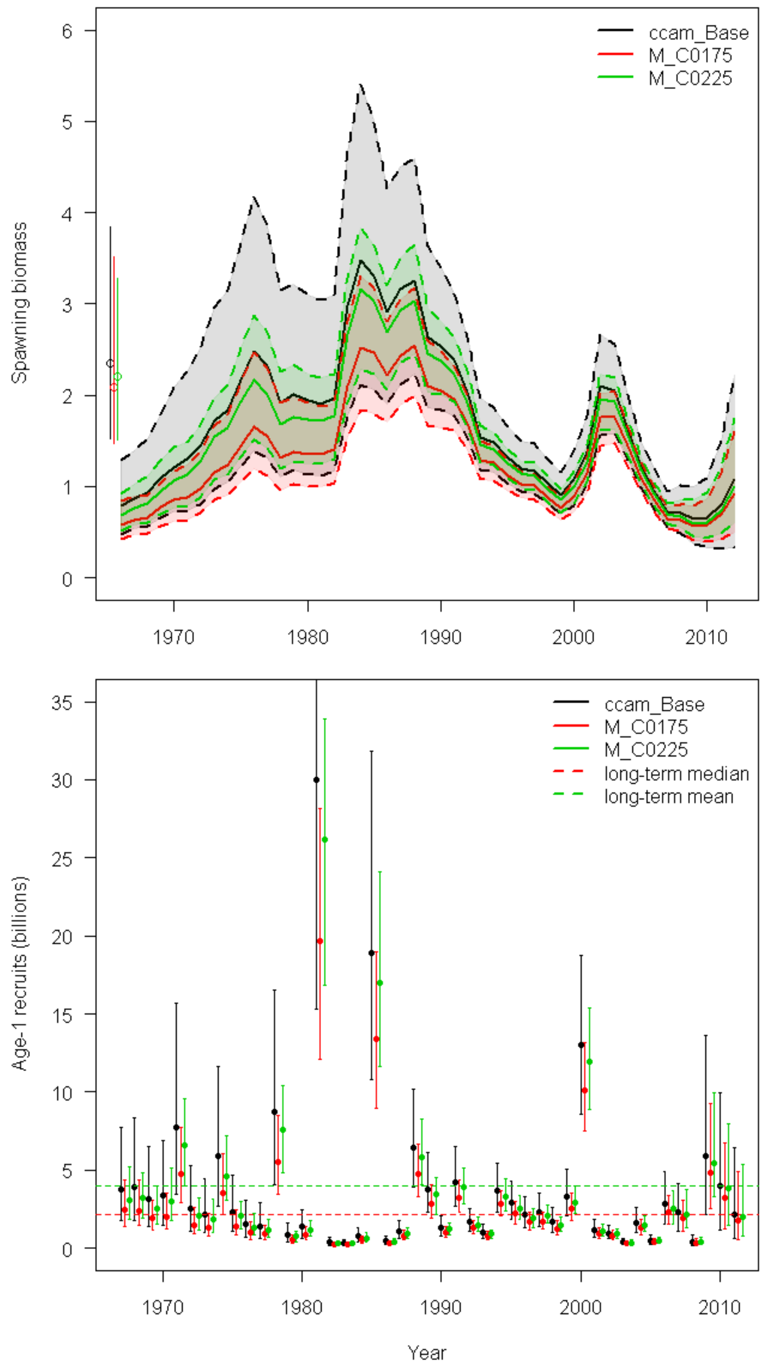


Figure 42. Results of sensitivity analysis for the CCAM model to mean of the prior on log(M) where the mean on the prior was: 0.2 for the CCAM base case (ccam_Base), 0.175 (M_C0175) and 0.225 (M_CO225). Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

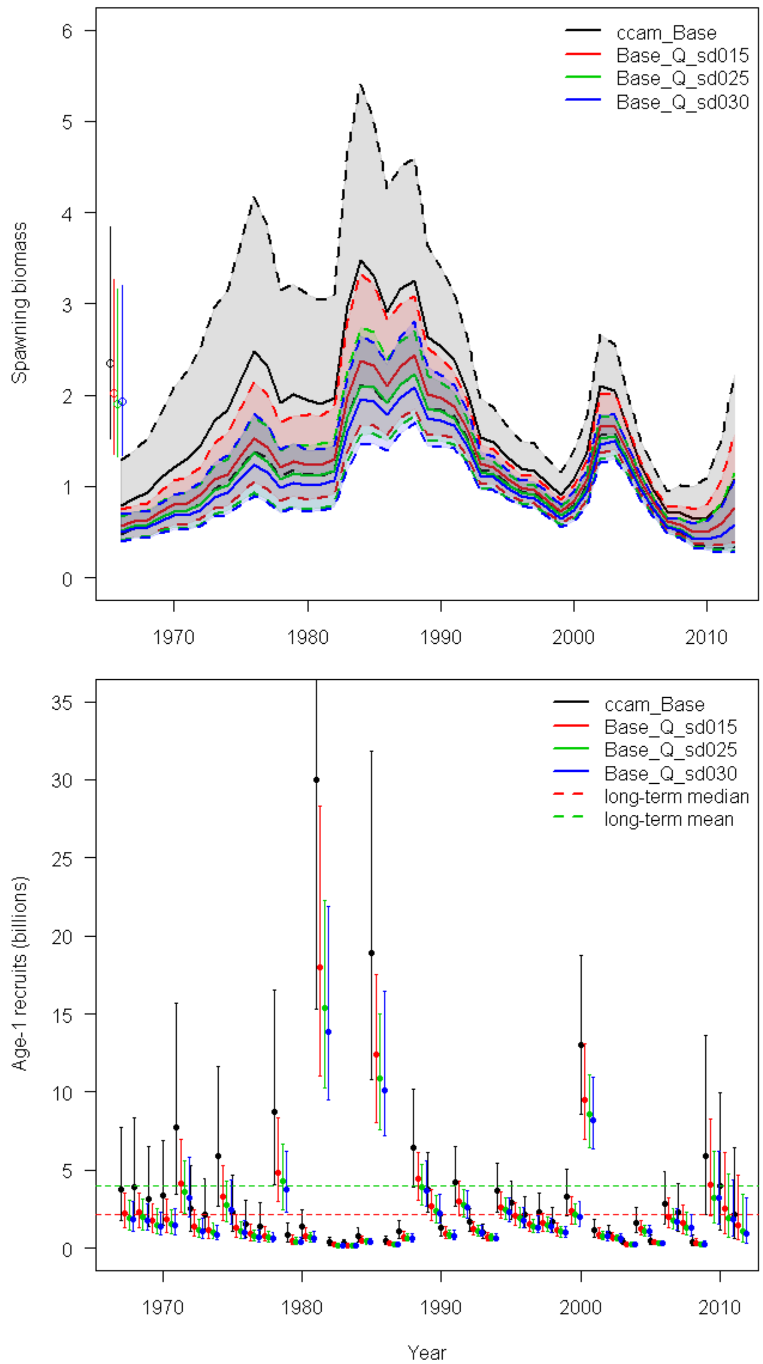


Figure 43. Results of sensitivity analysis for the CCAM model where prior standard deviation for survey q was: 0.1 for ccam_base, 0.15 for Base_Q_sd015, 0.25 for Base_Q_sd025, 0.3 for Base_Q_sd030. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting. Therefore, the CCAM base case is not reflective of the updated CCAM base case (see text).

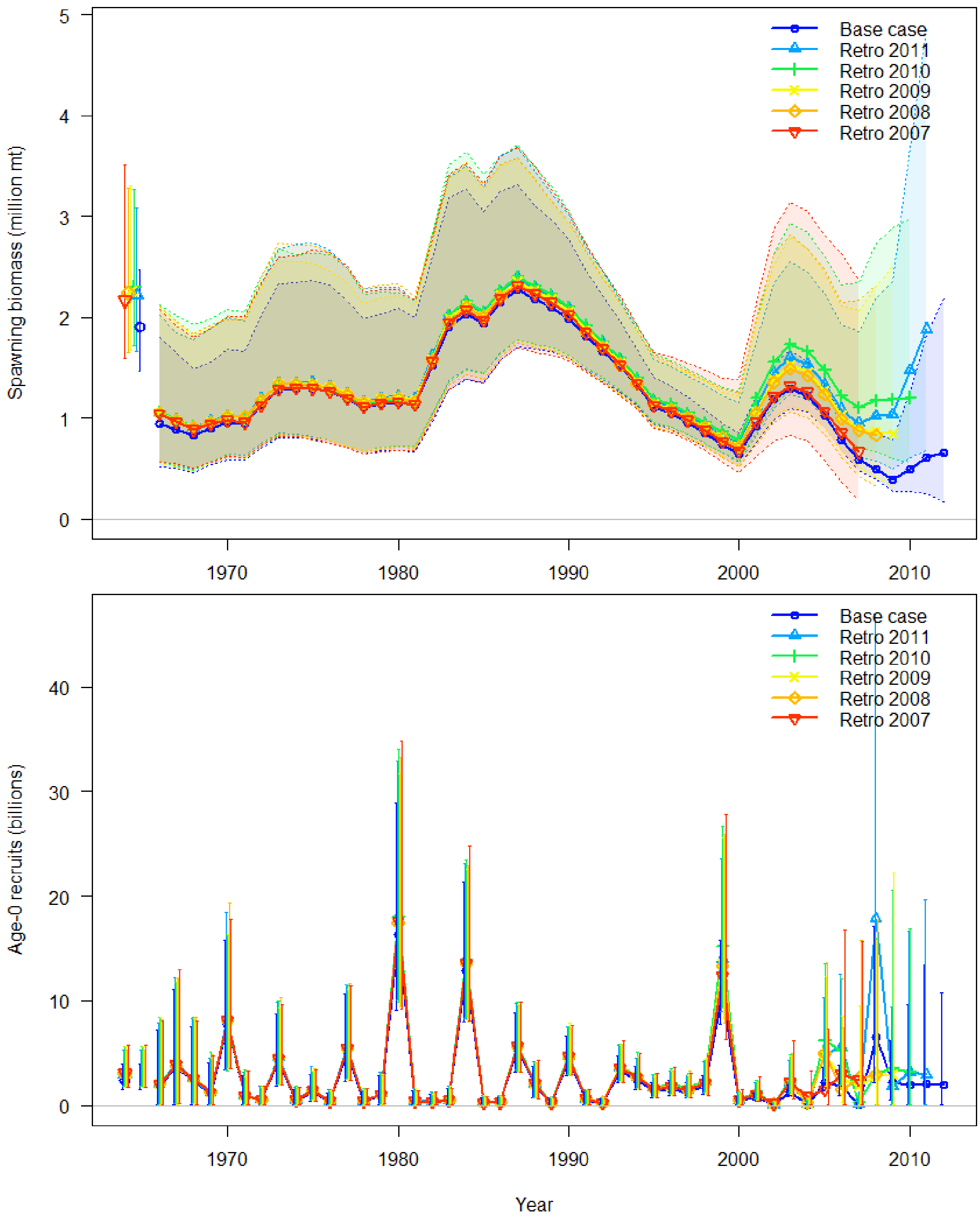


Figure 44. Retrospective pattern for the base-case model over the terminal years 2012 (base case) to 2007 as data from each terminal year are sequentially removed from the model. Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

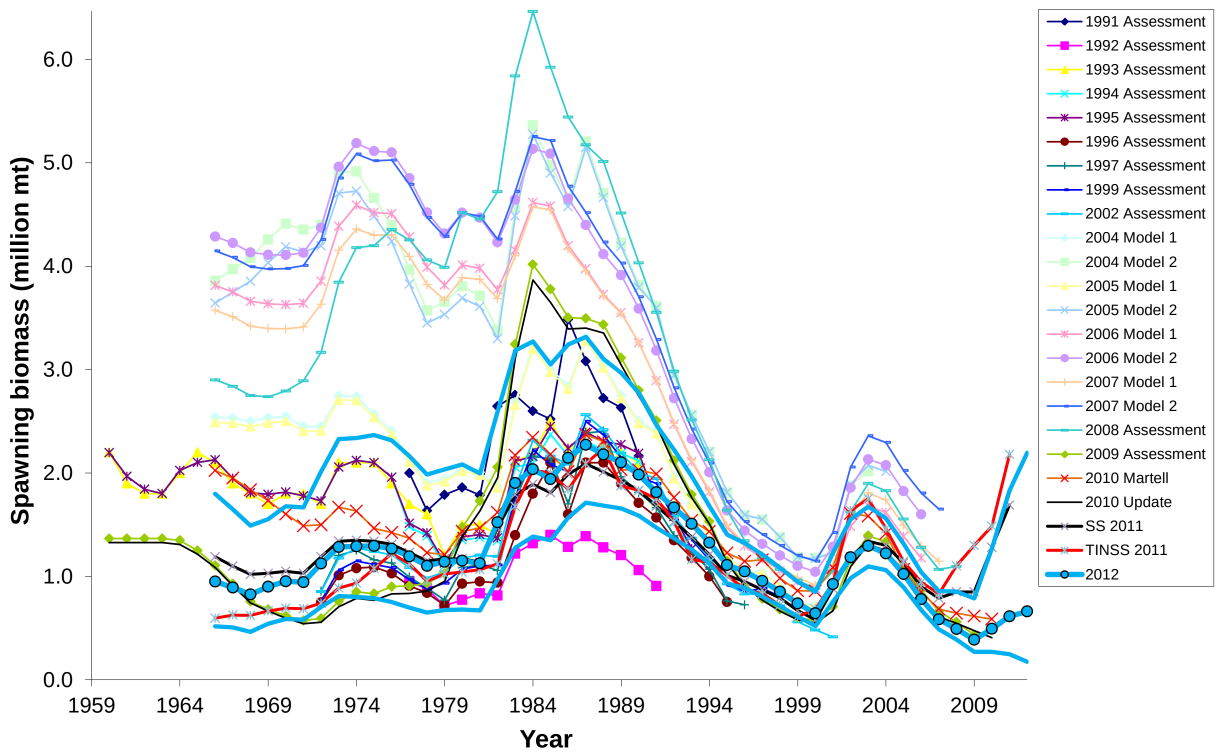


Figure 45. Posterior medians for the base-case model (thick blue line with ~95% credibility intervals) models in a retrospective comparing 2011 model results with previous stock assessments since 1991 (updates in 1998, 2000, 2001, 2003 are not included). Note that these results do not reflect the 2011 acoustic survey results revised during the SRG meeting.

8. Appendix A. List of terms and acronyms used in this document

Note: Many of these definitions are relevant to the historical management of Pacific hake and the U.S. Pacific Fishery Management Council process, and are included here only to improve interpretability of previous assessment and background documents.

40:10 Harvest control rule: The calculation leading to the ABC catch level (see below) for future years. This calculation decreases the catch linearly (given a constant age structure in the population) from the catch implied by the F_{MSY} (see below) harvest level when the stock declines below $SB_{40\%}$ (see below) to a value of 0 at $SB_{10\%}$.

40:10 Adjustment: an adjustment to the overall total allowable catch that is triggered when the biomass falls below 40% of its average equilibrium level in the absence of fishing. This adjustment reduces the total allowable catch on a straight-line basis from the 40% level such that the total allowable catch would equal zero when the stock is at 10% of its average equilibrium level in the absence of fishing.

ABC: Acceptable biological catch. See below.

Acceptable biological catch (ABC): The Acceptable biological catch is a scientific calculation of the sustainable harvest level of a fishery used historically to set the upper limit for fishery removals by the Pacific Fishery Management Council. It is calculated by applying the estimated (or proxy) harvest rate that produces maximum sustainable yield (MSY, see below) to the estimated exploitable stock biomass (the portion of the fish population that can be harvested). For Pacific hake, the calculation of the acceptable biological catch and application of the 40:10 adjustment is now replaced with the default harvest rate and the Total Allowable Catch.

Advisory Panel (AP): The advisory panel on Pacific Hake/Whiting established by the Agreement.

Agreement ("Treaty"): The Agreement between the government of the United States and the Government of Canada on Pacific hake/whiting, signed at Seattle, Washington, on November 21, 2003, and formally established in 2011.

AFSC: Alaska Fisheries Science Center (National Marine Fisheries Service)

Backscatter: The scattering by a target back in the direction of an acoustic source. Specifically, the Nautical Area Scattering Coefficient (a measure of scattering per area denoted by S_A) is frequently referred to as backscatter.

California Current Ecosystem: The waters of the continental shelf and slope off the west coast of North America; commonly referring to the area from central California to southern British Columbia.

Catchability: The parameter defining the proportionality between a relative index of stock abundance (often a fishery independent survey) and the estimated stock abundance available to that survey (as modified by selectivity) in the assessment model.

Catch-per-unit-effort: A raw or (frequently) standardized and model-based metric of fishing success based on the catch and relative effort expended to generate that catch. Catch-per-unit-effort is often used as an index of stock abundance in the absence of fishery independent indices and/or where the two are believed to be proportional. See CPUE below.

CCAM: Canadian Catch at Age Model. The model used for analysis of sensitivity to structural uncertainty. The model was developed at the University of British Columbia by Dr. Steven Martell, and customized by the JTC to calculate the outputs needed for this assessment. The model is fully described in Appendix F.

Cohort: A group of fish born in the same year. Also see recruitment and year-class.

CPUE: Catch-per-unit-effort. See above.

CV: Coefficient of variation. A measure of uncertainty defined as the standard deviation (SD, see below) divided by the mean.

Default harvest rate: The application of F-40 Percent with the 40:10 adjustment. Having considered any advice provided by the Joint Technical Committee, Scientific Review Group or Advisory Panel, the Joint Management Committee may recommend a different harvest rate if the scientific evidence demonstrates that a different rate is necessary to sustain the offshore hake/whiting resource.

Depletion: Abbreviated term for relative depletion (see below).

DFO: Fisheries and Oceans Canada. Federal organization which delivers programs and services that support sustainable use and development of Canada’s waterways and aquatic resources.

DOC: United States Department of Commerce. Parent organization of the National Marine Fisheries Service (NMFS).

El Niño: Abnormally warm ocean climate conditions in the California Current Ecosystem (see above) as a result of broad changes in the Eastern Pacific Ocean across the eastern coast of Latin America (centered on Peru) often around the end of the calendar year.

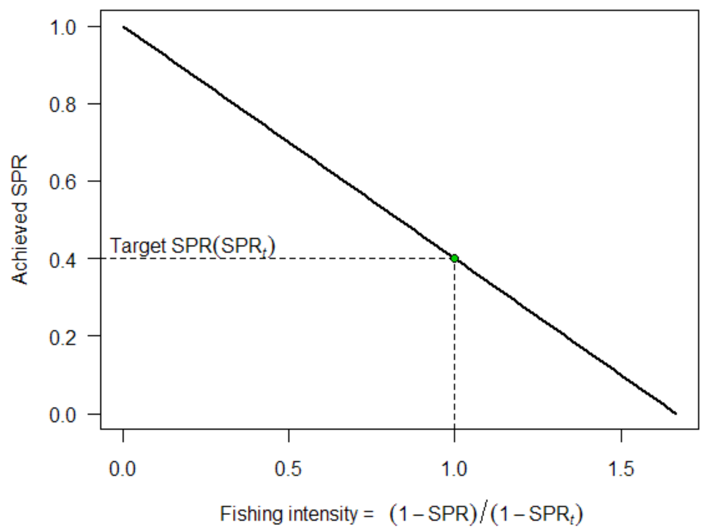
Exploitation fraction: A metric of fishing intensity that represents the total annual catch divided by the estimated population biomass over a range of ages assumed to be vulnerable to the fishery. This value is not equivalent to the instantaneous rate of fishing mortality (see below) or the Spawning Potential Ratio (*SPR*, see below).

F: Instantaneous rate of fishing mortality (or fishing mortality rate, see below).

$F_{40\%}$ (F-40 Percent): The rate of fishing mortality estimated to reduce the spawning potential ratio (SPR, see below) to 40%.

Female spawning biomass: The biomass of mature female fish at the beginning of the year. Occasionally, especially in reference points, this term is used to mean spawning output (expected egg production, see below) when this is not proportional to spawning biomass. See also spawning biomass.

Fishing intensity: A measure of the magnitude of fishing relative to a specified target. In this assessment it is defined as: relative SPR, or the ratio of (1-SPR) to (1-$SPR_{xx\%}$), where "*xx*" is the 40% proxy.



Fishing mortality rate, or instantaneous rate of fishing mortality (*F*): A metric of fishing intensity that is usually reported in reletion to the most highly selected ages(s) or length(s), or occasionally as an average over an age range that is vulnerable to the fishery. Because it is an instantaneous rate operating simultaneously with natural mortality, it is *not* equivalent to exploitation fraction (or percent annual removal; see above) or the Spawning Potential Ratio (*SPR*, see below).

F_{MSY}: The rate of fishing mortality estimated to produce the maximum sustainable yield from the stock.

Joint Management Committee (JMC): The joint management committee established by the Agreement.

Joint Technical Committee (JTC): The joint technical committee established by the Agreement.

Kt: Knots (nautical miles per hour).

Magnuson-Stevens Fishery Conservation and Management Act: The MSFCMA, sometimes known as the "Magnuson-Stevens Act," established the 200-mile fishery conservation zone, the regional fishery management council system, and other provisions of U.S. marine fishery law.

Maximum sustainable yield (*MSY*): An estimate of the largest average annual catch that can be continuously taken over a long period of time from a stock under prevailing ecological and environmental conditions.

MCMC: Markov-Chain Monte-Carlo. A numerical method used to sample from the posterior distribution (see below) of parameters and derived quantities in a Bayesian analysis.

MSY: Maximum sustainable yield. See above.

Mt: Metric ton(s). A unit of mass (often referred to as weight) equal to 1000 kilograms or 2,204.62 pounds.

NA: Not available.

National Marine Fisheries Service: A division of the U.S. Department of Commerce, National Ocean and Atmospheric Administration (NOAA). NMFS is responsible for conservation and management of offshore fisheries (and inland salmon).

NMFS: National Marine Fisheries Service. See above.

NOAA: National Oceanic and Atmospheric Administration. The parent agency of the National Marine Fisheries Service.

NORPAC: North Pacific Database Program. A database storing U.S. fishery observer data collected at sea.

NWFSC: Northwest Fisheries Science Center. A division of the NMFS located primarily in Seattle, Washington, but also in Newport, Oregon and other locations.

Optimum yield: The amount of fish that will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems. The OY is developed based on the acceptable biological catch from the fishery, taking into account relevant economic, social, and ecological factors. In the case of overfished fisheries, the OY provides for rebuilding to the target stock abundance.

OY: Optimum yield. See above.

PacFIN: Pacific Coast Fisheries Information Network. A database that provides a central repository for commercial fishery information from Washington, Oregon, and California.

PBS: Pacific Biological Station of Fisheries and Oceans Canada (DFO, see above).

Pacific Fishery Management Council (PFMC): The U.S. organization under which historical stock assessments for Pacific hake were conducted.

Pacific hake/whiting ("Pacific hake"): The stock of *Merluccius productus* located in the offshore waters of the United States and Canada (not including smaller stocks located in Puget Sound and the Strait of Georgia).

Posterior distribution: The probability distribution for parameters or derived quantities from a Bayesian model representing the prior probability distributions (see below) updated by the observed data via the likelihood equation. For stock assessments posterior distributions are approximated via numerical methods; one frequently employed method is MCMC (see above).

Prior distribution: Probability distribution for a parameter in a Bayesian analysis that represents the information available before evaluating the observed data via the likelihood equation. For some parameters noninformative priors can be constructed which allow the data to dominate the posterior distribution (see above). For others, informative priors can be constructed based on auxiliary information and/or expert knowledge or opinions.

q: Catchability. See above.

R_0: Estimated average level of annual recruitment occurring at SB_0 (see below).

Recruits/recruitment: A group of fish born in the same year or the estimated production of new members to a fish population of the same age. Recruitment is reported at a specific life stage, often age 0 or 1, but sometimes corresponding to the age at which the fish first become vulnerable to the fishery. See also cohort and year-class.

Recruitment deviation: The offset of the recruitment in a given year relative to the stock-recruit function; values occur on a log scale.

Relative depletion: The ratio of the estimated beginning of the year female spawning biomass to estimated average unfished equilibrium female spawning biomass (SB_0, see below).

Relative SPR: A measure of fishing intensity transformed to have an interpretation more like *F*: as fishing increases the metric increases. Relative SPR is the ratio of (1-SPR) to (1-$SPR_{xx\%}$), where "*xx*" is the proxy or estimated SPR rate that produces MSY.

SB_0: The estimated average unfished equilibrium female spawning biomass or spawning output if not directly proportional to spawning biomass.

$SB_{10\%}$: The level of female spawning biomass (output) corresponding to 10% of average unfished equilibrium female spawning biomass (SB_0, size of fish stock without fishing; see below). For many groundfish (including hake), this is the level at which the calculated catch based on the 40:10 harvest control rule (see above) is equal to 0.

$SB_{25\%}$: The level of female spawning biomass (output) corresponding to 25% of average unfished equilibrium female spawning biomass (SB_0, size of fish stock without fishing; see below). For many groundfish (including hake), this is the threshold below which the stock is designated as overfished.

$SB_{40\%}$: The level of female spawning biomass (output) corresponding to 40% of average unfished equilibrium female spawning biomass (SB_0, size of fish stock without fishing; see below). For many groundfish (including hake) this is the management target stock size and the proxy for SB_{MSY} (see below). This is also the Pacific Fishery Management Council's threshold for declaring a stock rebuilt if it has previously been designated as overfished.

SB_{MSY}: The estimated female spawning biomass (output) that produces the maximum sustainable yield (*MSY*). Also see $SB_{40\%}$.

Scientific Review Group (SRG): The scientific review group established by the Agreement.

Scientific and Statistical Committee (SSC): The scientific advisory committee to the PFMC. The Magnuson-Stevens Act requires that each council maintain an SSC to assist in gathering and analyzing statistical, biological, ecological, economic, social, and other scientific information that is relevant to the management of council fisheries.

SD: Standard deviation. A measure of uncertainty within a sample.

Spawning biomass: Abbreviated term for female spawning biomass (see above).

Spawning output: The total production of eggs (or possibly viable egg equivalents if egg quality is taken into account) given the number of females at age (and maturity and fecundity at age).

Spawning potential ratio (SPR): A metric of fishing intensity. The ratio of the spawning output per recruit under a given level of fishing to the estimated spawning output per recruit in the absence of fishing. It achieves a value of 1.0 in the absence of fishing and declines toward 0.0 as fishing intensity increases.

Spawning stock biomass (SSB): Alternative term for female spawning biomass (see above).

SPR: Spawning potential ratio. See above.

SPR_{MSY}: The estimated spawning potential ratio that produces the largest sustainable harvest (*MSY*).

$SPR_{40\%}$: The estimated spawning potential ratio that stabilizes the female spawning biomass at the MSY-proxy target of $SB_{40\%}$. Also referred to as $SPR_{MSY\text{-}proxy}$.

SS: One of two age-structured stock assessment models applied in this stock assessment analysis (Stock Synthesis; see also TINSS).

SSC: Scientific and Statistical Committee (see above).

STAR Panel: Stock Assessment Review Panel. A panel set up to provide independent review of all stock assessments used by the Pacific Fishery Management Council.

STAT: Stock Assessment Team. The individuals preparing the scientific analysis leading to, and including, stock assessments submitted to the Pacific Fishery Management Council's review process.

Steepness (*h*): A stock-recruit relationship parameter representing the proportion of R_0 expected (on average) when the female spawning biomass is reduced to 20% of SB_0 (i.e., when relative depletion is equal to 20%). This parameter can be thought of one important component to the productivity of the stock.

Target strength: The amount of backscatter from an individual acoustic target.

TINSS: One of two age-structured stock assessment models applied in the 2011 stock assessment analysis (This Is Not Stock Synthesis; see also SS).

Total Allowable Catch (TAC): The maximum fishery removal under the terms of the Agreement.

Total Biomass: Aggregate biomass of all individual fish in the stock regardless of age or sex.

U.S./Canadian allocation: The division of the total allowable catch of - 73.88% as the United States' share and 26.12% as the Canadian share.

Vulnerable biomass: The demographic portion of the stock available for harvest by the fishery.

Year-class: A group of fish born in the same year. See also cohort and recruitment.

9. Appendix B. List of all estimated parameters in the SS model

Parameter	Posterior median
NatM_p_1_Fem_GP_1	0.22
SR_R0	14.66
SR_steep	0.81
Early_InitAge_20	-0.20
Early_InitAge_19	-0.04
Early_InitAge_18	-0.01
Early_InitAge_17	-0.02
Early_InitAge_16	-0.04
Early_InitAge_15	-0.15
Early_InitAge_14	-0.12
Early_InitAge_13	-0.13
Early_InitAge_12	-0.17
Early_InitAge_11	-0.17
Early_InitAge_10	-0.27
Early_InitAge_9	-0.30
Early_InitAge_8	-0.31
Early_InitAge_7	-0.31
Early_InitAge_6	-0.45
Early_InitAge_5	-0.34
Early_InitAge_4	-0.38
Early_InitAge_3	-0.36
Early_InitAge_2	-0.09
Early_InitAge_1	0.20
Early_RecrDev_1966	0.42
Early_RecrDev_1967	1.33
Early_RecrDev_1968	0.84
Early_RecrDev_1969	-0.01
Main_RecrDev_1970	2.17
Main_RecrDev_1971	-0.26
Main_RecrDev_1972	-0.74
Main_RecrDev_1973	1.50
Main_RecrDev_1974	-0.89
Main_RecrDev_1975	0.37
Main_RecrDev_1976	-1.02
Main_RecrDev_1977	1.69
Main_RecrDev_1978	-1.19
Main_RecrDev_1979	-0.02
Main_RecrDev_1980	2.91
Main_RecrDev_1981	-1.15
Main_RecrDev_1982	-1.30

Parameter	Posterior median
Main_RecrDev_1983	-0.83
Main_RecrDev_1984	2.64
Main_RecrDev_1985	-1.66
Main_RecrDev_1986	-1.52
Main_RecrDev_1987	1.78
Main_RecrDev_1988	0.74
Main_RecrDev_1989	-1.63
Main_RecrDev_1990	1.59
Main_RecrDev_1991	-0.56
Main_RecrDev_1992	-1.61
Main_RecrDev_1993	1.30
Main_RecrDev_1994	1.01
Main_RecrDev_1995	0.47
Main_RecrDev_1996	0.59
Main_RecrDev_1997	0.40
Main_RecrDev_1998	0.76
Main_RecrDev_1999	2.58
Main_RecrDev_2000	-0.81
Main_RecrDev_2001	-0.03
Main_RecrDev_2002	-2.58
Main_RecrDev_2003	0.40
Main_RecrDev_2004	-2.60
Main_RecrDev_2005	0.88
Main_RecrDev_2006	0.71
Main_RecrDev_2007	-2.40
Late_RecrDev_2008	1.99
Late_RecrDev_2009	0.94
Late_RecrDev_2010	0.26
Late_RecrDev_2011	0.00
Q_extraSD_2_Acoustic_Survey	0.46
AgeSel_1P_3_Fishery	2.98
AgeSel_1P_4_Fishery	1.60
AgeSel_1P_5_Fishery	0.53
AgeSel_1P_6_Fishery	0.16
AgeSel_1P_7_Fishery	0.23
AgeSel_2P_4_Acoustic_Survey	0.08
AgeSel_2P_5_Acoustic_Survey	0.27
AgeSel_2P_6_Acoustic_Survey	-0.08
AgeSel_2P_7_Acoustic_Survey	0.45

10. Appendix C. SS model input files

```
# 2012 Hake data file

########################################

### Global model specifications ###
1966     # Start year
2011     # End year
1        # Number of seasons/year
12       # Number of months/season
1        # Spawning occurs at beginning of season
1        # Number of fishing fleets
1        # Number of surveys
1        # Number of areas
Fishery%Acoustic_Survey
0.5 0.5 # fleet timing_in_season
1 1      # Area of each fleet
1        # Units for catch by fishing fleet: 1=Biomass(mt),2=Numbers(1000s)
0.01     # SE of log(catch) by fleet for equilibrium and continuous options
1        # Number of genders
20       # Number of ages in population dynamics

### Catch section ###
0  # Initial equilibrium catch (landings + discard) by fishing fleet

46 # Number of lines of catch
# Catch Year Season
137700   1966   1
214370   1967   1
122180   1968   1
180130   1969   1
234590   1970   1
154620   1971   1
117540   1972   1
162640   1973   1
211260   1974   1
221350   1975   1
237520   1976   1
132690   1977   1
103640   1978   1
137110   1979   1
89930    1980   1
139120   1981   1
107741   1982   1
113931   1983   1
138492   1984   1
110399   1985   1
210616   1986   1
234148   1987   1
248840   1988   1
298079   1989   1
261286   1990   1
319710   1991   1
299687   1992   1
198924   1993   1
362422   1994   1
249644   1995   1
306383   1996   1
325257   1997   1
320815   1998   1
311844   1999   1
228214   2000   1
227531   2001   1
180698   2002   1
205177   2003   1
```

```
338654    2004    1
363157    2005    1
361761    2006    1
291129    2007    1
322145    2008    1
177459    2009    1
226202    2010    1
286055    2011    1

8 # Number of index observations
# Units: 0=numbers,1=biomass,2=F; Errortype: -1=normal,0=lognormal,>0=T
# Fleet Units Errortype
1 1 0 # Fishery
2 1 0 # Acoustic Survey

# Year seas index obs se(log)
# Acoustic survey
1995    1    2    1517948    0.0666
1998    1    2    1342740    0.0492
2001    1    2    918622     0.0823
2003    1    2    2520641    0.0709
2005    1    2    1754722    0.0847
2007    1    2    1122809    0.0752
2009    1    2    1612027    0.1375
2011    1    2    521476  0.1015

0 #_N_fleets_with_discard
0 #_N_discard_obs
0 #_N_meanbodywt_obs
30 #_DF_for_meanbodywt_T-distribution_like

## Population size structure
2 # Length bin method: 1=use databins; 2=generate from binwidth,min,max below;
2 # Population length bin width
10 # Minimum size bin
70 # Maximum size bin

-1       # Minimum proportion for compressing tails of observed compositional data
0.001    # Constant added to expected frequencies
0        # Combine males and females at and below this bin number

26 # Number of Data Length Bins
# Lower edge of bins
20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70
0 #_N_Length_obs

15 #_N_age_bins
# Age bins
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

39 # N_ageerror_definitions
# Annual keys with cohort effect
0.5       1.5       2.5       3.5       4.5       5.5       6.5       7.5       8.5       9.5       10.5      11.5      12.5
          13.5      14.5      15.5      16.5      17.5      18.5      19.5      20.5
0.329242  0.329242  0.346917  0.368632  0.395312  0.42809   0.468362  0.517841  0.57863   0.653316  0.745076  0.857813  0.996322
          1.1665    1.37557   1.63244   1.858     2.172     2.53      2.934     3.388
0.5       1.5       2.5       3.5       4.5       5.5       6.5       7.5       8.5       9.5       10.5      11.5      12.5
          13.5      14.5      15.5      16.5      17.5      18.5      19.5      20.5
0.329242  0.329242  0.346917  0.368632  0.395312  0.42809   0.468362  0.517841  0.57863   0.653316  0.745076  0.857813  0.996322
          1.1665    1.37557   1.63244   1.858     2.172     2.53      2.934     3.388
0.5       1.5       2.5       3.5       4.5       5.5       6.5       7.5       8.5       9.5       10.5      11.5      12.5
          13.5      14.5      15.5      16.5      17.5      18.5      19.5      20.5
0.329242  0.329242  0.346917  0.368632  0.395312  0.42809   0.468362  0.517841  0.57863   0.653316  0.745076  0.857813  0.996322
          1.1665    1.37557   1.63244   1.858     2.172     2.53      2.934     3.388
0.5       1.5       2.5       3.5       4.5       5.5       6.5       7.5       8.5       9.5       10.5      11.5      12.5
          13.5      14.5      15.5      16.5      17.5      18.5      19.5      20.5
```

0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.1810831	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.19080435		0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813
	0.996322	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.2027476	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.2174216	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.1810831	0.346917	0.368632	0.395312	0.2354495	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.19080435		0.368632	0.395312	0.42809	0.2575991	0.517841	0.57863	0.653316	0.745076	0.857813
	0.996322	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.2027476	0.395312	0.42809	0.468362	0.28481255		0.57863	0.653316	0.745076	0.857813
	0.996322	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.2174216	0.42809	0.468362	0.517841	0.3182465	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.2354495	0.468362	0.517841	0.57863	0.3593238	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.2575991	0.517841	0.57863	0.653316	0.4097918	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.28481255		0.57863	0.653316	0.745076	
	0.47179715		0.996322	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388	
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.3182465	0.653316	0.745076	0.857813	0.5479771
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				

0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.3593238	0.745076	0.857813	0.996322
	0.641575	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.4097918	0.857813	0.996322
	1.1665	0.7565635	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.47179715	
	0.996322	1.1665	1.37557	0.897842	1.858	2.172	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.5479771
	1.1665	1.37557	1.63244	1.0219	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	0.641575	1.37557	1.63244	1.858	1.1946	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	0.7565635	1.63244	1.858	2.172	1.3915	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	0.897842	1.858	2.172	2.53	1.6137	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.1810831	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.0219	2.172	2.53	2.934	1.8634				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.19080435		0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813
	0.996322	1.1665	1.37557	1.63244	1.858	1.1946	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.2027476	0.395312	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	1.3915	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.2174216	0.42809	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	1.6137	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.2354495	0.468362	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	1.8634				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.2575991	0.517841	0.57863	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.28481255		0.57863	0.653316	0.745076	0.857813
	0.996322	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388			
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.3182465	0.653316	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				
0.329242	0.329242	0.346917	0.368632	0.395312	0.42809	0.468362	0.517841	0.57863	0.3593238	0.745076	0.857813	0.996322
	1.1665	1.37557	1.63244	1.858	2.172	2.53	2.934	3.388				
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5				

0.329242 0.1810831 0.346917 0.368632 0.395312 0.42809 0.468362 0.517841 0.57863 0.653316 0.4097918 0.857813 0.996322
1.1665 1.37557 1.63244 1.858 2.172 2.53 2.934 3.388
0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5 11.5 12.5
13.5 14.5 15.5 16.5 17.5 18.5 19.5 20.5
0.329242 0.329242 0.19080435 0.368632 0.395312 0.42809 0.468362 0.517841 0.57863 0.653316 0.745076
0.47179715 0.996322 1.1665 1.37557 1.63244 1.858 2.172 2.53 2.934 3.388
0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5 11.5 12.5
13.5 14.5 15.5 16.5 17.5 18.5 19.5 20.5
0.329242 0.329242 0.346917 0.202748 0.395312 0.428090 0.468362 0.517841 0.578630 0.653316 0.745076 0.471797 0.547977
1.166500 1.375570 1.632440 1.858000 2.172000 2.530000 2.934000 3.388000

45 # Number of age comp observations
1 # Length bin refers to: 1=population length bin indices; 2=data length bin indices
0 #_combine males into females at or below this bin number
Acoustic survey ages (N=8)
1995 1 2 0 0 23 -1 -1 68 0.000 0.304 0.048 0.014
0.209 0.012 0.042 0.144 0.003 0.001 0.165 0.001 0.007 0.000 0.051
1998 1 2 0 0 26 -1 -1 103 0.000 0.125 0.144 0.168
0.191 0.016 0.076 0.093 0.014 0.028 0.061 0.005 0.003 0.061 0.015
2001 1 2 0 0 29 -1 -1 57 0.000 0.641 0.104 0.054
0.060 0.030 0.037 0.022 0.011 0.010 0.008 0.008 0.010 0.002 0.004
2003 1 2 0 0 31 -1 -1 71 0.000 0.024 0.023 0.635
0.092 0.031 0.070 0.042 0.028 0.026 0.011 0.007 0.005 0.004 0.004
2005 1 2 0 0 33 -1 -1 47 0.000 0.229 0.021 0.069
0.048 0.492 0.053 0.020 0.027 0.016 0.013 0.007 0.002 0.001 0.002
2007 1 2 0 0 35 -1 -1 70 0.000 0.366 0.022 0.108
0.013 0.044 0.030 0.334 0.034 0.017 0.014 0.007 0.007 0.003 0.001
2009 1 2 0 0 37 -1 -1 66 0.000 0.006 0.299 0.421
0.023 0.082 0.012 0.016 0.015 0.073 0.032 0.013 0.003 0.004 0.002
2011 1 2 0 0 39 -1 -1 59 0.000 0.244 0.631 0.039
0.029 0.030 0.004 0.004 0.003 0.002 0.001 0.007 0.003 0.001 0.000

Aggregate marginal fishery ages (N=37)
1975 1 1 0 0 3 -1 -1 13 0.046 0.338 0.074 0.012
0.254 0.055 0.080 0.105 0.010 0.006 0.009 0.005 0.000 0.005 0.000
1976 1 1 0 0 4 -1 -1 142 0.001 0.013 0.145 0.067
0.041 0.246 0.098 0.089 0.121 0.054 0.043 0.041 0.011 0.024 0.007
1977 1 1 0 0 5 -1 -1 320 0.000 0.084 0.037 0.275
0.036 0.091 0.227 0.076 0.065 0.040 0.036 0.023 0.006 0.003 0.001
1978 1 1 0 0 6 -1 -1 341 0.005 0.011 0.065 0.063
0.264 0.061 0.089 0.215 0.098 0.047 0.047 0.023 0.005 0.004 0.003
1979 1 1 0 0 7 -1 -1 116 0.000 0.065 0.102 0.094
0.057 0.177 0.103 0.174 0.128 0.042 0.029 0.010 0.016 0.000 0.004
1980 1 1 0 0 8 -1 -1 221 0.001 0.006 0.298 0.019
0.045 0.081 0.112 0.050 0.089 0.112 0.096 0.026 0.039 0.016 0.011
1981 1 1 0 0 9 -1 -1 154 0.194 0.041 0.014 0.267
0.039 0.055 0.034 0.147 0.038 0.032 0.103 0.023 0.005 0.002 0.007
1982 1 1 0 0 10 -1 -1 170 0.000 0.321 0.035 0.005
0.273 0.015 0.037 0.039 0.118 0.033 0.036 0.076 0.002 0.003 0.007
1983 1 1 0 0 11 -1 -1 117 0.000 0.000 0.341 0.040
0.018 0.235 0.051 0.056 0.053 0.094 0.039 0.031 0.023 0.011 0.007
1984 1 1 0 0 12 -1 -1 123 0.000 0.000 0.014 0.619
0.036 0.039 0.168 0.029 0.015 0.012 0.033 0.009 0.006 0.014 0.006
1985 1 1 0 0 13 -1 -1 56 0.009 0.001 0.003 0.070
0.675 0.084 0.055 0.069 0.020 0.005 0.007 0.002 0.000 0.000 0.000
1986 1 1 0 0 14 -1 -1 120 0.000 0.157 0.055 0.005
0.008 0.432 0.068 0.081 0.083 0.022 0.028 0.018 0.032 0.005 0.006
1987 1 1 0 0 15 -1 -1 56 0.000 0.000 0.297 0.029
0.001 0.010 0.531 0.004 0.013 0.071 0.000 0.008 0.019 0.018 0.000
1988 1 1 0 0 16 -1 -1 81 0.000 0.009 0.000 0.381
0.010 0.015 0.001 0.395 0.010 0.005 0.112 0.009 0.000 0.000 0.053
1989 1 1 0 0 17 -1 -1 77 0.000 0.073 0.032 0.003
0.501 0.016 0.003 0.001 0.321 0.023 0.001 0.023 0.001 0.000 0.000
1990 1 1 0 0 18 -1 -1 163 0.000 0.053 0.180 0.017
0.006 0.345 0.003 0.002 0.000 0.321 0.003 0.001 0.060 0.000 0.009
1991 1 1 0 0 19 -1 -1 160 0.000 0.036 0.209 0.199
0.025 0.008 0.273 0.012 0.001 0.002 0.188 0.004 0.000 0.037 0.007

1992	1	1	0	0	20	-1	-1	243	0.005	0.043	0.042	0.131
	0.187	0.022	0.011	0.339	0.008	0.001	0.003	0.180	0.004	0.000	0.024	
1993	1	1	0	0	21	-1	-1	175	0.000	0.011	0.236	0.032
	0.129	0.157	0.015	0.008	0.276	0.007	0.001	0.000	0.116	0.001	0.013	
1994	1	1	0	0	22	-1	-1	234	0.000	0.000	0.030	0.232
	0.012	0.132	0.197	0.010	0.003	0.283	0.001	0.003	0.000	0.088	0.008	
1995	1	1	0	0	23	-1	-1	147	0.002	0.025	0.005	0.058
	0.315	0.018	0.072	0.189	0.024	0.006	0.179	0.030	0.005	0.001	0.071	
1996	1	1	0	0	24	-1	-1	186	0.000	0.184	0.161	0.015
	0.077	0.184	0.009	0.052	0.108	0.004	0.003	0.157	0.000	0.001	0.044	
1997	1	1	0	0	25	-1	-1	222	0.000	0.008	0.278	0.253
	0.009	0.082	0.129	0.022	0.047	0.065	0.014	0.002	0.063	0.005	0.022	
1998	1	1	0	0	26	-1	-1	243	0.000	0.053	0.188	0.204
	0.283	0.032	0.050	0.091	0.010	0.017	0.037	0.003	0.001	0.026	0.005	
1999	1	1	0	0	27	-1	-1	514	0.000	0.095	0.199	0.181
	0.187	0.136	0.028	0.034	0.036	0.009	0.014	0.040	0.004	0.003	0.035	
2000	1	1	0	0	28	-1	-1	529	0.010	0.044	0.094	0.147
	0.134	0.210	0.137	0.067	0.047	0.027	0.020	0.022	0.011	0.008	0.024	
2001	1	1	0	0	29	-1	-1	541	0.000	0.167	0.153	0.236
	0.174	0.081	0.078	0.048	0.012	0.013	0.012	0.007	0.007	0.005	0.009	
2002	1	1	0	0	30	-1	-1	450	0.000	0.000	0.500	0.148
	0.104	0.057	0.039	0.064	0.046	0.007	0.007	0.012	0.002	0.004	0.009	
2003	1	1	0	0	31	-1	-1	457	0.000	0.001	0.012	0.691
	0.115	0.035	0.049	0.031	0.026	0.022	0.007	0.003	0.005	0.002	0.003	
2004	1	1	0	0	32	-1	-1	501	0.000	0.000	0.046	0.061
	0.690	0.084	0.022	0.044	0.025	0.011	0.009	0.003	0.002	0.002	0.001	
2005	1	1	0	0	33	-1	-1	613	0.000	0.006	0.004	0.066
	0.053	0.690	0.083	0.023	0.028	0.022	0.011	0.010	0.002	0.001	0.002	
2006	1	1	0	0	34	-1	-1	720	0.003	0.028	0.105	0.018
	0.089	0.052	0.588	0.054	0.015	0.022	0.011	0.008	0.004	0.001	0.001	
2007	1	1	0	0	35	-1	-1	629	0.008	0.114	0.037	0.152
	0.015	0.071	0.039	0.450	0.057	0.019	0.018	0.008	0.003	0.006	0.003	
2008	1	1	0	0	36	-1	-1	794	0.008	0.090	0.303	0.023
	0.150	0.011	0.037	0.033	0.286	0.030	0.010	0.008	0.004	0.003	0.004	
2009	1	1	0	0	37	-1	-1	686	0.007	0.005	0.287	0.270
	0.030	0.109	0.010	0.024	0.019	0.181	0.034	0.008	0.012	0.002	0.003	
2010	1	1	0	0	38	-1	-1	873	0.000	0.240	0.032	0.368
	0.216	0.025	0.030	0.007	0.007	0.011	0.049	0.012	0.001	0.001	0.002	
2011	1	1	0	0	39	-1	-1	802	0.013	0.054	0.654	0.032
	0.097	0.074	0.017	0.012	0.005	0.004	0.006	0.021	0.004	0.003	0.003	

0 # No Mean size-at-age data
0 # Total number of environmental variables
0 # Total number of environmental observations
0 # No Weight frequency data
0 # No tagging data
0 # No morph composition data

999 # End data file

##
2012 Hake control file
##

1 # N growth patterns
1 # N sub morphs within patterns
0 # Number of block designs for time varying parameters

Mortality and growth specifications
0.5 # Fraction female (birth)
0 # M setup: 0=single parameter,1=breakpoints,2=Lorenzen,3=age-specific;4=age-specific,seasonal interpolation
1 # Growth model: 1=VB with L1 and L2, 2=VB with A0 and Linf, 3=Richards, 4=Read vector of L@A
1 # Age for growth Lmin
20 # Age for growth Lmax
0.0 # Constant added to SD of LAA (0.1 mimics SS2v1 for compatibility only)
0 # Variability of growth: 0=CV~f(LAA), 1=CV~f(A), 2=SD~f(LAA), 3=SD~f(A)

```
5	#_maturity_option:  1=length logistic; 2=age logistic; 3=read age-maturity matrix by growth_pattern; 4=read age-fecundity; 5=read fec and wt from wtatage.ss
2	# First age allowed to mature
1	# Fecundity option:(1)eggs=Wt*(a+b*Wt);(2)eggs=a*L^b;(3)eggs=a*Wt^b
0	# Hermaphroditism option:  0=none; 1=age-specific fxn
1	# MG parm offset option: 1=none, 2= M,G,CV_G as offset from GP1, 3=like SS2v1
1	# MG parm env/block/dev_adjust_method: 1=standard; 2=logistic transform keeps in base parm bounds; 3=standard w/ no bound check

# Lo	Hi	Init	Prior	Prior	Prior	Param	Env	Use	Dev	Dev	Dev	Block	block
# bnd	bnd	value	mean	type	SD	phase	var	dev	minyr	maxyr	SD	design	switch
 0.05	0.4	0.2	-1.609438	3	0.1	4	0	0	0	0	0	0	0	# M

### Growth parameters ignored in empirical input approach
2	15	5	32	-1	99	-5	0	0	0	0	0	0	0	# A0
45	60	53.2	50	-1	99	-3	0	0	0	0	0	0	0	# Linf
0.2	0.4	0.30	0.3	-1	99	-3	0	0	0	0	0	0	0	# VBK
0.03	0.16	0.066	0.1	-1	99	-5	0	0	0	0	0	0	0	# CV of length at age 0
0.03	0.16	0.062	0.1	-1	99	-5	0	0	0	0	0	0	0	# CV of length at age inf
# W-L, maturity and fecundity parameters
# Female placeholders
-3	3	7.0E-06	7.0E-06	-1	99	-50	0	0	0	0	0	0	0	# F W-L slope
-3	3	2.9624	2.9624	-1	99	-50	0	0	0	0	0	0	0	# F W-L exponent
# Maturity from 2010 assessment
-3	43	36.89	36.89	-1	99	-50	0	0	0	0	0	0	0	# L at 50% maturity
-3	3	-0.48	-0.48	-1	99	-50	0	0	0	0	0	0	0	# F Logistic maturity slope
# No fecundity relationship
-3	3	1.0	1.0	-1	99	-50	0	0	0	0	0	0	0	# F Eggs/gm intercept
-3	3	0.0	0.0	-1	99	-50	0	0	0	0	0	0	0	# F Eggs/gm slope
# Unused recruitment interactions
0	2	1	1	-1	99	-50	0	0	0	0	0	0	0	# placeholder only
0	2	1	1	-1	99	-50	0	0	0	0	0	0	0	# placeholder only
0	2	1	1	-1	99	-50	0	0	0	0	0	0	0	# placeholder only
0	2	1	1	-1	99	-50	0	0	0	0	0	0	0	# placeholder only
0 0 0 0 0 0 0 0 0 0 # Unused MGparm_seas_effects

# Spawner-recruit parameters
3 # S-R function: 1=B-H w/flat top, 2=Ricker, 3=standard B-H, 4=no steepness or bias adjustment
# Lo	Hi	Init	Prior	Prior	Prior	Param
# bnd	bnd	value	mean	type	SD	phase
13	17	15.9	15	-1	99	1	# Ln(R0)
0.2	1	0.88	0.777	2	0.113	4	# Steepness with Myers' prior
1.0	1.6	1.4	1.1	-1	99	-6	# Sigma-R
-5	5	0	0	-1	99	-50	# Env link coefficient
-5	5	0	0	-1	99	-50	# Initial equilibrium recruitment offset
 0	2	0	1	-1	99	-50	# Autocorrelation in rec devs
0 # index of environmental variable to be used
0 # SR environmental target: 0=none;1=devs;_2=R0;_3=steepness
1 # Recruitment deviation type: 0=none; 1=devvector; 2=simple deviations
```

```
# Recruitment deviations
1970        # Start year standard recruitment devs
2007        # End year standard recruitment devs
1           # Rec Dev phase

1 # Read 11 advanced recruitment options: 0=no, 1=yes
1946        # Start year for early rec devs
3           # Phase for early rec devs
5           # Phase for forecast recruit deviations
1           # Lambda for forecast recr devs before endyr+1
1965        # Last recruit dev with no bias_adjustment
1971        # First year of full bias correction (linear ramp from year above)
2008        # Last year for full bias correction in_MPD
2009        # First_recent_yr_nobias_adj_in_MPD
0.86        # Maximum bias adjustment in MPD
0           # Period of cycles in recruitment (N parms read below)
-6          # Lower bound rec devs
6           # Upper bound rec devs
0           # Read init values for rec devs

# Fishing mortality setup
0.1         # F ballpark for tuning early phases
-1999       # F ballpark year
1           # F method:  1=Pope's; 2=Instan. F; 3=Hybrid
0.95        # Max F or harvest rate (depends on F_Method)

# Init F parameters by fleet
#LO         HI          INIT        PRIOR       PR_type     SD          PHASE
0           1           0.0         0.01        -1          99           -50

# Catchability setup
# A=do power: 0=skip, survey is prop. to abundance, 1= add par for non-linearity
# B=env. link: 0=skip, 1= add par for env. effect on Q
# C=extra SD: 0=skip, 1= add par. for additive constant to input SE (in ln space)
# D=type: <0=mirror lower abs(#) fleet, 0=no par Q is median unbiased, 1=no par Q is mean unbiased, 2=estimate par for ln(Q)
#               3=ln(Q) + set of devs about ln(Q) for all years. 4=ln(Q) + set of devs about Q for indexyr-1
# A B C D
# Create one par for each entry > 0 by row in cols A-D
0           0           0           0            # US_Foreign
0           0           1           0            # Acoustic_Survey

#LO         HI          INIT        PRIOR       PR_type     SD          PHASE
0.05 1.2    0.0755      0.0755      -1          0.1          4 # additive value for acoustic survey

#_SELEX_&_RETENTION_PARAMETERS
# Size-based setup
# A=Selex option: 1-24
# B=Do_retention: 0=no, 1=yes
# C=Male offset to female: 0=no, 1=yes
# D=Extra input (#)
# A B C D
# Size selectivity
0           0           0           0  # Fishery
0           0           0           0  # Acoustic_Survey
# Age selectivity
17          0           0           20  # Fishery
17          0           0           20  # Acoustic_Survey

# Selectivity parameters
# Lo        Hi          Init        Prior       Prior       Prior       Param       Env         Use         Dev         Dev         Dev         Block
            block
# bnd       bnd         value       mean        type        SD          phase       var         dev         minyr       maxyr       SD          design
            switch
# Fishery age-based
  -1002     3           -1000       -1          -1          0.01        -2          0 0 0 0 0 0 0 # 0.0 at age 0
  -1        1            0.0        -1          -1          0.01        -2          0 0 0 0 0 0 0 # Age 1 is Reference
  -5        9            2.8        -1          -1          0.01        2           0 0 0 0 0 0 0 # Change to age 2
```

-5	9	0.1	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 3
-5	9	0.1	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 4
-5	9	0.1	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 5
-5	9	0.0	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 6
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 7
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 8
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 9
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 10
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 11
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 12
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 13
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 14
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 15
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 16
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 17
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 18
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 19
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 20

Acoustic survey - nonparametric age-based selectivity
Acoustic Survey double non-parametric age-based selectivity

-1002	3	-1000	-1	-1	0.01	-2	0 0 0 0 0 0 0 # 0.0 at age 0
-1002	3	-1000	-1	-1	0.01	-2	0 0 0 0 0 0 0 # 0.0 at age 1
-1	1	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Age 2 is reference
-5	9	0.1	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 3
-5	9	0.1	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 4
-5	9	0.0	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 5
-5	9	0.0	-1	-1	0.01	2	0 0 0 0 0 0 0 # Change to age 6
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 7
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 8
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 9
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 10
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 11
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 12
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 13
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 14
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 15
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 16
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 17
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 18
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 19
-5	9	0.0	-1	-1	0.01	-2	0 0 0 0 0 0 0 # Change to age 20

0 # Tagging flag: 0=no tagging parameters,1=read tagging parameters

Likelihood related quantities
1 # Do variance/sample size adjustments by fleet (1)
Component
0 0 # Constant added to index CV
0 0 # Constant added to discard SD
0 0 # Constant added to body weight SD
1 1 # multiplicative scalar for length comps
0.12 0.94 # multiplicative scalar for agecomps
1 1 # multiplicative scalar for length at age obs

1 # Lambda phasing: 1=none, 2+=change beginning in phase 1
1 # Growth offset likelihood constant for Log(s): 1=include, 2=not
0 # N changes to default Lambdas = 1.0
Component codes:
1=Survey, 2=discard, 3=mean body weight
4=length frequency, 5=age frequency, 6=Weight frequency
7=size at age, 8=catch, 9=initial equilibrium catch
10=rec devs, 11=parameter priors, 12=parameter devs
13=Crash penalty
Component fleet/survey phase value wtfreq_method

```
1             # Extra SD reporting switch
2  2 -1 15 # selex type (fleet), len=1/age=2, year, N selex bins (4 values)
1  1          # Growth pattern, N growth ages (2 values)
1 -1  1       # NatAge_area(-1 for all), NatAge_yr, N Natages (3 values)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 # placeholder for vector of selex bins to be reported
-1 # growth ages
-1 # NatAges

999 # End control file

# 2012 hake model forecast file

1             # Benchmarks: 0=skip; 1=calc F_spr,F_btgt,F_msy
2             # MSY: 1= set to F(SPR); 2=calc F(MSY); 3=set to F(Btgt); 4=set to F(endyr)
0.4           # SPR target (e.g. 0.40)
0.4           # Biomass target (e.g. 0.40)
# Enter either: actual year, -999 for styr, 0 for endyr, neg number for rel. endyr
-999 -999 -999 -999 -999 -999 # Bmark_years: beg_bio end_bio beg_selex end_selex beg_alloc end_alloc
2             # Bmark_relF_Basis: 1 = use year range; 2 = set relF same as forecast below
1             # Forecast: 0=none; 1=F(SPR); 2=F(MSY) 3=F(Btgt); 4=Ave F (use first-last alloc yrs); 5=input annual F
3             # N forecast years
1.0           # F scalar (only used for Do_Forecast==5)
# Enter either: actual year, -999 for styr, 0 for endyr, neg number for rel. endyr
2006 2011 2006 2011 # Fcast_years:  beg_selex end_selex beg_alloc end_alloc
1             # Control rule method (1=catch=f(SSB) west coast; 2=F=f(SSB) )
0.4           # Control rule Biomass level for constant F (as frac of Bzero, e.g. 0.40)
0.1           # Control rule Biomass level for no F (as frac of Bzero, e.g. 0.10)
1.0           # Control rule target as fraction of Flimit (e.g. 0.75)
3             # N forecast loops (1-3) (fixed at 3 for now)
3             # First forecast loop with stochastic recruitment (fixed at 3 for now)
-1            # Forecast loop control #3 (reserved)
0             #_Forecast loop control #4 (reserved for future bells&whistles)
0             #_Forecast loop control #5 (reserved for future bells&whistles)
2011          # FirstYear for caps and allocations (should be after any fixed inputs)
0.0           # stddev of log(realized catch/target catch) in forecast
0             # Do West Coast gfish rebuilder output (0/1)
1999          # Rebuilder:  first year catch could have been set to zero (Ydecl)(-1 to set to 1999)
2002          # Rebuilder:  year for current age structure (Yinit) (-1 to set to endyear+1)
1             # fleet relative F:  1=use first-last alloc year; 2=read seas(row) x fleet(col) below
2             # basis for fcast catch tuning and for fcast catch caps and allocation  (2=deadbio; 3=retainbio; 5=deadnum; 6=retainnum)
-1            # max totalcatch by fleet (-1 to have no max)
-1            # max totalcatch by area (-1 to have no max)
1             # fleet assignment to allocation group (enter group ID# for each fleet, 0 for not included in an alloc group)
# assign fleets to groups
1.0
# allocation fraction for each of: 2 allocation groups
3 # Number of forecast catch levels to input (else calc catch from forecast F)
2 # basis for input Fcast catch:  2=dead catch; 3=retained catch; 99=input Hrate(F) (units are from fleetunits; note new codes in SSV3.20)
2012      1        1        274024
2013      1        1        282668
2014      1        1        283845
999 # verify end of input

# 2012 hake starter file

2012_hake_data.SS    # Data file
2012_hake_control.SS # Control file

0             # Read initial values from .par file: 0=no,1=yes
0             # DOS display detail: 0,1,2
2             # Report file detail: 0,1,2
0             # Detailed checkup.sso file (0,1)
0             # Write parameter iteration trace file during minimization
0             # Write cumulative report: 0=skip,1=short,2=full
0             # Include prior likelihood for non-estimated parameters
0             # Use Soft Boundaries to aid convergence (0,1) (recommended)
1             # N bootstrap datafiles to create
```

```
25        # Last phase for estimation
1         # MCMC burn-in
1         # MCMC thinning interval
0         # Jitter initial parameter values by this fraction
-1        # Min year for spbio sd_report (neg val = styr-2, virgin state)
-2        # Max year for spbio sd_report (neg val = endyr+1)
0         # N individual SD years
0.00001 # Ending convergence criteria
0         # Retrospective year relative to end year
3         # Min age for summary biomass
1         # Depletion basis: denom is: 0=skip; 1=rel X*B0; 2=rel X*Bmsy; 3=rel X*B_styr
1.0       # Fraction (X) for Depletion denominator (e.g. 0.4)
1         # (1-SPR)_reporting:  0=skip; 1=rel(1-SPR); 2=rel(1-SPR_MSY); 3=rel(1-SPR_Btarget); 4=notrel
1         # F_std reporting: 0=skip; 1=exploit(Bio); 2=exploit(Num); 3=sum(frates)
0         # F_report_basis: 0=raw; 1=rel Fspr; 2=rel Fmsy ; 3=rel Fbtgt

999 # end of file marker
```

11. Appendix D. CCAM model input files

CCAM data input file for all model cases.

```
#NB The data herein were taken from the 2010 Pacific Hake Assessment using TINSS.
## ________________________
## ____Model Dimensions____
1966                #first year of data
2011                #last year of data
1                   #age of youngest age class
15                  #age of plus group
2                   #number of gears (ngear)
## Allocation for fishery selectivity (1) or survey (0) in ngears
1       0
## ________________________
#
## ________________________
#Age-schedule and population parameters
#natural mortality rate (m)
0.23
#growth parameters (linf,k,to)
52.948, 0.334, 0
#length-weight allometry (a,b)
6.5359e-6, 2.98684
#ah and gh: maturity at age (am=log(3)/k) & gm=std for logistic
2.721, 0.488
## ________________________

#Time series data
#Observed catch (1977-2009, 1,000,000 metric t)
#yr     commercial survey
1966    0.137700   0
1967    0.214370   0
1968    0.122180   0
1969    0.180130   0
1970    0.234590   0
1971    0.154620   0
1972    0.117540   0
1973    0.162640   0
1974    0.211260   0
1975    0.221350   0
1976    0.237520   0
1977    0.132690   0
1978    0.103640   0
1979    0.137110   0
1980    0.089930   0
1981    0.139120   0
1982    0.107741   0
1983    0.113931   0
1984    0.138492   0
1985    0.110399   0
1986    0.210616   0
1987    0.234148   0
1988    0.248840   0
1989    0.298079   0
1990    0.261286   0
1991    0.319710   0
1992    0.299687   0
1993    0.198924   0
1994    0.362422   0
1995    0.249644   0
1996    0.306383   0
1997    0.325257   0
1998    0.320815   0
1999    0.311844   0
2000    0.228214   0
2001    0.227531   0
```

```
2002	0.180698	0
2003	0.205177	0
2004	0.338654	0
2005	0.363157	0
2006	0.361761	0
2007	0.291129	0
2008	0.322145	0
2009	0.177459	0
2010	0.226202	0
2011	0.286055	0
#
#Relative Abundance index from fisheries independent survey (it) 1970-2008
#nit
1
#nit_nobs
8
#survey type
## 1 = survey is proportional to vulnerable numbers
## 2 = survey is proportional to vulnerable biomass
## 3 = survey is proportional to spawning biomass (e.g., herring spawn survey)
2
#iyr	it	gear it_wt survey timing
1995	1.517948	2	0.7376	0.5
1998	1.342740	2	1.0000	0.5
2001	0.918622	2	0.5971	0.5
2003	2.520641	2	0.6930	0.5
2005	1.754722	2	0.5795	0.5
2007	1.122809	2	0.6534	0.5
2009	1.612027	2	0.3562	0.5
2011	0.553991	2	0.5125	0.5
##Note about survey it_wt
##it_wt is the inverse of the relative CV in the survey index (relative to the 1998 (smallest) CV)
##relative CVs in survey index points assumed multiplicative
##iscam estimates varphi and rho
##varphi is the inverse of the total standard deviation (observation error in index of abundance + process error)
##rho is the proportion of total sd that is observation error
##sig = standard deviation of log residuals in survey index (residuals modelled as lognormal)
##tau = standard deviation of log recruitment residuals (residuals modelled as lognormal)
##sig = (rho/varphi)/it_wt;
##tau = (1.-rho)/varphi;
#
#Age composition data by year, gear (ages 2-15+)
#na_gears
2
#na_nobs
37	8
#a_sage
1	2
#a_page
15	15
#comm catch age - not normalised
#yr	gear	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14
1975	1	0.0460	0.3380	0.0740	0.0120	0.2540	0.0550	0.0800	0.1050	0.0100	0.0060	0.0090
	0.0050	0.0000	0.0050	0.0000
1976	1	0.0010	0.0130	0.1450	0.0670	0.0410	0.2460	0.0980	0.0890	0.1210	0.0540	0.0430
	0.0410	0.0110	0.0240	0.0070
1977	1	0.0000	0.0840	0.0370	0.2750	0.0360	0.0910	0.2270	0.0760	0.0650	0.0400	0.0360
	0.0230	0.0060	0.0030	0.0010
1978	1	0.0050	0.0110	0.0650	0.0630	0.2640	0.0610	0.0890	0.2150	0.0980	0.0470	0.0470
	0.0230	0.0050	0.0040	0.0030
1979	1	0.0000	0.0650	0.1020	0.0940	0.0570	0.1770	0.1030	0.1740	0.1280	0.0420	0.0290
	0.0100	0.0160	0.0000	0.0040
1980	1	0.0010	0.0060	0.2980	0.0190	0.0450	0.0810	0.1120	0.0500	0.0890	0.1120	0.0960
	0.0260	0.0390	0.0160	0.0110
1981	1	0.1940	0.0410	0.0140	0.2670	0.0390	0.0550	0.0340	0.1470	0.0380	0.0320	0.1030
	0.0230	0.0050	0.0020	0.0070
```

1982	1	0.0000	0.3210	0.0350	0.0050	0.2730	0.0150	0.0370	0.0390	0.1180	0.0330	0.0360
	0.0760	0.0020	0.0030	0.0070								
1983	1	0.0000	0.0000	0.3410	0.0400	0.0180	0.2350	0.0510	0.0560	0.0530	0.0940	0.0390
	0.0310	0.0230	0.0110	0.0070								
1984	1	0.0000	0.0000	0.0140	0.6190	0.0360	0.0390	0.1680	0.0290	0.0150	0.0120	0.0330
	0.0090	0.0060	0.0140	0.0060								
1985	1	0.0090	0.0010	0.0030	0.0700	0.6750	0.0840	0.0550	0.0690	0.0200	0.0050	0.0070
	0.0020	0.0000	0.0000	0.0000								
1986	1	0.0000	0.1570	0.0550	0.0050	0.0080	0.4320	0.0680	0.0810	0.0830	0.0220	0.0280
	0.0180	0.0320	0.0050	0.0060								
1987	1	0.0000	0.0000	0.2970	0.0290	0.0010	0.0100	0.5310	0.0040	0.0130	0.0710	0.0000
	0.0080	0.0190	0.0180	0.0000								
1988	1	0.0000	0.0090	0.0000	0.3810	0.0100	0.0150	0.0010	0.3950	0.0100	0.0050	0.1120
	0.0090	0.0000	0.0000	0.0530								
1989	1	0.0000	0.0730	0.0320	0.0030	0.5010	0.0160	0.0030	0.0010	0.3210	0.0230	0.0010
	0.0230	0.0010	0.0000	0.0000								
1990	1	0.0000	0.0530	0.1800	0.0170	0.0060	0.3450	0.0030	0.0020	0.0000	0.3210	0.0030
	0.0010	0.0600	0.0000	0.0090								
1991	1	0.0000	0.0360	0.2090	0.1990	0.0250	0.0080	0.2730	0.0120	0.0010	0.0020	0.1880
	0.0040	0.0000	0.0370	0.0070								
1992	1	0.0050	0.0430	0.0420	0.1310	0.1870	0.0220	0.0110	0.3390	0.0080	0.0010	0.0030
	0.1800	0.0040	0.0000	0.0240								
1993	1	0.0000	0.0110	0.2360	0.0320	0.1290	0.1570	0.0150	0.0080	0.2760	0.0070	0.0010
	0.0000	0.1160	0.0010	0.0130								
1994	1	0.0000	0.0000	0.0300	0.2320	0.0120	0.1320	0.1970	0.0100	0.0030	0.2830	0.0010
	0.0030	0.0000	0.0880	0.0080								
1995	1	0.0020	0.0250	0.0050	0.0580	0.3150	0.0180	0.0720	0.1890	0.0240	0.0060	0.1790
	0.0300	0.0050	0.0010	0.0710								
1996	1	0.0000	0.1840	0.1610	0.0150	0.0770	0.1840	0.0090	0.0520	0.1080	0.0040	0.0030
	0.1570	0.0000	0.0010	0.0440								
1997	1	0.0000	0.0080	0.2780	0.2530	0.0090	0.0820	0.1290	0.0220	0.0470	0.0650	0.0140
	0.0020	0.0630	0.0050	0.0220								
1998	1	0.0000	0.0530	0.1880	0.2040	0.2830	0.0320	0.0500	0.0910	0.0100	0.0170	0.0370
	0.0030	0.0010	0.0260	0.0050								
1999	1	0.0000	0.0950	0.1990	0.1810	0.1870	0.1360	0.0280	0.0340	0.0360	0.0090	0.0140
	0.0400	0.0040	0.0030	0.0350								
2000	1	0.0100	0.0440	0.0940	0.1470	0.1340	0.2100	0.1370	0.0670	0.0470	0.0270	0.0200
	0.0220	0.0110	0.0080	0.0240								
2001	1	0.0000	0.1670	0.1530	0.2360	0.1740	0.0810	0.0780	0.0480	0.0120	0.0130	0.0120
	0.0070	0.0070	0.0050	0.0090								
2002	1	0.0000	0.0000	0.5000	0.1480	0.1040	0.0570	0.0390	0.0640	0.0460	0.0070	0.0070
	0.0120	0.0020	0.0040	0.0090								
2003	1	0.0000	0.0010	0.0120	0.6910	0.1150	0.0350	0.0490	0.0310	0.0260	0.0220	0.0070
	0.0030	0.0050	0.0020	0.0030								
2004	1	0.0000	0.0000	0.0460	0.0610	0.6900	0.0840	0.0220	0.0440	0.0250	0.0110	0.0090
	0.0030	0.0020	0.0020	0.0010								
2005	1	0.0000	0.0060	0.0040	0.0660	0.0530	0.6900	0.0830	0.0230	0.0280	0.0220	0.0110
	0.0100	0.0020	0.0010	0.0020								
2006	1	0.0030	0.0280	0.1050	0.0180	0.0890	0.0520	0.5880	0.0540	0.0150	0.0220	0.0110
	0.0080	0.0040	0.0010	0.0010								
2007	1	0.0080	0.1140	0.0370	0.1520	0.0150	0.0710	0.0390	0.4500	0.0570	0.0190	0.0180
	0.0080	0.0030	0.0060	0.0030								
2008	1	0.0080	0.0900	0.3030	0.0230	0.1500	0.0110	0.0370	0.0330	0.2860	0.0300	0.0100
	0.0080	0.0040	0.0030	0.0040								
2009	1	0.0070	0.0050	0.2870	0.2700	0.0300	0.1090	0.0100	0.0240	0.0190	0.1810	0.0340
	0.0080	0.0120	0.0020	0.0030								
2010	1	0.0000	0.2400	0.0320	0.3680	0.2160	0.0250	0.0300	0.0070	0.0070	0.0110	0.0490
	0.0120	0.0010	0.0010	0.0020								
2011	1	0.0130	0.0540	0.6540	0.0320	0.0970	0.0740	0.0170	0.0120	0.0050	0.0040	0.0060
	0.0210	0.0040	0.0030	0.0030								
#												
1995	2	0.3040	0.0480	0.0140	0.2090	0.0120	0.0420	0.1440	0.0030	0.0010	0.1650	0.0010
	0.0070	0.0000	0.0510									
1998	2	0.1250	0.1440	0.1680	0.1910	0.0160	0.0760	0.0930	0.0140	0.0280	0.0610	0.0050
	0.0030	0.0610	0.0150									
2001	2	0.6410	0.1040	0.0540	0.0600	0.0300	0.0370	0.0220	0.0110	0.0100	0.0080	0.0080
	0.0100	0.0020	0.0040									

2003	2	0.0240	0.0230	0.6350	0.0920	0.0310	0.0700	0.0420	0.0280	0.0260	0.0110	0.0070	0.0050	0.0040	0.0040
2005	2	0.2290	0.0210	0.0690	0.0480	0.4920	0.0530	0.0200	0.0270	0.0160	0.0130	0.0070	0.0020	0.0010	0.0020
2007	2	0.3660	0.0220	0.1080	0.0130	0.0440	0.0300	0.3340	0.0340	0.0170	0.0140	0.0070	0.0070	0.0030	0.0010
2009	2	0.0060	0.2990	0.4210	0.0230	0.0820	0.0120	0.0160	0.0150	0.0730	0.0320	0.0130	0.0030	0.0040	0.0020
2011	2	0.2440	0.6310	0.0390	0.0290	0.0300	0.0040	0.0040	0.0030	0.0020	0.0010	0.0070	0.0030	0.0010	0.0000

#n_wt_obs
46
#Year wa (kg)

1966	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1967	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1968	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1969	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1970	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1971	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1972	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1973	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1974	0.0885	0.2562	0.3799	0.4913	0.5434	0.5906	0.662	0.7215	0.791	0.8629	0.9315	0.9681	1.0751	1.0016	1.0202
1975	0.1575	0.2987	0.3658	0.6143	0.6306	0.7873	0.8738	0.9678	0.9075	0.9700	1.6933	1.5000	1.9000	1.9555	2.7445
1976	0.0986	0.2359	0.4973	0.5188	0.6936	0.8041	0.9166	1.2097	1.3375	1.4498	1.6532	1.8066	1.8588	1.9555	2.7445
1977	0.2286	0.4021	0.4870	0.5902	0.6650	0.7493	0.8267	0.9781	1.1052	1.2349	1.3148	1.4058	1.7511	2.0367	2.2094
1978	0.1026	0.1360	0.4699	0.5300	0.6027	0.6392	0.7395	0.8391	0.9775	1.0971	1.2349	1.3028	1.4814	1.7419	2.3379
1979	0.0913	0.2410	0.2587	0.5821	0.6868	0.7677	0.8909	0.9128	1.0369	1.1987	1.2482	1.5326	1.5520	1.7950	1.9817
1980	0.0800	0.2236	0.4529	0.3922	0.4904	0.5166	0.6554	0.7125	0.8740	1.0616	1.1623	1.2898	1.3001	1.2699	1.3961
1981	0.1079	0.2137	0.3422	0.5264	0.3933	0.5254	0.5462	0.7464	0.7204	0.8231	1.0413	1.0989	1.3449	1.4926	1.2128
1982	0.1183	0.2465	0.3336	0.3097	0.5496	0.3956	0.5275	0.5629	0.7606	0.6837	0.8539	1.0670	0.8793	1.0186	1.1693
1983	0.1287	0.1357	0.3410	0.3694	0.3277	0.5200	0.5028	0.6179	0.7060	0.8800	0.9299	1.0356	1.0310	1.3217	1.4823
1984	0.1315	0.1642	0.2493	0.4385	0.4113	0.4352	0.5872	0.5802	0.6758	0.7010	0.9513	1.1364	1.0258	1.2807	1.8800
1985	0.1740	0.2297	0.2679	0.4414	0.5497	0.5474	0.6014	0.7452	0.6933	0.7231	0.8584	0.8698	0.9458	0.6759	1.1217
1986	0.1555	0.2771	0.2909	0.3024	0.3735	0.5425	0.5717	0.6421	0.8209	0.9403	1.1860	1.1900	1.3864	1.6800	1.6142
1987	0.1478	0.1388	0.3790	0.2786	0.2870	0.3621	0.5775	0.5975	0.6369	0.7638	0.9820	0.9250	1.2407	1.2031	1.4157
1988	0.1400	0.1870	0.3189	0.4711	0.3689	0.3731	0.5163	0.6474	0.6851	0.7183	0.9167	1.0924	1.0225	1.4500	1.4537
1989	0.1389	0.2737	0.3047	0.2931	0.5134	0.4386	0.4064	0.5167	0.6263	0.6611	0.6027	0.8758	0.6686	0.8282	1.1264
1990	0.1378	0.2435	0.3506	0.3906	0.5111	0.5462	0.6076	0.6678	0.5300	0.7691	0.8313	2.2000	1.1847	1.0166	1.4668
1991	0.1367	0.2754	0.3697	0.4598	0.5138	0.5437	0.5907	0.7210	0.8497	1.0997	0.7185	0.6403	1.0174	1.2051	2.3828
1992	0.1356	0.2316	0.3473	0.4743	0.5334	0.5817	0.6210	0.6406	0.6530	0.6330	0.7217	0.7354	0.8501	0.9750	1.0272

1993	0.1274	0.2486	0.3384	0.3960	0.4539	0.4935	0.5017	0.4880	0.5491	0.5100	1.2630	1.0250	0.6135	0.5995	0.6850
1994	0.1191	0.3000	0.3626	0.4469	0.4473	0.5262	0.5700	0.6218	0.5598	0.6341	0.4850	0.6491	0.7300	0.7013	0.7455
1995	0.1108	0.2682	0.3418	0.4876	0.5367	0.6506	0.6249	0.6597	0.7560	0.6670	0.7442	0.7998	0.9101	0.6804	0.8008
1996	0.1007	0.2876	0.3982	0.4674	0.5317	0.5651	0.6509	0.5957	0.6362	0.6049	0.7500	0.6756	0.8109	1.4853	0.7509
1997	0.0906	0.3555	0.4322	0.4931	0.5476	0.5453	0.5833	0.5855	0.6071	0.6315	0.8633	0.5946	0.7118	0.6618	0.8693
1998	0.0805	0.2091	0.3539	0.5041	0.5172	0.5420	0.6412	0.6099	0.6769	0.8078	0.7174	0.8100	0.7733	0.7510	0.7714
1999	0.1352	0.2502	0.3455	0.4251	0.5265	0.5569	0.5727	0.6117	0.7030	0.6650	0.7989	0.7554	0.8787	0.7348	0.8187
2000	0.1899	0.3216	0.4729	0.5766	0.6598	0.7176	0.7279	0.7539	0.8378	0.8159	0.8814	0.8554	0.9391	0.8744	0.9336
2001	0.0512	0.2867	0.4843	0.6527	0.6645	0.7469	0.8629	0.8555	0.8802	0.9630	0.9790	1.0054	1.0494	0.9927	0.9768
2002	0.0756	0.3583	0.4575	0.6058	0.8160	0.7581	0.8488	0.9771	0.9322	0.9176	0.9974	0.9890	0.9236	1.1250	1.0573
2003	0.1000	0.2551	0.4355	0.5225	0.5879	0.7569	0.6915	0.7469	0.8246	0.7692	0.8887	0.9266	0.7894	0.8414	0.9965
2004	0.1081	0.2577	0.4360	0.4807	0.5319	0.6478	0.7068	0.6579	0.7094	0.8050	0.8581	0.7715	0.9704	0.8631	0.8959
2005	0.1162	0.2603	0.4311	0.5086	0.5393	0.5682	0.6336	0.6550	0.7027	0.7962	0.8104	0.8109	0.7602	1.1449	0.9678
2006	0.1324	0.3831	0.4575	0.5341	0.5740	0.5910	0.5979	0.6560	0.6997	0.7259	0.7220	0.7753	0.6580	0.6399	0.9550
2007	0.0461	0.2272	0.3776	0.5352	0.5530	0.6073	0.6328	0.6475	0.7055	0.7723	0.7627	0.8137	0.8702	0.8008	0.8698
2008	0.1403	0.2445	0.4081	0.5630	0.6371	0.6865	0.6818	0.7084	0.7210	0.7488	0.8073	0.8483	0.7755	0.8834	0.8332
2009	0.0667	0.2448	0.3431	0.4712	0.6371	0.6702	0.6942	0.7463	0.8226	0.7672	0.8115	1.0147	0.8503	0.9582	1.0334
2010	0.1089	0.2325	0.2535	0.4335	0.5293	0.6577	0.8349	1.0828	1.0276	0.9409	0.8763	0.8373	1.1253	0.7200	0.9021
2011	0.0796	0.2399	0.3185	0.3822	0.5134	0.5863	0.6674	0.8199	0.8760	0.9199	1.0508	0.9844	0.9878	0.9877	0.8909

```
#
 #eof
999
```

Control File for CCAM Base

```
## ___________________________________________________________________________ ##
##                        PACIFIC HAKE CONTROLS
## ___________________CONTROLS FOR ESTIMATED PARAMETERS________________________ ##
##  Prior descriptions:
##                  -0 uniform (0,0)
##                  -1 normal (p1=mu,p2=sig)
##                  -2 lognormal (p1=log(mu),p2=sig)
##                  -3 beta (p1=alpha,p2=beta)
##                  -4 gamma(p1=alpha,p2=beta)
## ___________________________________________________________________________ ##
7   ## npar

#2012 Management oriented priors
##  ival     lb     ub     phz     prior    p1     p2     parameter name
## ___________________________________________________________________________ ##
#0.2        0.01        3.00        1            2            -1.609438  0.5          #msy -1.609438  0.133939
#0.35       0.01        3.00        1            2            -1.049822  0.4          #fmsy
#-1.481141     -5.0    0.0     2     1      -1.609438  0.1    #log.m   #-1.481141
#1.163151      -5.0    15            1      0      -5.0    15     #log_avgrec
#1.163151      -5.0    15            1    0      -5.0    15    #log_recinit
##0.2      0.001    0.999    3      3       12.0    52.8    #rho
##1.25      0.01    10.     3      4       39.0625 62.5  #varphi (precision)
#0.15       0.01          0.999       4      3      3.0    12.0    #rho
#1.25       0.01          150.         3      4      7.49836 5.78354    #varphi (precision)  (RF Change - SJDM had called this kappa)
```

```
##0.223412                    0.05     0.9                 -1         2         -1.609438  0.1 #m


#Original iscam biological oriented priors
## _____________________________________________________________________________ ##

## ival    lb   ub   phz   prior  p1   p2   parameter name
## _____________________________________________________________________________ ##
1.9     -1.0   4    1    0     -1.   4.    #log_ro  priors - see SS_ro_prior.xls
0.77     0.2   1.0    1    3     9.766627     2.803034      #steepness  a and b parameters approximate prior from SS - see Betapars.r
-1.609438    -5.0   0.0    2    1     -1.609438  0.2  #log.m
1.9     -5.0   15    1    0     -5.0   15    #log_avgrec
1.9     -5.0   15    1   0     -5.0   15    #log_recinit
0.15     0.01       0.999     4    3     3.0   12.0   #rho
1.25     0.01       150.      3    4     7.49836 5.78354    #varphi (precision)  (RF Change - SJDM had called this kappa)
## _____________________________________________________________________________ ##



## ________________________SELECTIVITY PARAMETERS____________________________ ##
## OPTIONS FOR SELECTIVITY:
##     1) logistic selectivity parameters
##     2) selectivity coefficients
##     3) a constant cubic spline with age-nodes
##     4) a time varying cubic spline with age-nodes
##     5) a time varying bicubic spline with age & year nodes.
##     6) fixed logistic (set isel_type=1, and estimation phase is set to -1 in tpl (ie estimation phase below is ignored))
## Gear 1 fishery:  Gear 2 survey
## isel_type
1         1
## Age at 50% selectivity (logistic) ahat
#4.       4.5
#4.82102   4.5
3.5       3.5
## STD at 50% selectivity (logistic) ghat
#1.1      0.5
#1.31762   2.1
0.45      0.45
## No. of age nodes for each gear (0 to ignore).
3         0
## No. of year nodes for each gear (0 to ignore).
5         0
## Estimation phase - any negative number means it is fixed!
1         1
## Penalty weight for 2nd differences w=1/(2*sig^2)
150.0     200.0
## Penalty weight for dome-shaped selectivity 1=1/(2*sig^2)
50.0      200.0
#GAMMA prior for  STD at 50% selectivity (logistic) ghat for SURVEY
#prior type (4=gamma)   par1    par2       switch
#ghat_p1 ghat_p2 ghat_pswitch
2.        4.        0

## _____________________________________________________________________________ ##
## _____________________________________________________________________________ ##
##                  Priors for Survey q                    ##
## _____________________________________________________________________________ ##
## nits  #number of surveys
1
## priors 0=uniform density    1=normal density
1
## prior log(mean);
0
## prior sd
0.1
## _____________________________________________________________________________ ##
```

```
## ______________________OTHER MISCELLANEOUS CONTROLS cntrl________________________ ##
0          ## 1 verbose ADMB output (0=off, 1=on)
1          ## 2 recruitment model (1=beverton-holt, 2=ricker)
0.05       ## 3 std in observed catches in first phase.
0.01       ## 4 std in observed catches in last phase.
0          ## 5 Assume unfished in first year (0=FALSE, 1=TRUE)
0.00       ## 6 Minimum proportion to consider in age-proportions for dmvlogistic
0.2        ## 7 Mean fishing mortality for regularizing the estimates of Ft
0.05       ## 8 std in mean fishing mortality in first phase
2.00       ## 9 std in mean fishing mortality in last phase
-1         ## 10 phase for estimating m_deviations (use -1 to turn off mdevs)
0.1        ## 11 std in deviations for natural mortality
12                         ## 12 number of estimated nodes for deviations in natural mortality
0.00       ## 13 fraction of total mortality that takes place prior to spawning
1          ## 14 switch for age-composition likelihood (1=dmvlogistic,2=dmultinom)
0          ## 15 1=estimate Management parameters, 0=estimate population parameters
## __________________________________________________________________________ ##

## RF ADDED NUMBER OF PROJECTION YEARS
##pyrs
3

## RF ADDED harvest control rule switch
##hcr
1 ## 1 = 40-10 Rule ... nothing else implemented yet

##Catch stream from SS (OY)
#SSstream
0.274024
0.282668
0.283845

## eofc
999

Control File for CCAM base with steep selectivity
## __________________________________________________________________________ ##
##                    PACIFIC HAKE CONTROLS
## __________________CONTROLS FOR ESTIMATED PARAMETERS_______________________ ##
##  Prior descriptions:
##                -0 uniform (0,0)
##                -1 normal (p1=mu,p2=sig)
##                -2 lognormal (p1=log(mu),p2=sig)
##                -3 beta (p1=alpha,p2=beta)
##                -4 gamma(p1=alpha,p2=beta)
## __________________________________________________________________________ ##
7   ## npar

#Original iscam biological oriented priors
## __________________________________________________________________________ ##

##  ival     lb     ub     phz     prior    p1     p2     parameter name
## __________________________________________________________________________ ##
1.9        -1.0    4       1       0       -1.    4.    #log_ro  priors - see SS_ro_prior.xls
0.77       0.2     1.0     1       3       9.766627     2.803034      #steepness  a and b parameters approximate prior from SS - see Betapars.r
-1.609438    -5.0    0.0     2       1       -1.609438  0.2   #log.m
1.9      -5.0    15      1       0       -5.0    15      #log_avgrec
1.9      -5.0    15      1     0         -5.0    15     #log_recinit
0.15       0.01          0.999       4       3       3.0    12.0    #rho
1.25       0.01          150.        3       4       7.49836 5.78354    #varphi (precision)  (RF Change - SJDM had called this kappa)
## __________________________________________________________________________ ##


## ________________________SELECTIVITY PARAMETERS___________________________ ##
## OPTIONS FOR SELECTIVITY:
```

```
##      1) logistic selectivity parameters
##      2) selectivity coefficients
##      3) a constant cubic spline with age-nodes
##      4) a time varying cubic spline with age-nodes
##      5) a time varying bicubic spline with age & year nodes.
##      6) fixed logistic (set isel_type=1, and estimation phase is set to -1 in tpl (ie estimation phase below is ignored))
## Gear 1 fishery:  Gear 2 survey
## isel_type
1            6
## Age at 50% selectivity (logistic) ahat
#4.          4.5
#4.82102   4.5
3.5          2
## STD at 50% selectivity (logistic) ghat
#1.1         0.2
#1.31762   2.1
0.45         0.1
## No. of age nodes for each gear (0 to ignore).
3            0
## No. of year nodes for each gear (0 to ignore).
5            0
## Estimation phase - any negative number means it is fixed!
1            1
## Penalty weight for 2nd differences w=1/(2*sig^2)
150.0        200.0
## Penalty weight for dome-shaped selectivity 1=1/(2*sig^2)
50.0         200.0
#GAMMA prior for  STD at 50% selectivity (logistic) ghat for SURVEY
#prior type (4=gamma)   par1      par2          switch
#ghat_p1 ghat_p2 ghat_pswitch
2.           4.           0

## _____________________________________________________________________________ ##
## _____________________________________________________________________________ ##
##                        Priors for Survey q                          ##
## _____________________________________________________________________________ ##
## nits  #number of surveys
1
## priors 0=uniform density     1=normal density
1
## prior log(mean);
0
## prior sd
0.1
## _____________________________________________________________________________ ##

## _______________________OTHER MISCELLANEOUS CONTROLS cntrl_________________________ ##
0          ## 1 verbose ADMB output (0=off, 1=on)
1          ## 2 recruitment model (1=beverton-holt, 2=ricker)
0.05       ## 3 std in observed catches in first phase.
0.01       ## 4 std in observed catches in last phase.
0          ## 5 Assume unfished in first year (0=FALSE, 1=TRUE)
0.00       ## 6 Minimum proportion to consider in age-proportions for dmvlogistic
0.2        ## 7 Mean fishing mortality for regularizing the estimates of Ft
0.05       ## 8 std in mean fishing mortality in first phase
2.00       ## 9 std in mean fishing mortality in last phase
-1         ## 10 phase for estimating m_deviations (use -1 to turn off mdevs)
0.1        ## 11 std in deviations for natural mortality
12                         ## 12 number of estimated nodes for deviations in natural mortality
0.00       ## 13 fraction of total mortality that takes place prior to spawning
1          ## 14 switch for age-composition likelihood (1=dmvlogistic,2=dmultinom)
0          ## 15 1=estimate Management parameters, 0=estimate population parameters
## _____________________________________________________________________________ ##

## RF ADDED NUMBER OF PROJECTION YEARS
##pyrs
3
```

```
## RF ADDED harvest control rule switch
##hcr
1 ## 1 = 40-10 Rule ... nothing else implemented yet

##Catch stream from SS (OY)
#SSstream
0.274024
0.282668
0.283845

## eofc
999
```

12. Appendix E. Documentation of the transition from TINSS to CCAM

Background

From 2008 to 2010, U.S. and Canadian scientists prepared separate stock assessments for Pacific hake. To an extent, this continued in 2011, although the U.S. and Canadian stock assessment teams collaborated to a much greater degree than previously and presented parallel results from the two models in the same document (Stewart et al. 2011). In all these assessments, the Canadian stock assessment team used a management-oriented model named TINSS (Martell 2008; 2009; 2010; Stewart et al. 2011).

TINSS is an age-structured model that is conditioned on historical catch and parameterized from a management-oriented perspective, where leading estimated parameters are long term Maximum Sustainable Yield (*MSY*) and the equilibrium fishing mortality that results in MSY (F_{MSY}). In management-oriented models (see also Schnute and Kronlund (1996); Richards and Schnute (1998); and Forrest et al. (2008)), *MSY* and F_{MSY} are directly estimated as parameters and analytically transformed to their biological equivalents: unfished recruitment R_0 and the productivity parameter steepness, through the survivorship, growth, maturity and selectivity schedules of the stock (see Stewart et al. (2011): their Appendix F; and Martell et al. (2008) for a detailed description of the transformation from estimated management parameters to biological parameters). Potential advantages of using a management-oriented approach include some improved statistical properties (less confounding between scale and productivity parameters) and the ability to set priors on quantities that are directly observable, such as long term catch and fishing mortality rates (Schnute and Kronlund 1996). However, difficulties in interpreting these reference points and initializing the model may arise when biological or other properties of the stock are not stationary through time. The Pacific hake stock has undergone large fluctuations in mean weight at age since observations began in the 1970s, and it is unlikely that fishery selectivity has remained constant throughout the time series, although time-invariant selectivity has been assumed in recent assessments (and the present assessment) for reasons of parsimony.

In the 2011 stock assessment, results from Stock Synthesis (SS) and TINSS were closer than they had been in previous years (Stewart et al. 2011). This was in large part due to efforts by the two assessment teams to use the same data and underlying assumptions. There were, however, some outstanding differences that were attributed mostly to differences in model parameterisation, priors and selectivity, although the relative contributions of these differences were not able to be quantified in the time available. In part, differences due to the different parameterisations could not be quantified because TINSS could not be parameterised with leading estimated biological parameters. Furthermore, during its four years of use in the Pacific hake assessment, TINSS underwent a number of additions and modifications, largely in response to requests from scientific reviewers. This gradual accumulation of customizations resulted in a model less flexible than was desired for the 2012 assessment.

The Canadian members of the 2012 stock assessment team opted to switch to a new modelling platform in 2012. This was largely in response to a need for greater flexibility than could be provided by TINSS and also because of a desire to develop a more general modelling tool for Canadian Pacific groundfish assessments and management strategy evaluations into the future. Furthermore, it was decided to switch to a model parameterized with leading biological parameters to avoid difficulties associated with initialising a model with *MSY* and F_{MSY} in the presence of non-stationarity in hake weight at age. A new model has been developed at the University of British Columbia by Dr Steven Martell, who has posted it as an open source project with the title ISCAM (Integrated Statistical Catch Age Model). The model contains options for a wide range of structural configurations, including alternative forms for fixed or time-varying selectivity; fixed or time-varying natural mortality; alternative stock-recruit relationships and options for multiple fishing fleets (Martell 2011). During 2011 and 2012, this model has been customized by the Canadian assessment team to calculate the outputs needed for the 2012 Pacific hake assessment. It is referred to here as the "Canadian" Catch Age Model (CCAM) to distinguish the customized version from the original software. Technical details of the model are described in Appendix G of this document. The original ISCAM source code and additional documentation are available at http://code.google.com/p/iscam-project/source/checkout.

A key modification made by the Canadian assessment team has been the addition of a module that allows the model to be parameterized with leading estimated management parameters *MSY* and F_{MSY} (as in TINSS). The ability to switch between alternative biological and management parameterizations provides the option to switch to a biologically-parameterized model for the 2012 assessment, while keeping track of changes in assessment outputs arising from the switch to a new model. The following pages briefly document the steps taken in transitioning from the 2011 TINSS model to the current CCAM model with estimated survey selectivity, through changes in underlying data and model assumptions. This will in part address the 2011 STAR panel request to better understand the differences between TINSS and SS. It will also contribute to greater understanding of the differences between SS and CCAM in the present assessment.

Note that more combinations of settings were tested than are shown in the figures. Some steps that resulted in negligible change in model results are omitted for clarity of presentation, resulting in some skipped letters in step names. All graphs are the result of 500,000 MCMC iterations, thinned to produce 2,000 retained samples, with the first 1,000 discarded. It should be noted that results from these short chains were likely not fully converged and are presented to illustrate broad trends rather than precise results. For the same reason, the final steps presented here may not be identical to those presented in the main body of the assessment.

1. Compare CCAM and TINSS under 2011 conditions

The first step was to compare CCAM and TINSS under the same set of assumptions, priors and data as used in the 2011 assessment. For this set of comparisons, CCAM was run in management-oriented mode, i.e., *MSY* and F_{MSY} were directly estimated, with biological parameters R_0 and steepness analytically derived from them. Figure E1 shows the comparison of posterior estimated female spawning biomass and depletion for TINSS and CCAM in management-oriented mode (CCAM-m), with *MSY* fixed in CCAM-m at the maximum posterior density estimate from TINSS (all other parameters estimated). Figure E2 shows the same comparison, for two alternative steps: C) all parameters in CCAM-m are estimated; and D) CCAM is configured with biologically-oriented leading estimated parameters, R_0 and steepness (CCAM-b), all parameters estimated.

Figure E1 shows very close agreement between the two models when MSY is fixed in CCAM-m, indicating close agreement in the dynamic equations in both models. However, when MSY is allowed to be estimated in CCAM-m (Figure E2), the spawning biomass series still show very close agreement, but the estimated unfished equilibrium spawning biomass from CCAM-m (2.55 million mt) is about twice that estimated in TINSS (1.24 million mt). This is because the estimate of MSY in CCAM-m is about twice of that estimated in TINSS. The CCAM-m median posterior estimate of unfished spawning biomass from step C is closer to that estimated by the 2011 Stock Synthesis model (2.03 million mt) and results in estimates of spawning depletion that are lower than those from the 2011 TINSS assessment (and closer to the 2011 SS assessment).

Investigations to date have not revealed the source of the difference in estimates of MSY (and therefore unfished spawning biomass) between CCAM-m and TINSS. Extensive tests with CCAM in biological and management-oriented mode and process errors turned off have shown that the analytical transformations from *MSY* and F_{MSY} to R_0 and steepness and the numerical back-transformations from R_0 and steepness to *MSY* and F_{MSY} are internally correct within CCAM (identical results are obtained in either direction). Similarly, Figure E1 indicates that these calculations are also consistent between CCAM-m and TINSS (i.e., when MSY is fixed in CCAM-m at the same value as in TINSS, the estimated unfished spawning biomass is very close; Figure E1). Work is continuing to identify the reason for the differences in estimates of *MSY* between the two models, although a number of possible causes have been eliminated (e.g., differences in weights at age used in equilibrium calculations). Differences between treatment of fishing mortality (directly estimated *vs* direct solving of the Baranov equation) and treatment of average recruitment and residuals between CCAM and TINSS mean that there are some fundamental differences in the objective functions and penalties applied in the two models. Given the strong agreement between CCAM and SS in the current (2012) assessment, it appears that the estimate of *MSY* in TINSS was one of the causes of the difference in estimates of spawning depletion and reference point calculations between SS and TINSS in 2011.

Switching to biological-oriented mode in CCAM (CCAM-b) did not result in major differences in estimates of spawning biomass (Figure E2), although the estimate of unfished spawning biomass was higher, leading to lower estimated depletion (but see note above about convergence). This is likely because the estimate of unfished spawning biomass in this case was analytically derived from estimates of log(R_0), which had a broad uniform prior rather than the informative log normal prior for MSY that was used in CCAM-m. The finding that estimates of spawning biomass were similar for all four steps (TINSS, A, C and D), indicates that switching from TINSS to CCAM, configured in either biological or management mode, has not had a major effect on predicted population dynamics. Differences in reference point calculations and, therefore, estimates of depletion appear to be due to differences in priors and properties of the objective function rather than structural differences in the platform itself.

2. Correct and update data from 2011 assessment

Despite the best efforts of the 2011 stock assessment teams to line up the data streams in the two models, a number of inconsistencies were discovered after the assessment period. Therefore, the next step was to bring the 2011 data in line with those used by SS, using CCAM-b. Most of the data updates had negligible effects on model results. One large inconsistency was in the age composition data from the acoustic survey. In the short time frame given for the assessment in

2011, the Canadian team had omitted to update the acoustic age composition data from the 2010 assessment. This was the only correction to the 2011 assessment data that had a significant effect on estimated spawning biomass, with a smaller effect on estimated spawning depletion (Figure E3). See Figure E caption for description of other updates to the data.

3. Add 2012 data

The next steps were to bridge from the 2011 assessment to the 2012 assessment by updating the data file with data from the 2011 fishery and acoustic survey. Figures E4 and E5 show the effects of step-wise additions of new data. Steps taken were: F) update 2010 commercial catch with last of 2010 data; G) update with 2011 commercial catch, catch age and weight at age; H) update with 2011 acoustic survey catch age; I) update with 2011 acoustic survey index; J) update all weight at age data with small changes since 2011; K) update all catch age data with new weighting scheme (see Section 2.1.2 of main document); L) include age-1 in commercial catch age data (TINSS had not previously included commercial age 1 age composition data, largely due to legacies from previous separate Canadian and U.S. modeling efforts, where age-1 data had not always been available to the Canadian scientists). Finally, Figure E6 shows steps: M) match priors for R_0 and steepness to those in SS; and N) set standard deviation for the normal prior on log(M) to 0.2, as in the CCAM model with estimated survey selectivity.

Updating the 2010 catch data with the final numbers (which had not been available in time for the 2011 assessment) had a negligible effect on estimates of spawning biomass. Figure E4 shows that adding the 2011 commercial and survey data, however, had noticeable effects on model outcomes. Notably, when compared to step F (updated 2010 catch), adding the 2011 fishery catch and age composition data resulted in an increase in predicted spawning biomass (Figure E4, red line). The same effect was reported for Stock Synthesis and is discussed in the main body of this assessment document (Figure 12 and Section 3.4.1). Adding the 2011 survey age composition data (step H) resulted in a slight decrease in estimated spawning biomass, and adding the 2011 acoustic survey index (step I) further downgraded the estimate (Figure E4). The effect of adding the 2011 acoustic index appeared to have a much lesser effect than that observed in the SS bridge model (Figure 12, main body of this assessment document). This is because the model showed very poor fit to the survey index data at this step, particularly the 2011 index point (Figure E7).

Figure E5 shows the effect of updates to the weight at age data and weighting of the U.S. and Canadian age composition data (steps J and K). Both of these steps had very minor effects on estimated spawning biomass. The greatest change to the estimates spawning biomass and depletion resulted from the addition of the age-1 commercial age composition data (step L; Figure E5). This is because the age-1 commercial age composition data provided more information for estimation of commercial selectivity for 1-2 year old fish and resulted in a steeper parametric curve that was shifted further left than in steps where those data were excluded (Figure E7). The steeper selectivity curve resulted in a closer fit to the low 2011 acoustic index point (Figure E7) than had been achieved by addition of the survey index alone. Exclusion of age 1 commercial age composition data is likely a reason for the more optimistic results obtained with TINSS in 2011, which had commercial and survey selectivity curves shifted further right than the SS model. Note that the 2011 TINSS model achieved a closer fit to the high 2009 survey index point than the 2011 SS model had. This is likely in part due to the omission of age-1 fish from the commercial age composition data.

Figure E6 shows that matching the priors to those in SS had a small effect when compared to the effect of adding age-1s to the commercial age composition data (step M). Finally, broadening the prior on log (*M*) had the effect of increasing the estimated spawning biomass slightly. This is presented as one of the key sensitivities in the 2012 assessment and is discussed in more detail in the main body of this assessment document.

In summary, this appendix has summarised the steps taken from the TINSS model used in the 2011 stock assessment, through data updates, to the current key sensitivity case presented for the CCAM model. Differences in estimated spawning biomass between the 2011 TINSS assessment and the current CCAM configuration can be explained wholly by addition of new data to the assessment rather than a switch in modelling platforms. Differences in estimates of depletion and MSY-based reference points must also be largely due to updated data, but are also in part due to the switch from TINSS. Further investigation will reveal the source of the differences, although it is noted that results from the CCAM with the 2011 data (steps C and D above) appear to have been more consistent with SS than those from TINSS.

References

Forrest, R.E., S.J.D. Martell, M.C. Melnychuk and C.J. Walters. 2008. An age-structured model with leading management parameters, incorporating age-specific selectivity and maturity. Canadian Journal of Fisheries and Aquatic Sciences 65: 286-296.

Martell, S.J.D. 2008. Assessment and Management Advice for Pacific Hake in U.S. and Canadian Waters in 2008. Technical Report, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest and Alaska Fisheries Science Center.

Martell, S.J.D. 2009. Assessment and Management Advice for Pacific Hake in U.S. and Canadian Waters in 2009. DFO Canadian Science Advis. Sec. Res. Doc., 2009/021:iv+54p.

Martell, S. J. D. 2010. Assessment and management advice for Pacific hake in U.S. and Canadian waters in 2010. Pacific Fishery Management Council. Portland, Oregon. 80 p.

Martell, S. J. D. 2011. iSCAM User's Guide. Version 1.0. University of British Columbia, Vancouver. 34 pp. Available online at http://code.google.com/p/iscam-project/source/checkout.

Martell, S.J.D., Pine, W.E., Walters, C.J. 2008. Parameterizing Age-Structured Models from a Fisheries Management Perspective. Canadian Journal of Fisheries and Aquatic Sciences, 65:1586-1600.

Richards, L.J., Schnute, J.T. 1998. Model Complexity and Catch-Age Analysis. Canadian Journal of Fisheries and Aquatic Sciences, 55: 949-957.

Richards, L. J., J. T. Schnute, and N. Olsen. 1997. Visualizing catch-age analysis: a case study. Canadian Journal of Fisheries and Aquatic Sciences 54: 1646-1658.

Schnute, J.T., Richards, L.J. 1998. Analytical Models for Fishery Reference Points. Canadian Journal of Fisheries and Aquatic Sciences, 55: 515-528.

Schnute, J.T. and Kronlund, A.R. 1996. A management oriented approach to stock recruitment analysis. Can. J. Fish. Aquat. Sci. 53: 1281-1293.

Stewart, I. J., R. E. Forrest, C.J. Grandin, O.S. Hamel, A.C. Hicks, S.J.D. Martell and I.G. Taylor. 2011. Status of the Pacific hake (whiting) stock in U.S. and Canadian waters in 2011, In Status of the Pacific Coast Groundfish Fishery through 2011, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and rebuilding analyses. Pacific Fishery Management Council, Portland, Oregon. 217 p.

Appendix E Figures

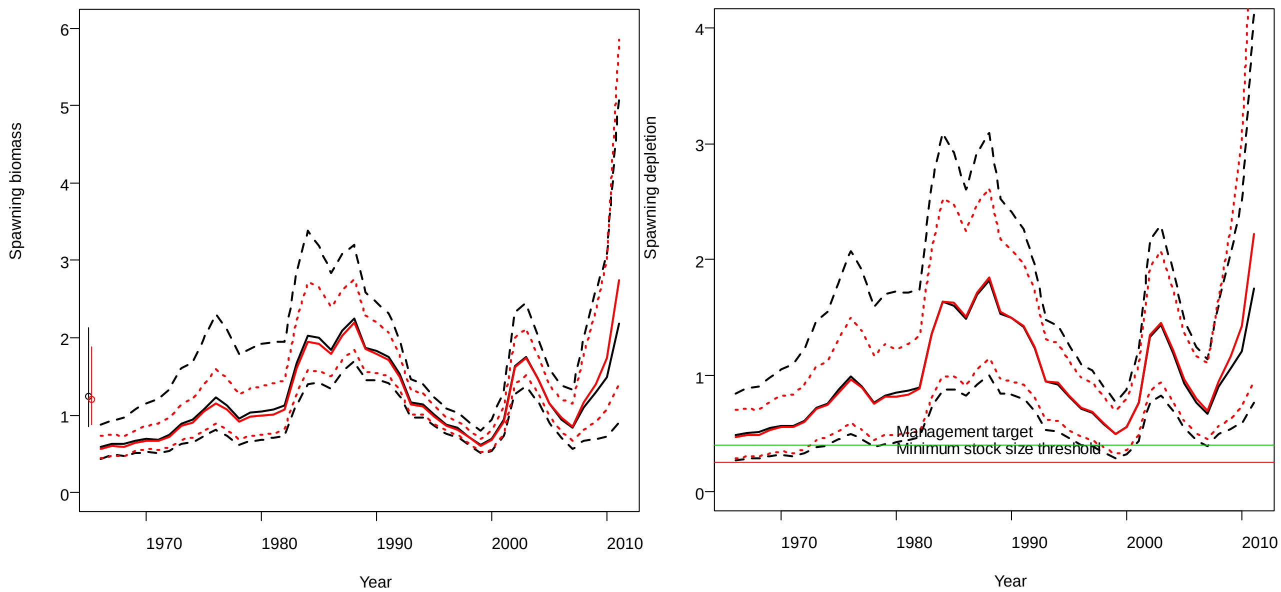
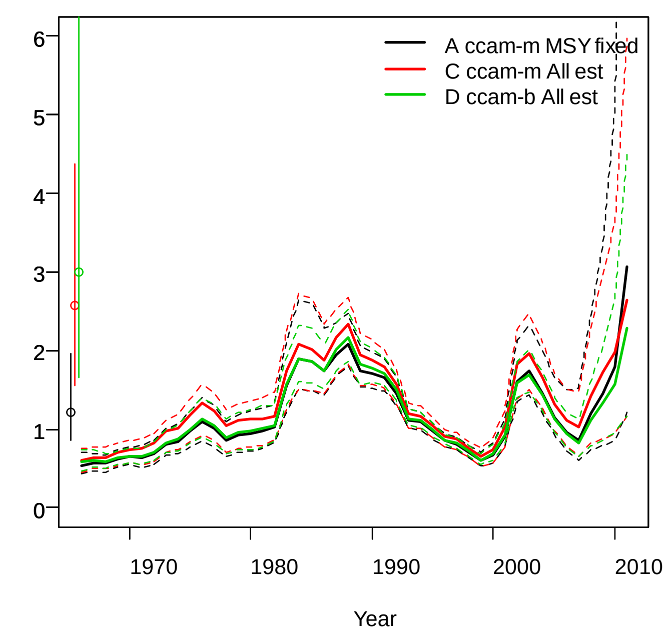
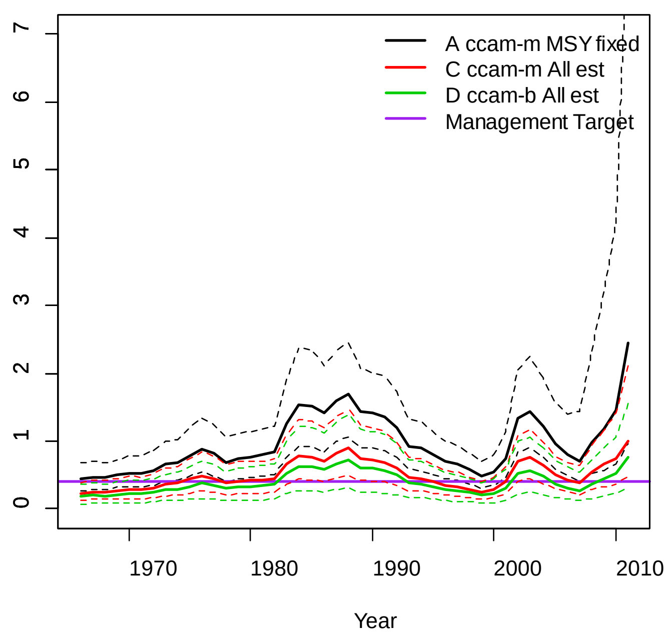


Figure E1. Comparison of female spawning biomass between TINSS and CCAM-m, with MSY fixed in CCAM-m at the maximum likelihood estimate from TINSS (all other parameters estimated).

Spawning biomass



Depletion



FigureE2. Comparison of female spawning biomass and depletion in CCAM-m, for B) all parameters in CCAM-m are estimated except M, which is fixed at the 2011 TINSS MLE value; C) all parameters in CCAM-m are estimated; and D) CCAM is configured with biologically-oriented leading estimated parameters (CCAM-b), all parameters estimated.

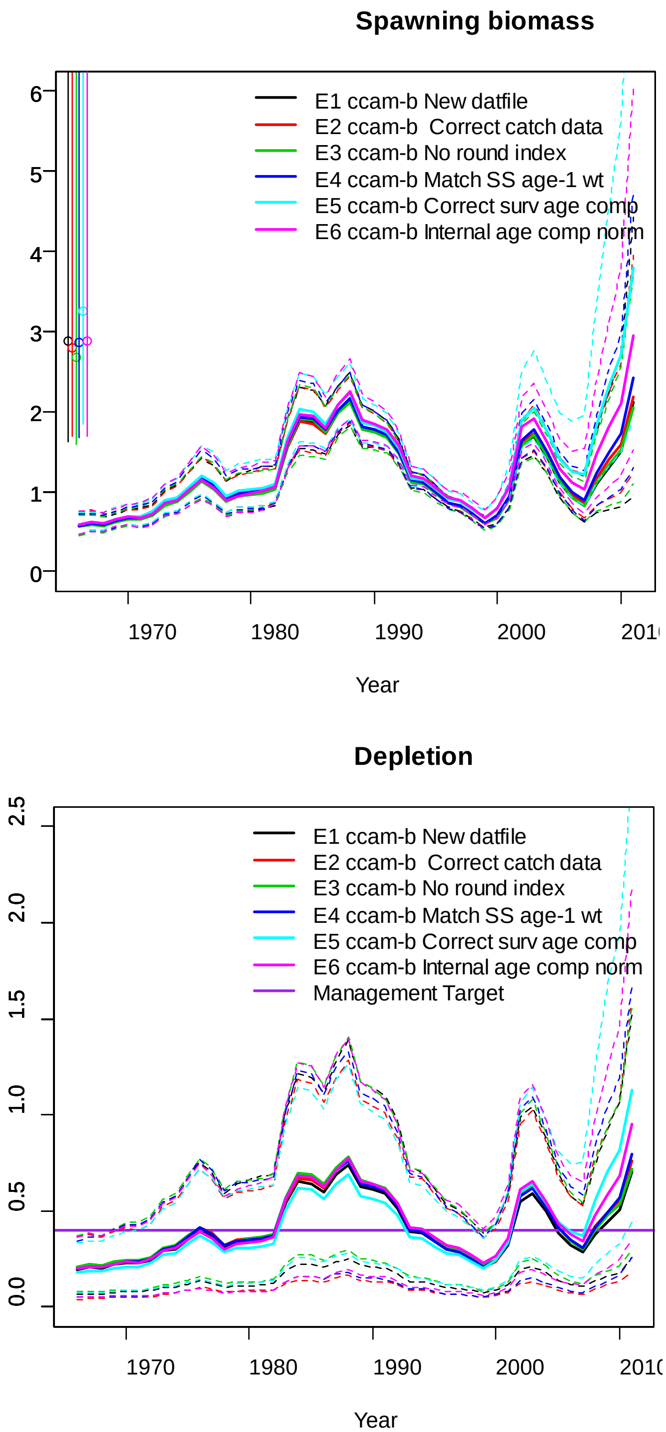
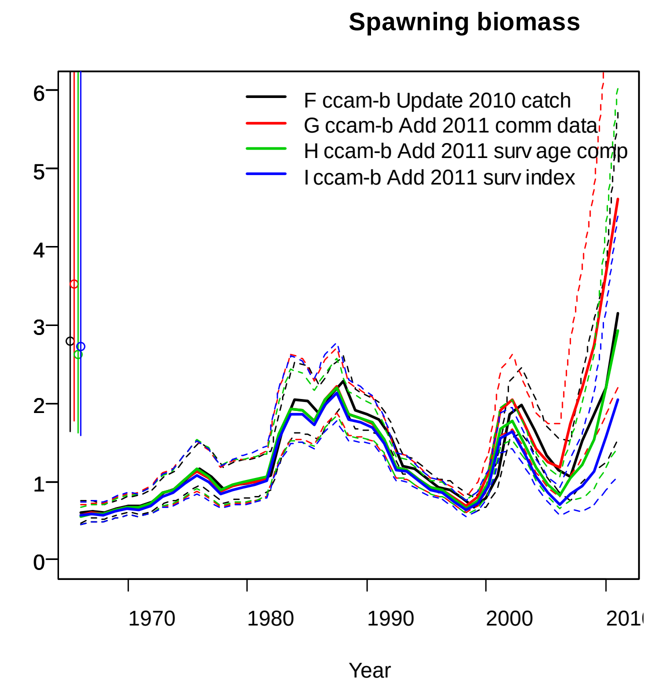


Figure E3. Comparison of estimated female spawning biomass and depletion in CCAM-b, for : E1) New 2011 datafile (but no changes to the data; same as D above); E2) Correct small errors in catch; E3) Don't round survey index; E4) Line up age-1 estimated weights with SS; E5) Correct the survey age composition data; and E6) use un-normalised fishery age composition data and normalise within the model.



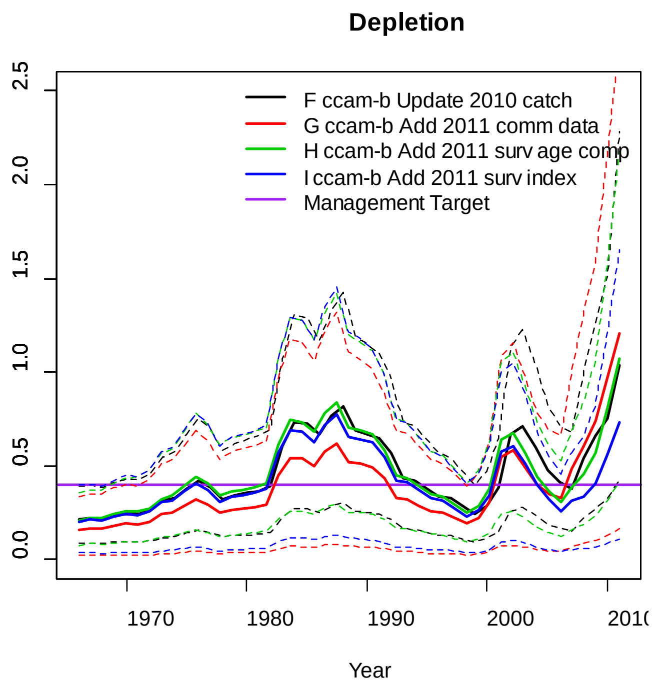
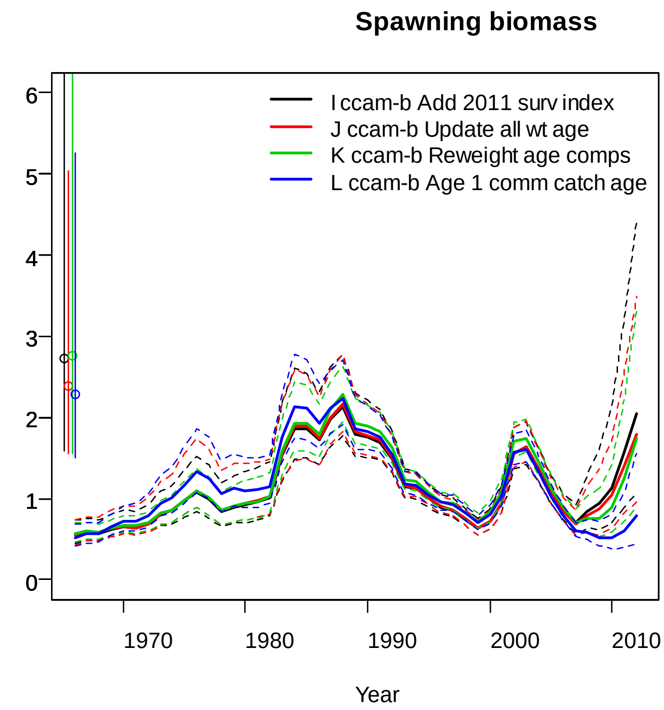


Figure E4. Comparison of female spawning biomass and depletion in CCAM-b for: F) Update 2010 commercial catch with last of 2010 data; G) Update with 2011 commercial catch, catch age and weight at age; H) Update with 2011 acoustic survey catch age; and I) Update with 2011 acoustic survey index.



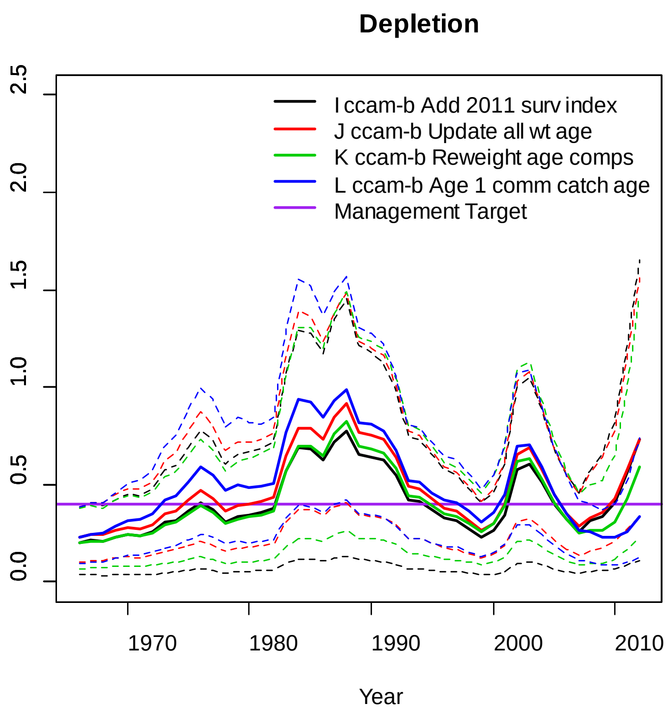


Figure E5. Comparison of female spawning biomass and depletion in CCAM-b for: I) Update with 2011 acoustic survey index; J) Update all weight at age data; K) Update all catch age data with new weighting scheme; and L) Include age-1 in commercial catch age data.

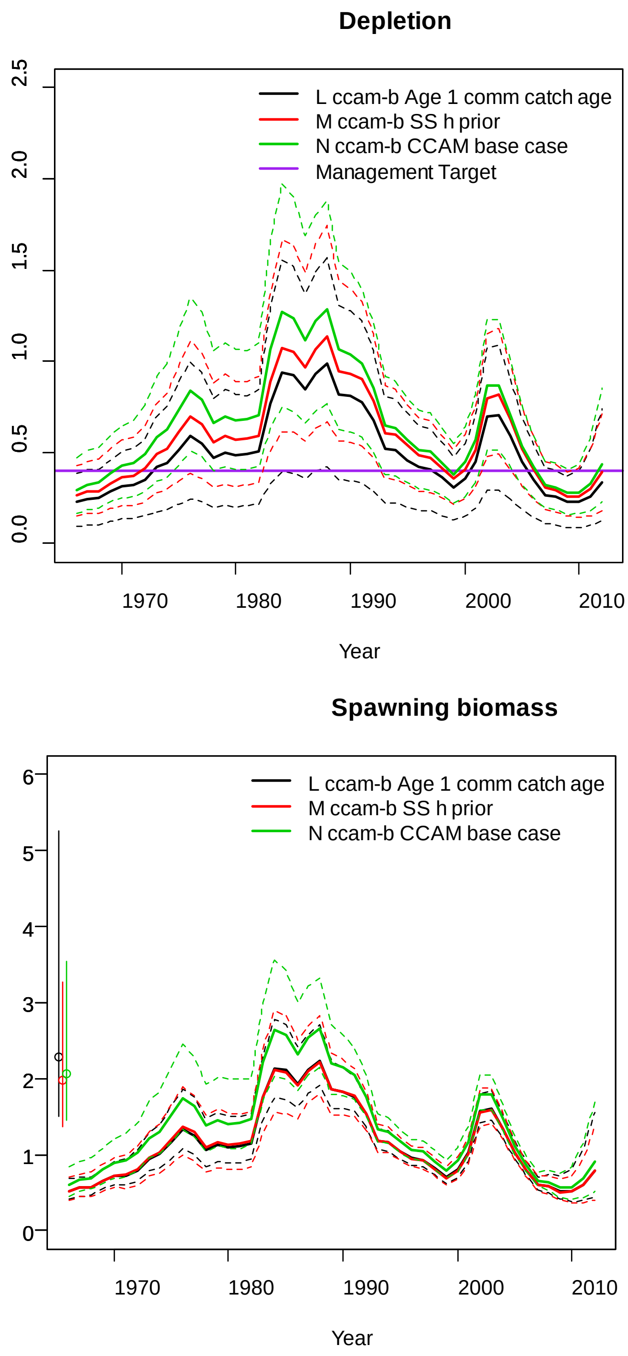


Figure E6. Comparison of female spawning biomass and depletion in CCAM-b for L) Include age-1 in commercial catch age data; M) Match priors for R_0 and steepness to those in SS; and N) Set standard deviation for the normal prior on log(M) to 0.2, as in the CCAM model with estimated survey selectivity.

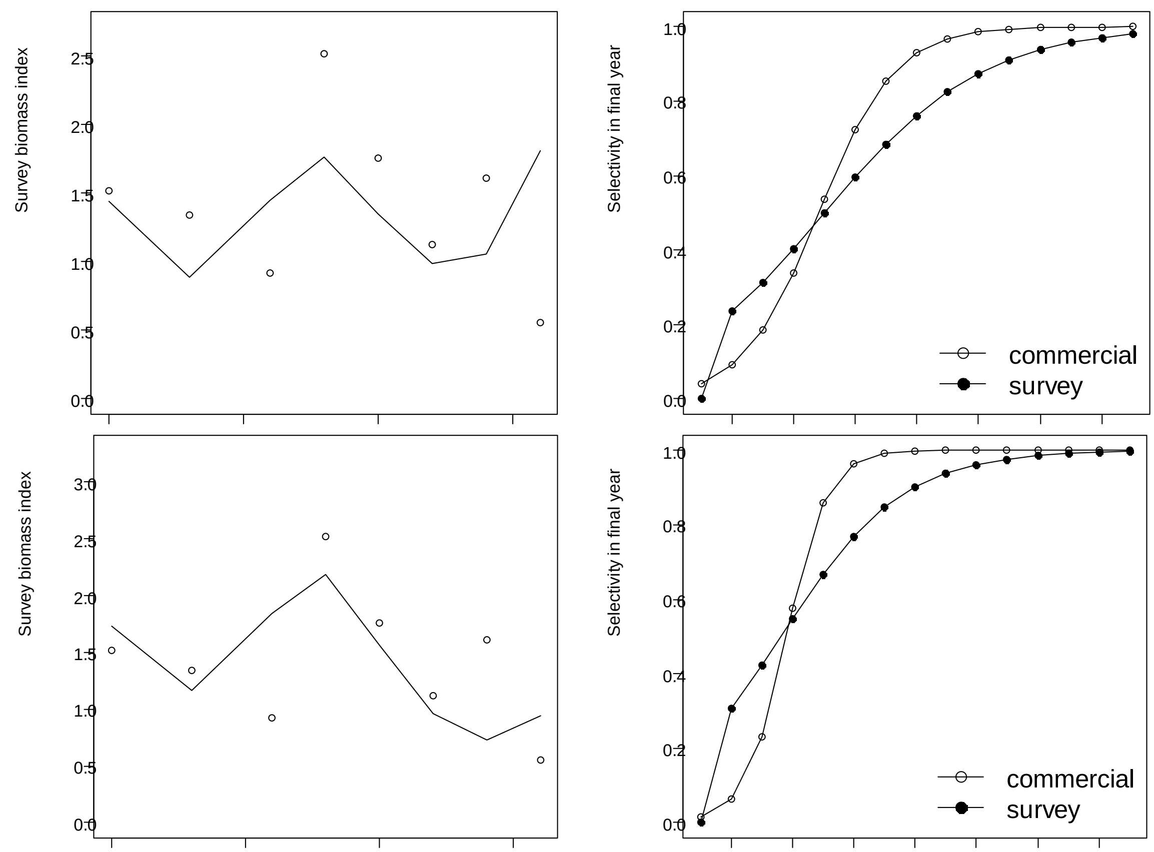


Figure E7. Fits to the acoustic survey index (left) and estimated commercial and survey selectivity (right) for Steps: I) Update with 2011 acoustic survey index; and L) Include age-1 in commercial catch age data.

13. Appendix F. CCAM model description and documentation

Technical description of the Canadian Catch Age Model (CCAM)

Analytic methods

The section contains technical documentation of the underlying age-structured model, its steady state version used to calculate reference points, the observation models used in predicting observations, and the components of the objective function that formulate the statistical criterion used to estimate model parameters. Model equations are presented in tables intended to represent the order of operations, or pseudocode, in which to implement the model. CCAM was implemented in AD Model Builder version 10.1. The model was originally developed at the University of British Columbia and has been posted as an open source project by its author, Dr Steven Martell, under the title ISCAM (Integrated Statistical Catch Age Model). The model has been customized by the Canadian assessment team to calculate the outputs needed for the assessment of Pacific hake and for production of this document. It is therefore referred to here as CCAM to distinguish this customized version from the original software. The original source code and additional documentation is available at `http://code.google.com/p/iscam-project/source/checkout`.

Equilibrium considerations

Steady-state conditions are presented in Table 1; here we assume the parameter vector Θ is an input (with the exception of F_e) that is estimated by fitting the dynamics model to time series data (Tables 2 and 3 below). Note however, that the equilibrium model is parameterized in terms of recruitment compensation κ (Table 1), whereas the estimation model is parameterized in terms steepness h; the conversion $\kappa = 4h/(1-h)$ (?) is applied to steepness before being passed from the estimation model to the equilibrium model. The definition of F_e is the steady-state fishing mortality rate, and the value of F_e that maximizes equilibrium yield corresponds to F_{MSY}(see section). The value of F_e where $\phi_e/\phi_E = 0.4$ is $F_{40\%}$.

For Pacific hake, weight at age w_a is given by the empirical weight-at-age data and the age-specific vulnerability is given by a logistic function (5). If alternative selectivity functions are implemented in CCAM, then (5) does not apply; other forms are described section . Mean fecundity-at-age is assumed to be proportional to the mean weight-at-age of mature fish, where maturity at age is specified by the parameters $\dot{a}$ and $\dot{\gamma}$ for the logistic function.

Survivorship for unfished and fished populations is defined by (7) and (8), respectively. It is assumed that all individuals ages A and older (i.e., the plus group) have the same total mortality rate. The incidence functions refer to the life-time or per-recruit quantities such as spawning biomass per recruit (ϕ_E) or vulnerable biomass per recruit (ϕ_b). Note that upper and lower case subscripts denote unfished and fished conditions, respectively. Spawning biomass per recruit is given by (9), the vulnerable biomass per recruit is given by (10) and the

Table 1: Steady-state age-structured model assuming unequal vulnerability-at-age, age-specific natural mortality, age-specific fecundity and Beverton-Holt type recruitment. Note that M is the average natural mortality rate between 1966-2011.

Parameters

$$\Theta = (B_o, \kappa, M, \hat{a}, \hat{\gamma}, F_e) \tag{1}$$

$$B_o > 0; \kappa > 1; M > 0; F_e \geq 0$$

$$\Phi = (l_\infty, k, t_o, a, b, \dot{a}, \dot{\gamma}) \tag{2}$$

Age-schedule information

$$l_a = l_\infty(1 - \exp(-k(a - t_o))) \tag{3}$$

$$w_a = a(l_a)^b \tag{4}$$

$$v_a = (1 + \exp(-(\hat{a} - a)/\gamma))^{-1} \tag{5}$$

$$f_a = w_a(1 + \exp(-(\dot{a} - a)/\dot{\gamma}))^{-1} \tag{6}$$

Survivorship

$$\iota_a = \begin{cases} 1, \quad a = 1 \\ \iota_{a-1}e^{-M}, \quad a > 1 \\ \iota_{a-1}/(1 - e^{-M}), \quad a = A \end{cases} \tag{7}$$

$$\hat{\iota}_a = \begin{cases} 1, \quad a = 1 \\ \hat{\iota}_{a-1}e^{-M-F_e v_{a-1}}, \quad a > 1 \\ \hat{\iota}_{a-1}e^{-M-F_e v_{a-1}}/(1 - e^{-M-F_e v_a}), \quad a = A \end{cases} \tag{8}$$

Incidence functions

$$\phi_E = \sum_{a=1}^{\infty} \iota_a f_a, \quad \phi_e = \sum_{a=1}^{\infty} \hat{\iota}_a f_a \tag{9}$$

$$\phi_B = \sum_{a=1}^{\infty} \iota_a w_a v_a, \quad \phi_b = \sum_{a=1}^{\infty} \hat{\iota}_a w_a v_a \tag{10}$$

$$\phi_q = \sum_{a=1}^{\infty} \frac{\hat{\iota}_a w_a v_a}{M + F_e v_a} \left(1 - e^{(-M-F_e v_a)}\right) \tag{11}$$

Steady-state conditions

$$R_o = B_o/\phi_B \tag{12}$$

$$R_e = R_o \frac{\kappa - \phi_E/\phi_e}{\kappa - 1} \tag{13}$$

$$C_e = F_e R_e \phi_q \tag{14}$$

per recruit yield to the fishery is given by (11). Unfished recruitment is given by (12) and the steady-state equilibrium recruitment for a given fishing mortality rate F_e is given by (13). Note that in (13) we assume that recruitment follows a Beverton-Holt model of the form:

$$R_e = \frac{s_o R_e \phi_e}{1 + \beta R_e \phi_e}$$

where

$$s_o = \kappa/\phi_E,$$
$$\beta = \frac{(\kappa - 1)}{R_o \phi_E},$$
$$\kappa = 4h/(1-h),$$

which simplifies to (13), for the Beverton-Holt model.

The equilibrium yield for a given fishing mortality rate is (14). These steady-state conditions are critical for determining various reference points such as F_{MSY}, $F_{40\%}$ and B_{MSY}. The description of calculating steady-state yield for a given value of F_e in Table 1 is written assuming that only one fishing fleet exists, as assumed for the current Pacific hake assessment.

It should be noted here that MSY and $F_{40\%}$-based reference points assume steady-state conditions, and the model structure that is implemented for the Pacific Hake stocks is non-stationary due to time-varying changes in weight at age and optionally, selectivity. For the purpose of this assessment, reference point estimates assume that the equilibrium weights at age are given by the average mean weight-at-age over the entire time series.

Reference points

CCAM calculates MSY-based reference points by finding the value of F_e that results in the zero derivative of the steady-state catch equation (14). This is accomplished numerically using a Newton-Raphson method where an initial guess for F_{MSY} is set equal to $1.5\bar{M}$, then use (15) to iteratively find F_{MSY}. Note that the partial derivatives in (15) can be found in Table 2.

$$F_{e+1} = F_e - \frac{\frac{\partial C_e}{\partial F_e}}{\frac{\partial^2 C_e}{\partial F_e}} \qquad (15)$$

where

$$\frac{\partial C_e}{\partial F_e} = R_e \phi_q + F_e \phi_q \frac{\partial R_e}{\partial F_e} + F_e R_e \frac{\partial \phi_q}{\partial F_e}$$
$$\frac{\partial^2 C_e}{\partial F_e} = \phi_q \frac{\partial R_e}{\partial F_e} + R_e \frac{\partial \phi_q}{\partial F_e}$$

The algorithm usually converges in less than 10 iterations depending on how close the initial guess of F_{MSY} is to the true value. A maximum of 20 iterations are allowed in CCAM, however, if $\frac{\partial C_e}{\partial F_e} < 10^{-6}$ the algorithm stops. Note also, that this is only performed on data type variables and not differentiable variables within AD Model Builder.

The equilibrium fishing mortality rate ($F_{40\%}$) that results in the spawning potential ratio (SPR) being reduced to 40% of the unfished level is calculated using the Newton-Raphson approach and partial derivatives described for F_{MSY}, where the criterion is to search for the value of F_e that results in $\phi_e/\phi_E = 0.4$. Similarly, $FB_{40\%}$ is defined as the value of F_e that results in $SB_e/SB_0 = 0.4$, where SB_e is equilibrium fished spawning biomass ($R_e\phi_e$) and SB_0 is unfished spawning biomass ($R_0\phi_E$).

Given an estimate of F_{MSY}, $F_{40\%}$ or $FB_{40\%}$, other reference points such as MSY are calculated use the equations in Table 1 where each of the expressions is evaluated at F_{MSY}, $F_{40\%}$ or $FB_{40\%}$.

Dynamic age-structured model

The estimated parameter vector in CCAM is defined in (22), where R_0, h and M are the leading unknown population parameters that define the overall population scale in the form of unfished recruitment and productivity in the form of steepness h and natural mortality, M. CCAM does not assume that the population is at unfished equilibrium in the first model year; instead, it assumes that initial recruitment is given by $\ddot{R}$. The total standard deviation ϑ^2 and the proportion of the total total standard deviation that is associated with observation errors ρ are also estimated, then the total is partitioned into observation errors (σ^2) and process errors (τ^2) using (23).

The unobserved state variables (24) include the numbers-at-age year year t ($N_{t,a}$), the spawning stock biomass (B_t) and the total age-specific total mortality rate ($Z_{t,a}$).

The initial numbers-at-age in the first year (25) and the annual recruits (26) are treated as estimated parameters and used to initialize the numbers-at-age matrix. Age-specific selectivity for gear type k is a function of the selectivity parameters γ_k (27), and the annual fishing mortality for each gear k in year t ($\Gamma_{k,t}$). The vector of log fishing mortality rate parameters $\Gamma_{k,t}$ is a bounded vector with a minimum value of -30 and an upper bound of 3.0. In arithmetic space this corresponds to a minimum value of 9.36e-14 and a maximum value of 20.01 for annual fishing mortality rates. In years where there are 0 reported catches for a given fleet, no corresponding fishing mortality rate parameter is estimated and the implicit assumption is there was no fishery in that year.

There is an option to treat natural mortality as a random walk process (28), where the natural mortality rate in the first year is the estimated leading parameter (22) and in subsequent years the mortality rate deviates from the previous year based on the estimated deviation parameter φ_t. If the mortality deviation parameters are not estimated, then M is assumed to be time invariant.

Table 2: Partial derivatives, based on components in Table 1, required for the numerical calculation of F_{MSY} using (15).

Mortality & Survival

$$Z_a = M + F_e v_a \tag{16}$$

$$S_a = 1 - e^{-Z_a} \tag{17}$$

Partial for survivorship

$$\frac{\partial \hat{\imath}_a}{\partial F_e} = \begin{cases} 0, & a = 1 \\ e^{-Z_{a-1}} \left(\frac{\partial \hat{\imath}_{a-1}}{\partial F_e} - \hat{\imath}_{a-1} v_{a-1} \right), & 1 < a < A \\ \frac{\frac{\partial \hat{\imath}_{a-1}}{\partial F_e}}{(1 - e^{-Z_a})} - \frac{\hat{\imath}_{a-1} e^{-Z_{a-1}} v_a e^{-Z_a}}{(1 - e^{-Z_a})^2}, & a = A \end{cases} \tag{18}$$

Partials for incidence functions

$$\frac{\partial \phi_e}{\partial F_e} = \sum_{a=1}^{\infty} f_a \frac{\partial \hat{\imath}_a}{\partial F_e} \tag{19}$$

$$\frac{\partial \phi_q}{\partial F_e} = \sum_{a=1}^{\infty} \frac{w_a v_a S_a}{Z_a} \frac{\partial \hat{\imath}_a}{\partial F_e} + \frac{\hat{\imath}_a w_a v_a^2}{Z_a} \left(e^{-Z_a} - \frac{S_a}{Z_a} \right) \tag{20}$$

Partial for recruitment

$$\frac{\partial R_e}{\partial F_e} = \frac{R_o}{\kappa - 1} \frac{\phi_E}{\phi_e^2} \frac{\partial \phi_e}{\partial F_e} \tag{21}$$

Table 3: Statistical catch-age model using the Baranov catch equation, where R_0 and h are the leading parameters that define population scale and productivity, respectively.

Estimated parameters

$$\Theta = \left(R_0, h, M, \bar{R}, \ddot{R}, \rho, \vartheta, \vec{\gamma}_k, \mathit{\Gamma}_{k,t}, \{\ddot{\omega}_a\}_{a=\acute{a}+1}^{a=A}, \{\omega_t\}_{t=1}^{t=T}, \{\varphi_t\}_{t=2}^{T}\right) \tag{22}$$

$$\sigma = \rho/\vartheta, \quad \tau = (1-\rho)/\vartheta \tag{23}$$

Unobserved states

$$N_{t,a}, B_t, Z_{t,a} \tag{24}$$

Initial states ($t = \acute{t}$)

$$N_{t,a} = \ddot{R}e^{\ddot{\omega}_a} \exp(-M_t)^{(a-\acute{a})}; \quad t = \acute{t}; \acute{a} \leq a \leq A \tag{25}$$

$$N_{t,a} = \bar{R}e^{\omega_t}; \quad \acute{t} \leq t \leq T; a = \acute{a} \tag{26}$$

$$v_{k,a} = f(\vec{\gamma}_k) \tag{27}$$

$$M_t = M_{t-1}\exp(\varphi_t), \quad t > 1, \varphi_t \sim N(0, \sigma_M) \tag{28}$$

$$F_{k,t} = \exp(\mathit{\Gamma}_{k,t}) \tag{29}$$

State dynamics ($t > \acute{t}$)

$$B_t = \sum_a N_{t,a} f_a \tag{30}$$

$$Z_{t,a} = M_t + \sum_k F_{k,t} v_{k,t,a} \tag{31}$$

$$\hat{C}_{k,t} = \sum_a \frac{N_{t,a} w_a F_{k,t} v_{k,t,a}\left(1 - e^{-Z_{t,a}}\right)}{Z_{t,a}} e^{\eta_t} \tag{32}$$

$$N_{t,a} = \begin{cases} N_{t-1,a-1}\exp(-Z_{t-1,a-1}) & a > \acute{a} \\ N_{t-1,a}\exp(-Z_{t-1,a}) & a = A \end{cases} \tag{33}$$

Recruitment models

$$R_t = \frac{s_o B_{t-k}}{1 + \beta B_{t-k}} e^{\delta_t - 0.5\tau^2} \quad \text{Beverton-Holt} \tag{34}$$

$$R_t = s_o B_{t-k} e^{-\beta B_{t-k} + \delta_t - 0.5\tau^2} \quad \text{Ricker} \tag{35}$$

Table 4: An incomplete list of symbols, constants and description for variables used in CCAM.

Symbol	Constant value	Description
Indexes		
a		index for age
t		index for year
k		index for gear
Model dimensions		
$\acute{a}, A$	2, 10	youngest and oldest age class (A is a plus group)
$\acute{t}, T$	1951, 2010	first and last year of catch data
K	5	Number of gears including survey gears
Observations (data)		
$C_{k,t}$		catch in weight by gear k in year t
$I_{k,t}$		relative abundance index for gear k in year t
$p_{k,t,a}$		observed proportion-at-age a in year t for gear k
Estimated parameters		
R_o		Age-$\acute{a}$ recruits in unfished conditions
h		recruitment steepness
M		instantaneous natural mortality rate
$\bar{R}$		average age-$\acute{a}$ recruitment from year $\acute{t}$ to T
$\ddot{R}$		average age-$\acute{a}$ recruitment in year $\acute{t}-1$
ρ		fraction of the total variance associated with observation error
ϑ		total precision (inverse of variance) of the total error
$\vec{\gamma}_k$		vector of selectivity parameters for gear k
$\Gamma_{k,t}$		logarithm of the instantaneous fishing mortality for gear k in year t
$\ddot{\omega}_a$		age-$\acute{a}$ deviates from $\ddot{R}$ for year $\acute{t}$
ω_t		age-$\acute{a}$ deviates from $\bar{R}$ for years $\acute{t}$ to T
φ_t		logarithm of annual change in natural mortality rate
Standard deviations		
σ_M	0.1	standard deviation in random walk for natural mortality
σ		standard deviation for observation errors in survey index
τ		standard deviation in process errors (recruitment deviations)
σ_C	0.0707	standard deviation in observed catch by gear
Residuals		
δ_t		annual recruitment residual
η_t		residual error in predicted catch

State variables in each year are updated using equations 30–33, where the spawning biomass is the product of the numbers-at-age and the mature biomass-at-age (30). The total mortality rate is given by (31), and the total catch (in weight) for each gear is given by (32) assuming that both natural and fishing mortality occur simultaneously throughout the year. The numbers-at-age are propagated over time using (33), where members of the plus group (age A) are all assumed to have the same total mortality rate.

Recruitment to age k can follow either a Beverton-Holt model (34) or a Ricker model (35) where the maximum juvenile survival rate (s_o) in either case is defined by $s_o = \kappa/\phi_E$. For the Beverton-Holt model, β is derived by solving (34) for β conditional on estimates of κ and R_o:

$$\beta = \frac{\kappa - 1}{R_o \phi_E},$$

and for the Ricker model this is given by:

$$\beta = \frac{\ln(\kappa)}{R_o \phi_E}$$

where $\kappa = 4h/(1-h)$ and $\kappa = 5h^{5/4}$ for the Beverton-Holt and Ricker models, respectively. Note that only the Beverton-Holt formulation is used in the current Pacific hake assessment.

Options for selectivity

At present, there are eight alternative age-specific selectivity options in CCAM. We describe a subset of these below. For further information, see additional documentation available at `http://code.google.com/p/iscam-project/source/checkout`. The simplest of the selectivity options is a simple logistic function with two parameters where it is assumed that selectivity is time-invariant. For the purposes of the current Pacific hake assessment, we confine our explorations of selectivity to the logistic form.

The more complex selectivity options assume that selectivity may vary over time a may have as many as (A-1)·T parameters. For time-varying selectivity, cubic and bicubic splines are used to reduce the number of estimated parameters. The last two options consider how selectivity may vary over time based on changes in mean weight-at-age. Prior to parameter estimation, CCAM will determine the exact number of selectivity parameters that need to be estimated based on which selectivity option was chosen for each gear type. It is not necessary for all gear types to have the same selectivity option. For example it is possible to have a simple two parameter selectivity curve for say a survey gear, and a much more complicated selectivity option for a commercial fishery.

Logistic selectivity The logistic selectivity option is a two parameter model of the form

$$v_a = \frac{1}{1 + \exp\left(-(a - \mu_a)/\sigma_a\right)}$$

where μ_a and σ_a are the two estimated parameters representing the age-at-50% vulnerability and the standard deviation, respectively. Throughout the main body of the assessment we occasionally refer to parameters μ_a and σ_a as *ahat* and *ghat* respectively.

Age-specific selectivity coefficients The second option also assumes that selectivity is time-invariant and estimates at total of A-1 selectivity coefficients, where the plus group age-class is assumed to have the same selectivity as the previous age-class. For example, if the ages in the model range from 1 to 15 years, then a total of 14 selectivity parameters are estimated, and age-15+ animals will have the same selectivity as age-14 animals.

When estimating age-specific selectivity coefficients, there are two additional penalties that are added to the objective function that control how much curvature there is and limit how much dome-shaped can occur. To penalize the curvature, the square of the second differences of the vulnerabilities-at-age are added to the objective function:

$$\lambda_k^{(1)} \sum_{a=2}^{A-1} (v_{k,a} - 2v_{k,a-1} + v_{k,a-2})^2 \tag{36}$$

The dome-shaped term penalty as:

$$\begin{cases} \lambda_k^{(2)} \sum_{a=1}^{A-1} (v_{k,a} - v_{k,a+1})^2 & (if) v_{k,a+1} < v_{k,a} \\ 0 & (if) v_{k,a+1} \geq v_{k,a} \end{cases} \tag{37}$$

For this selectivity option the user must specify the relative weights $(\lambda_k^{(1)}, \lambda_k^{(2)})$ to add to these two penalties.

Cubic spline interpolation The third option also assumes time-invariant selectivity and estimates a selectivity coefficients for a series age-nodes (or spline points) and uses a natural cubic spline to interpolate between these nodes. Given $n+1$ distinct knots x_i, selectivity can be interpolated in the intervals defined by

$$S(x) = \begin{cases} S_0(x) & x \in [x_0, x_1] \\ S_1(x) & x \in [x_1, x_2] \\ \dots & \\ S_{n-1}(x) & x \in [x_{n-1}, x_n] \end{cases}$$

where $S''(x_0) = S''(x_n) = 0$ is the condition that defines a natural cubic spline.

The same penalty functions for curvature and dome-shaped selectivity are also invoked for the cubic spline interpolation of selectivity.

Time-varying selectivity with cubic spline interpolation A fourth option allows for cubic spline interpolation for age-specific selectivity in each year. This option adds a considerable number of estimated parameters but the most extreme flexibility. For example, given 40 years of data and estimated 5 age nodes, this amounts 200 (40 years times 5 ages) estimated selectivity parameters. Note that the only constraints at this time are the dome-shaped penalty and the curvature penalty; there is no constraint implemented for say a random walk (first difference) in age-specific selectivity). As such this option should only be used in cases where age-composition data is available for every year of the assessment.

Bicubic spline to interpolate over time and ages The fifth option allows for a two-dimensional interpolation using a bicubic spline. In this case the user must specify the number of age and year nodes. Again the same curvature and dome shaped constraints are implemented. It is not necessary to have age-composition data each and every year as in the previous case, as the bicubic spline will interpolate between years. However, it is not advisable to extrapolate selectivity back in time or forward in time where there are no age-composition data unless some additional constraint, such as a random-walk in age-specific selectivity coefficients is implemented (as of February 6, 2012, this has not been implemented).

Residuals, likelihoods & objective function value components

There are three effective components to the overall objective function that is minimized. These components consist of the likelihood of the data, prior distributions and penalty functions that are invoked to regularize the solution during intermediate phases of the non-linear parameter estimation. This section discusses each of these in turn, starting first with the residuals between observed and predicted states followed by the negative loglikelihood that is minimized for the catch data, relative abundance data, age-composition, and stock-recruitment relationships.

Catch data It is assumed that the measurement errors in the non-zero catch observations are log-normally distributed, and the residuals is given by:

$$\eta_{k,t} = \ln(C_{k,t}) - \ln(\hat{C}_{k,t}), \tag{38}$$

The residuals are assumed to be normally distributed with a user specified standard deviation σ_C. At present, it is assumed that observed catches for each gear k is assumed to have the same standard deviation. To aid in parameter estimation, two separate standard deviations are specified in the control file: the first is the assumed standard deviation used in the first, second, to N-1 phases, and the second is the assumed standard deviation in the last phase. The negative loglikelihood (ignoring the scaling constant) for the catch data is given by:

$$\ell_C = \sum_k \left[T_k \ln(\sigma_C) + \frac{\sum_{t \in \hat{C}_{k,t} \neq 0} (\eta_{k,t})^2}{2\sigma_C^2} \right], \tag{39}$$

where T_k is the total number of non-zero catch observations for gear type k.

Relative abundance data The relative abundance data are assumed to be proportional to biomass that is vulnerable to the sampling gear:

$$V_{k,t} = \sum_a N_{t,a} e^{-\lambda_{k,t} Z_{t,a}} v_{k,a} w_{a,t}, \tag{40}$$

where $v_{k,a}$ is the age-specific selectivity of gear k, and w_a is the mean-weight-at-age. A user specified fraction of the total mortality $\lambda_{k,t}$ adjusts the numbers-at-age to correct for survey timing. The residuals between the observed and predicted relative abundance index is given by:

$$\epsilon_{k,t} = \ln(I_{k,t}) - \ln(q_k) - \ln(V_{k,t}), \tag{41}$$

where $I_{k,t}$ is the observed relative abundance index, q_k is the catchability coefficient for index k, and $V_{k,t}$ is the predicted vulnerable biomass at the time of sampling. The catchability coefficient q_k is evaluated at its conditional maximum likelihood estimate:

$$q_k = \frac{1}{N_k} \sum_{t \in I_{k,t}} \ln(I_{k,t}) - \ln(V_{k,t}),$$

where N_k is the number of relative abundance observations for index k (see **?**, for more information). The negative loglikelihood for relative abundance data is given by:

$$\ell_I = \sum_k \sum_{t \in I_{k,t}} \ln(\sigma_{k,t}) + \frac{\epsilon^2_{k,t}}{2\sigma^2_{k,t}} \tag{42}$$

where

$$\sigma_{k,t} = \frac{\rho\vartheta}{\omega_{k,t}},$$

where $\rho\vartheta$ is the proportion of the total error that is associated with observation errors, and $\omega_{k,t}$ is a user specified relative weight for observation t from gear k. The $\omega_{k,t}$ terms allow each observation to be weighted relative to the total error $\rho\vartheta$; for example, to omit a particular observation, set $\omega_{k,t} = 0$, or to give 2 times the weight, then set $\omega_{k,t} = 2.0$. To assume all observations have the same variance then simply set $\omega_{k,t} = 1$. Note that if $\omega_{k,t} = 0$ then equation (42) is undefined; therefore, CCAM adds a small constant to $\omega_{k,t}$ (1.e-10, which is equivalent to assuming an extremely large variance) to ensure the likelihood can be evaluated.

For Pacific hake, survey observations I_t are multiplicatively weighted in the objective function, relative to the year with the most precise survey index (in this case, 1998) See table 5. CCAM assumes that the survey occurs in the middle of year.

Table 5: Survey weighting and timing for Pacific hake

year	I_t	gear	wt	survey timing
1995	1.517948	2	0.7376	0.5
1998	1.34274	2	1	0.5
2001	0.918622	2	0.5971	0.5
2003	2.520641	2	0.693	0.5
2005	1.754722	2	0.5795	0.5
2007	1.122809	2	0.6534	0.5
2009	1.612027	2	0.3562	0.5
2011	0.553991	2	0.5125	0.5

Age composition data Sampling theory suggest that age composition data are derived from a multinomial distribution (?). However, CCAM assumes that age-proportions are obtained from a multivariate logistic distribution (**??**). The multinomial distribution, used in many stock assessments, requires the specification of an effective sample size. This may be done arbitrarily or through iterative re-weighting (?). In cases where there are very large numbers of observations, the age composition data may be too heavily weighted in the objective function, i.e., the assumed effective sample size can have a large impact on the overall model results.

In the multivariate logistic distribution, the age-proportion data can be weighted based on the conditional maximum likelihood estimate of the variance in the age-proportions. Therefore, the contribution of the age-composition data to the overall objective function is "self-weighting" and is conditional on other components in the model.

Ignoring the subscript for gear type for clarity, the observed and predicted proportions-at-age must satisfy the constraint

$$\sum_{a=1}^{A} p_{t,a} = 1$$

for each year. The multivariate logistic residuals between the observed ($p_{t,a}$) and predicted proportions ($\widehat{p_{t,a}}$) is given by:

$$\eta_{t,a} = \ln(p_{t,a}) - \ln(\widehat{p_{t,a}}) - \frac{1}{A}\sum_{a=1}^{A}\left[\ln(p_{t,a}) - \ln(\widehat{p_{t,a}})\right]. \tag{43}$$

The conditional maximum likelihood estimate of the variance is given by

$$\widehat{\tau}^2 = \frac{1}{(A-1)T}\sum_{t=1}^{T}\sum_{a=1}^{A}\eta_{t,a}^2,$$

and the negative loglikelihood evaluated at the conditional maximum likelihood estimate of the variance is given by:

$$\ell_A = (A-1)T\ln(\widehat{\tau}^2). \tag{44}$$

In short, the multivariate logistic likelihood for age-composition data is just the log of the residual variance weighted by the number observations over years and ages.

Examination of (43) reveals that observed and predicted proportions-at-age must be greater than zero. It is not uncommon in catch-age data sets to observe zero proportions for older, or young, age classes or weak year classes. In CCAM the same approach described by ? is adopted where the definition of age-classes is altered to require that $p_{t,a} \geq \dot{p}$ for every age in each year, where $\dot{p}$ is the minimum percentage specified by the user (e.g., $\dot{p} = 0.02$ corresponds to 2%). This is accomplished by grouping consecutive ages, where $p_{t,a} < \dot{p}$, into a single age-class and reducing the effective number of age-classes in the variance calculation ($\hat{\tau}^2$) by the number of groups created. The minimum proportion (which can be zero) is set by the user and can influence the results, especially in cases where there is sparse aging information. In the case of $\dot{p} = 0$, the pooling of the adjacent age-class still occurs, this ensures that (43) is defined. In the current Pacific hake assessment, the minimum proportion is set to zero.

Stock-recruitment

There are two alternative stock-recruitment models available in CCAM: the Beverton-Holt model and the Ricker model. Annual recruitment and the initial age-composition are treated as latent variables in CCAM, and residuals between estimated recruits and the deterministic stock-recruitment models are used to estimate unfished spawning stock biomass and recruitment compensation. The residuals between the estimated and predicted recruits is given by

$$\delta_t = \ln(\bar{R}e^{w_t}) - \ln(f(B_{t-\acute{a}})) \tag{45}$$

where $f(B_{t-k})$ is given by either (34) or (35), and $\acute{a}$ is the age at recruitment. Note that a bias correction term for the lognormal process errors is included in (34) and (35).

The negative log likelihood for the recruitment deviations is given by the normal density (ignoring the scaling constant):

$$\ell_\delta = n\ln(\tau) + \frac{\sum_{t=1+k}^{T} \delta_t^2}{2\tau^2} \tag{46}$$

Equations (45) and (46) are key for estimating unfished spawning stock biomass and recruitment compensation via the recruitment models. The relationship between (s_0, β) and (B_0, κ) is defined as:

$$s_o = \kappa/\phi_E \tag{47}$$

$$\beta = \begin{cases} \frac{\kappa-1}{B_0} & \text{Beverton-Holt} \\ \frac{\ln(\kappa)}{B_0} & \text{Ricker} \end{cases} \tag{48}$$

where s_0 is the maximum juvenile survival rate, β is the density effect on recruitment, and B_o is the unfished spawning stock biomass. Unfished steady-state spawning stock biomass per recruit is given by ϕ_E, which is the sum of products between age-specific survivorship and relative fecundity. In cases where the natural mortality rate is allowed to vary over time, the calculation of ϕ_E, and the corresponding unfished spawning stock biomass (B_0) is based on the average natural mortality rate over the entire time period. This subtle calculation has implications for reference point calculations in cases where there are increasing or decreasing trends in natural mortality rates over time; as estimates of natural mortality rates trend upwards, estimates of B_0 decrease.

Note that for this Pacific hake assessment, only the Beverton-Holt recruitment model was considered.

Parameter Estimation and Uncertainty

Parameter estimation and quantifying uncertainty was carried out using the tools available in AD Model Builder `http://admb-project.org/`. AD Model Builder (ADMB) is a software for creating computer programs to estimate the parameters and associated probability distributions for nonlinear statistical models. The software is freely available from `http://admb-project.org/`. This software was used to develop CCAM, and the source code and documentation for the original version of ISCAM (on which CCAM is based) is freely available from `https://sites.google.com/site/ISCAMproject/`, or from a subversion repository at `http://code.google.com/p/ISCAM-project/`.

There are actually five distinct components that make up the objective function that ADMB is minimizing:

$$f = \text{negative loglikelihoods} + \text{constraints} + \text{priors for parameters} + \text{survey priors} + \text{convergence penalties}.$$

The purpose of this section is to completely document all of the components that make up the objective function.

Negative loglikelihoods The negative loglikelihoods pertain specifically elements that deal with the data and variance partitioning and have already been described in detail in section . There are four specific elements that make up the vector of negative loglikelihoods:

$$\vec{\ell} = \ell_C, \ell_I, \ell_A, \ell_\delta. \tag{49}$$

To reiterate, these are the likelihood of the catch data ℓ_C, likelihood of the survey data ℓ_I, the likelihood of the age-composition data ℓ_A and the likelihood of the stock-recruitment residuals ℓ_δ. Each of these elements are expressed in negative log-space, and ADMB attempts to estimate model parameters by minimizing the sum of these elements.

Constraints There are two specific constraints that are described here: 1) parameter bounds, and 2) constraints to ensure that a parameter vector sums to 0. In CCAM the user must specify the lower and upper bounds for the leading parameters defined in the control file $(\ln(R_o), h, \ln(M), \ln(\bar{R}), \ddot{R}, \rho, \vartheta)$. All estimated selectivity parameters $\vec{\gamma}_k$ are estimated in log space and have a minimum and maximum values of -5.0 and 5.0, respectively. These values are hard-wired into the code, but should be sufficiently large/small enough to capture a wide range of selectivities. Estimated fishing mortality rates are also constrained (in log space) to have a minimum value of -30, and a maximum value of 3.0. Log annual recruitment deviations are also constrained to have minimum and maximum values of -15.0 and 15.0 and there is an additional constraint to ensure the vector of deviations sums to 0. This is necessary in order to be able to estimate the average recruitment $\bar{R}$. Finally, the annual log deviations in natural mortality rates are constrained to lie between -5.0 and 5.0, although we note that these are not implemented in the current assessment.

An array of selectivity parameters (i.e., `init_bounded_matrix_vector`) is estimated within CCAM, where each matrix corresponds to a specific gear type, and the number of rows and columns of each depends on the type of selectivity function assumed for the gear and if that selectivity changes over time. In cases where the nodes of a spline are estimated these nodes also have an additional constraint to sum to zero. This is effectively implemented by adding to the objective function:

$$1000\left(\frac{1}{N_{\vec{\lambda}_k}}\sum\vec{\lambda}_k\right)^2.$$

This additional constraint is necessary to ensure the model remains separable and the annual fishing mortality rates are less confounded with selectivity parameters.

Priors for parameters Each of the seven leading parameters specified in the control file $(\ln(R_o), h, \ln(M), \ln(\bar{R}), \ln(\ddot{R}), \rho, \vartheta)$ are declared as bounded parameters and in addition the user can also specify an informative prior distribution for each of these parameters. Five distinct prior distributions can be implemented: uniform, normal, lognormal, beta and a gamma distribution. For the Pacific Hake, a bounded uniform prior was specified for the log of unfished recruitment U(-1.0,4), a beta prior was assumed for steepness Beta(9.8,2.8), a normal prior was specified for the log of natural mortality rate N(-1.609,0.1), a bounded uniform prior for both the log of initial recruitment and average recruitment U(-5.0,15.0), a beta prior for the variance partitioning parameter $\rho\tilde{\beta}(3,12)$, and a gamma prior for the inverse total standard deviation parameter $\vartheta\tilde{\Gamma}(156.25,125.0)$. Priors for M, h, and $\hat{\gamma}$ are allowed to vary depending the sensitivity cases examined. Finally there is an optional prior on the slope of the selectivity ogive σ_a.

In addition to the priors specified for the seven leading parameters, there are several other informative distributions that are invoked for the non-parametric selectivity parameters. In cases were age-specific selectivity coefficients are estimated, or nodes of a spline function are estimated, two additional penalties are added to the objective function to control how smooth the selectivity changes

(36) and (if implemented) how much dome-shape is allowed in the nonparametric selectivities (37).

Survey priors The scaling parameter q for each of the surveys is not treated as an unknown parameter within the code; rather, the maximum likelihood estimate for $ln(q)$ conditional on all other parameters is used to scale the predicted spawning biomass to the observed acoustic biomass index. For Pacific Hake, we use a prior of convenience for $ln(q)$ $N(0,0.1)$. Sensitivity to the standard deviation of this prior were examined.

Convergence penalties AD Model Builder is unique in that the estimation process can be conducted in a series of phases where more and more parameters are 'freed up' as the model progress through each phase. Furthermore, the actual objective function can change between phases such that during the initial phases large penalties can be used to, "regularize the solution". For example, in the initial phases of parameter estimation CCAM uses fairly steep quadratic penalties for the annual recruitment deviations and average fishing mortality rates to initially aid in finding reasonable values of the average recruitment, natural mortality and selectivity parameters. In the final phase, these quadratic penalties are relaxed. In the case of the annual recruitment deviations, the quadratic penalty term is:

$$100 \sum_{t=1-A}^{T} \omega_t^2,$$

which is approximately a normal density with a standard deviation equal to 0.07. In the last phase this constraint is relaxed with a large standard deviation of 5.0. A similar penalty (a normal distribution for the log mean fishing rate) is also invoked for the mean fishing mortality rate, but in this case the user specifies the mean fishing mortality rate and the standard deviations in the initial phases and the last phase. Normally, a rather small standard deviation is used in the initial phases (e.g., 0.01) and this is then relaxed to a much larger value (e.g., 5.0) in the last phase. These standard deviations are specified by the user in the control file.