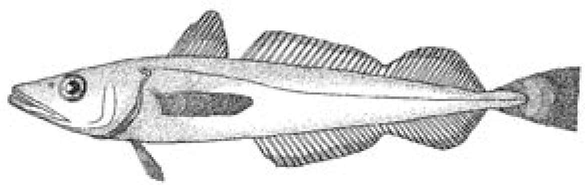
Stock Assessment of Pacific Hake, *Merluccius productus*, (a.k.a Whiting) in U.S. and Canadian Waters in 2008



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Executive Summary

Stock

This assessment reports the status of the coastal Pacific hake (*Merluccius productus*) resource off the west coast of the United States and Canada. The coastal stock of Pacific hake is currently the most abundant groundfish population in the California Current system. Smaller populations of hake occur in the major inlets of the north Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California. However, the coastal stock is distinguished from the inshore populations by larger body size, seasonal migratory behavior, and a pattern of low median recruitment punctuated by extremely large year classes. The population is modeled as a single stock, but the United States and Canadian fishing fleets are treated separately in order to capture some of the spatial variability in Pacific hake distribution.

Catches

Coastwide fishery landings from 1966 to 2007 have averaged 219 thousand mt, with a low of 90 thousand mt in 1980 and a peak harvest of 364 thousand mt in 2006. Recent landings have been above the long term average, at approximately 364 and 276 thousand mt in 2006 and 2007, respectively. Catches in both of these years were predominately comprised by fish from the large 1999 year class. The United States has averaged 163 thousand mt, or 74.6% of the total landings over the time series, with Canadian catch averaging 56 thousand mt. The 2006 and 2007 landings had similar distributions, with 74% and 72%, respectively, harvested by the United States fishery. The current model assumes no discarding mortality of Pacific hake.

Table a. Recent commercial fishery landings (1000s mt).

Year	US at-sea	US shore based	US Tribal	US total	Canadian foreign and JV	Canadian shore based	Canadian total	Total
1997	121	87	25	233	43	49	92	325
1998	120	88	25	233	40	48	88	321
1999	115	83	26	225	17	70	87	312
2000	116	86	7	208	16	6	22	231
2001	102	73	7	182	22	32	54	236
2002	63	46	23	132	0	51	51	183
2003	67	51	25	143	0	62	62	206
2004	90	89	31	210	59	65	124	335
2005	150	74	35	260	15	85	100	360
2006	138	97	35	266	14	80	94	360
2007	107	67	30	204	7	65	72	276

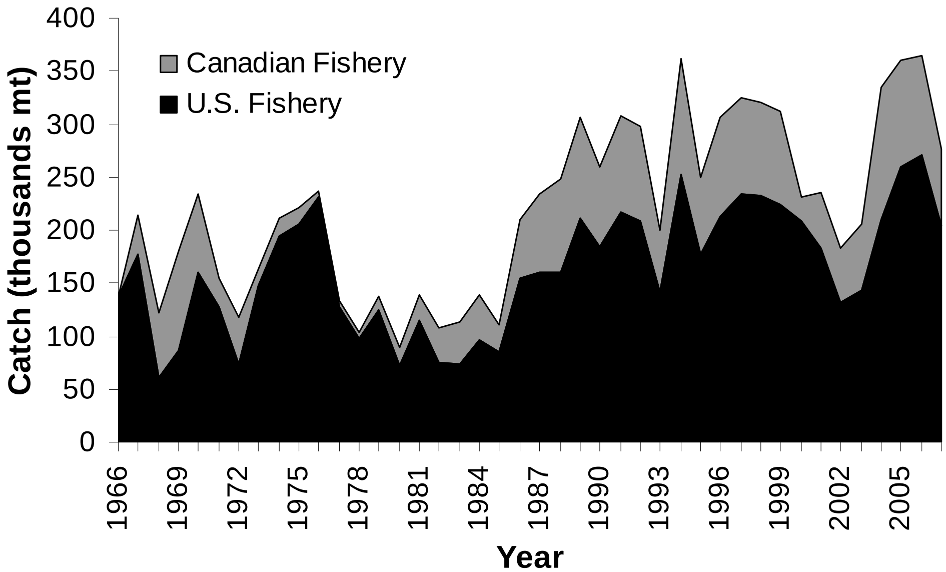

Figure a. Pacific whiting landings (1000s mt) by nation, 1966-2007.

Data and assessment

Age-structured assessment models of various forms have been used to assess Pacific hake since the early 1980's, using total fishery catches, fishery age compositions and abundance indices. 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) in 1999 by Dorn (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, 2004) used the same ADMB modeling platform to assess the hake stock and examine important assessment modifications and assumptions, including the time varying nature of the acoustic survey selectivity and catchability. The acoustic survey catchability coefficient (q) has been, and continues to be, one of the major sources of uncertainty in the model. Due to the lengthened acoustic survey biomass trends the assessment model in 2003 was able to freely estimate the acoustic survey q. These estimates were substantially below the assumed value of q=1.0 from earlier assessments. The 2003 and 2004 assessment 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 2005, the coastal hake stock was modeled using the Stock Synthesis modeling framework (SS2 Version 1.21, December, 2006) written by Dr. Richard Methot (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, 2) explicitly model the underlying hake growth dynamics, and 3) achieve parsimony[1] in terms of model complexity. "Incorporating less derived data" entailed fitting

[1] Parsimony is defined as a balance between the number of parameters needed to represent a complex state of nature and data quality/quantity to support accurate and precise estimation of those parameters.

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, through age-length keys for each fishery and survey, allowed explicit estimation of expected growth, dispersion about that expectation, and its temporal variability, all conditioned on selectivity. From 2003 to 2006, assessments have presented two models (which have been assumed to be equally likely) in an attempt to bracket the range of uncertainty in the acoustic survey catchability coefficient, q. In this year's assessment, also conducted in SS2 (Version 2.00n), an effort has been made to include the uncertainty in q, as well as additional uncertainty regarding the acoustic survey selectivity and the natural mortality rate of older fish within a single model. As a result, a broader range of uncertainty is presented via probability distributions and risk profiles using Markov Chain Monte Carlo simulation. Further refinements include, for the first time, incorporation of an age-reading error matrix.

Stock biomass

The base model estimates that the Pacific hake spawning biomass declined rapidly after 1984 (6.45 million mt) to the lowest point in the time series in 2000 (0.88 million mt). This long period of decline was followed by a brief increase to 1.89 million mt in 2003 as the 1999 year class matured. In 2008 (beginning of year), spawning biomass is estimated to be 1.10 million mt and approximately 37.9% of the unfished spawning biomass (SB_{zero}). Estimates of uncertainty in relative depletion range from 21.9%-53.9% of unfished biomass, based on asymptotic confidence intervals. It should be pointed out that the 2007 estimates of spawning biomass are lower and depletion level higher compared to last year's assessment result for 2007. The reason is that survey q was freely estimated and the assessment incorporated an age-reading error matrix that lowered estimates of SB_{zero} (through a lower reduction in mean log recruitment) and increased the size of the 1999 year class. As such, spawning biomass for the most recent years, while generally lower than predicted in the 2007 assessment, is greater relative to the estimate of SB_{zero} and therefore results in a higher depletion estimate.

Table b. Recent trend in Pacific hake spawning biomass and depletion level from the base and alternative SS2 models.

Year	Spawning biomass millions mt	~ 95% Interval	Relative Depletion	~ 95% Interval
1999	0.961	0.687 - 1.236	33.2%	-
2000	0.882	0.596 - 1.169	30.5%	-
2001	1.048	0.677 - 1.420	36.2%	-
2002	1.625	1.028 - 2.222	56.1%	-
2003	1.898	1.186 - 2.611	65.5%	-
2004	1.827	1.113 - 2.542	63.1%	-
2005	1.554	0.889 - 2.218	53.6%	-
2006	1.279	0.665 - 1.892	44.1%	
2007	1.067	0.472 - 1.663	36.8%	23.7% - 50.1%
2008	1.097	0.419 - 1.775	37.9%	21.9% - 53.9%

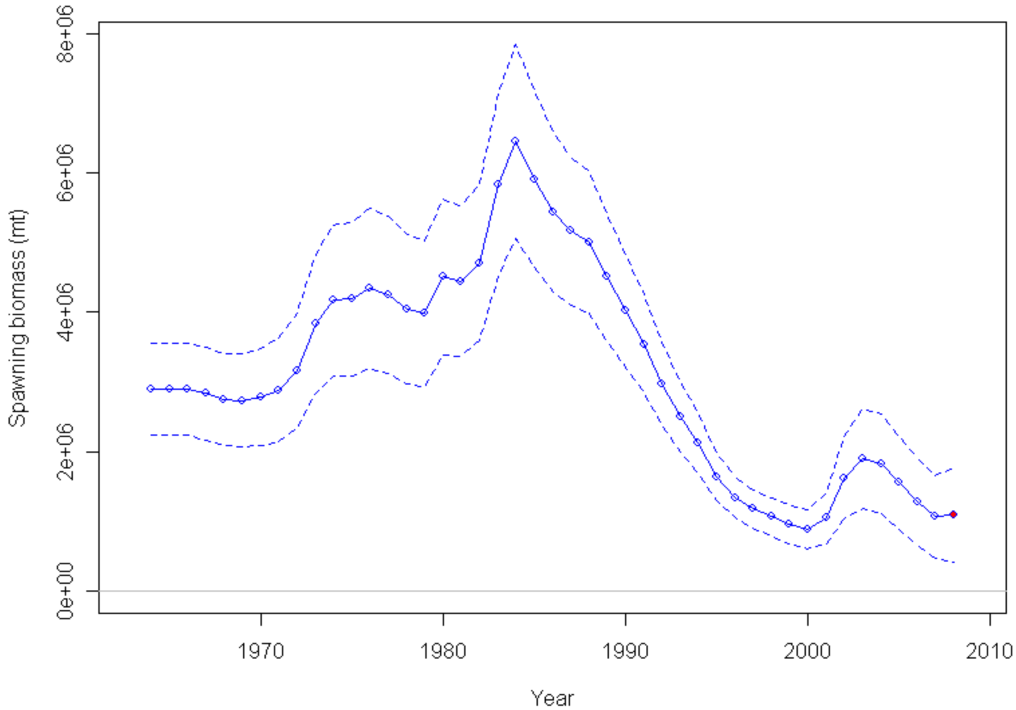

Figure b. Estimated spawning biomass time-series with approximate asymptotic 95% confidence intervals.

Recruitment

Estimates of historic Pacific hake recruitment indicate very large year classes in 1980 and 1984, with secondary recruitment events in 1970, 1973 and 1977. The more recent 1999 year class is the most dominant cohort since the late 1980s and has supported fishery catches since 2002. Uncertainty in recruitment can be substantial, especially for recent years, as indicated by the asymptotic 95% confidence intervals. Recruitment to age 0 before 1967 is assumed to be equal to the long-term mean recruitment. Age-0 recruitment in 2005 appears promising but is very uncertain, as it has only been observed in either the fishery or the acoustic survey for one season (2007).

Table c. Recent estimated trend in Pacific hake recruitment.

Year	Recruitment (billions)	~ 95% Interval		
1999	18.151	12.905	-	25.529
2000	0.030	0.012	-	0.073
2001	1.374	0.944	-	1.998
2002	0.035	0.015	-	0.081
2003	1.809	1.157	-	2.830
2004	0.414	0.236	-	0.728
2005	6.065	3.371	-	10.910
2006	3.676	0.604	-	22.365
2007	3.556	0.586	-	21.588
2008	3.575	0.573	-	22.317

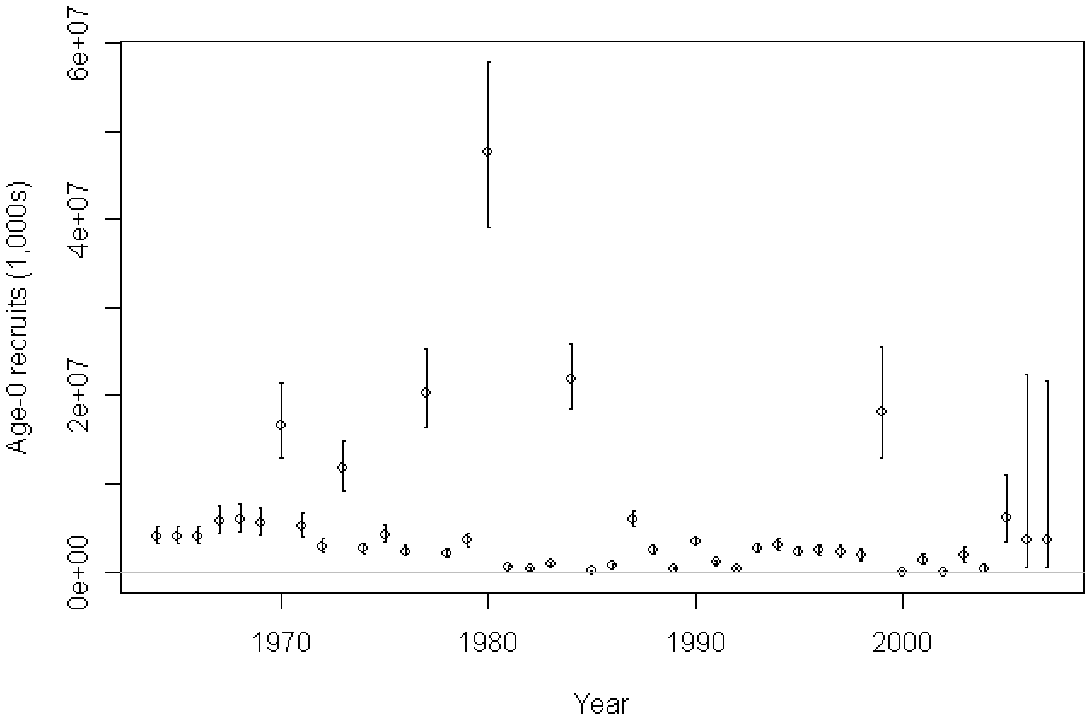

Figure c. Estimated recruitment time-series with approximate asymptotic 95% confidence intervals.

Reference points

Two types of reference points are reported in this assessment: those based on the assumed population parameters at the beginning of the modeled time period and those based on the most recent time period in a 'forward projection' mode of calculation. This distinction is important since temporal variability in growth and other parameters can result in different biological reference point calculations across alternative chronological periods. All strictly biological reference points (e.g., unexploited spawning biomass) are calculated based on the unexploited conditions at the start of the model, whereas management quantities (MSY, SB_{msy}, etc.) are based on the current growth and maturity schedules and are marked throughout this document with an asterisk (*).

Unexploited equilibrium Pacific hake spawning biomass (SB_{zero}) is estimated to be 2.89 million mt (~ 95% confidence interval: 1.556 – 2.50 million mt), with a mean expected recruitment of 4.06 billion age-0 hake (~ 95% confidence interval: 3.23 – 5.11). Associated management reference points for target and critical biomass levels based on $SB_{40\%}$ proxy are 1.16 million mt (B40%) and 0.72 million mt (B25%), respectively. The MSY-proxy harvest amount (F40%) under the base model is estimated to be 470,910* mt (~ 95% confidence interval: 253,115 - 688,705 mt). The spawning stock biomass that produces the MSY-proxy catch amount under the base model was estimated to be 0.81 million* mt (confidence interval is 0.42 - 1.90 millions mt)* given current life history parameters.

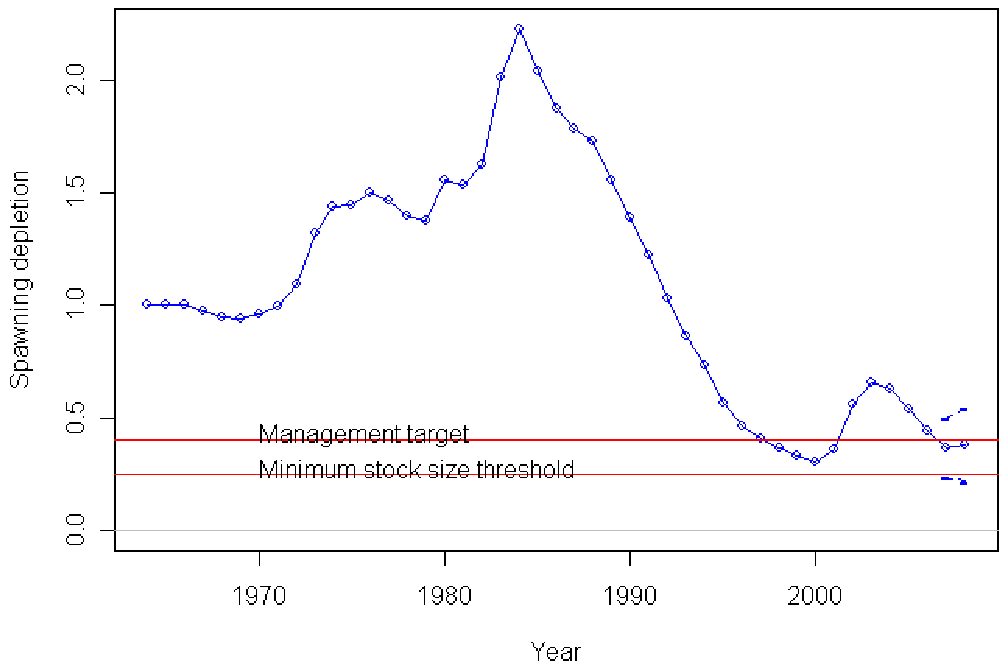

Figure d. Time series of estimated depletion, 1966-2008.

Exploitation status

The estimated spawning potential ratio (SPR) for Pacific hake has been above the proxy target of 40% for the history of this fishery. In terms of its exploitation status, Pacific hake are presently just below target biomass level (40% unfished biomass) and above the target SPR rate (40%). The full exploitation history is portrayed graphically below, plotting for each year the calculated SPR and spawning biomass level (B) relative to their corresponding targets, F40% and B40%, respectively.

Table d. Recent trend in spawning potential ratio (SPR).

	Base Model	
	Estimated	~ 95%
Year	SPR	Interval
1998	0.474	-
1999	0.456	-
2000	0.512	-
2001	0.527	-
2002	0.707	-
2003	0.736	-
2004	0.646	-
2005	0.580	-
2006	0.497	-
2007	0.485	

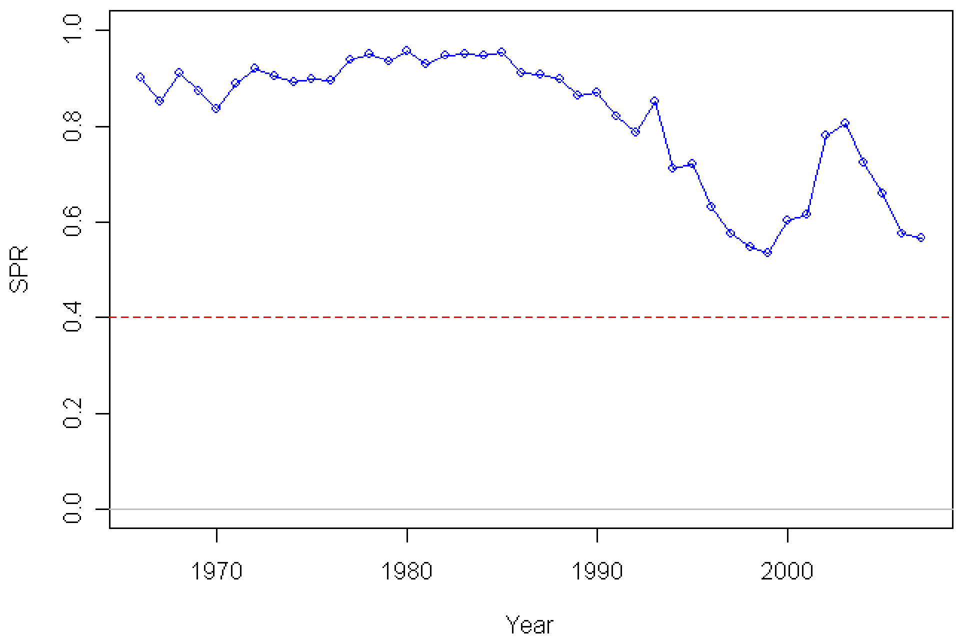

Figure e. Time series of estimated spawning potential.

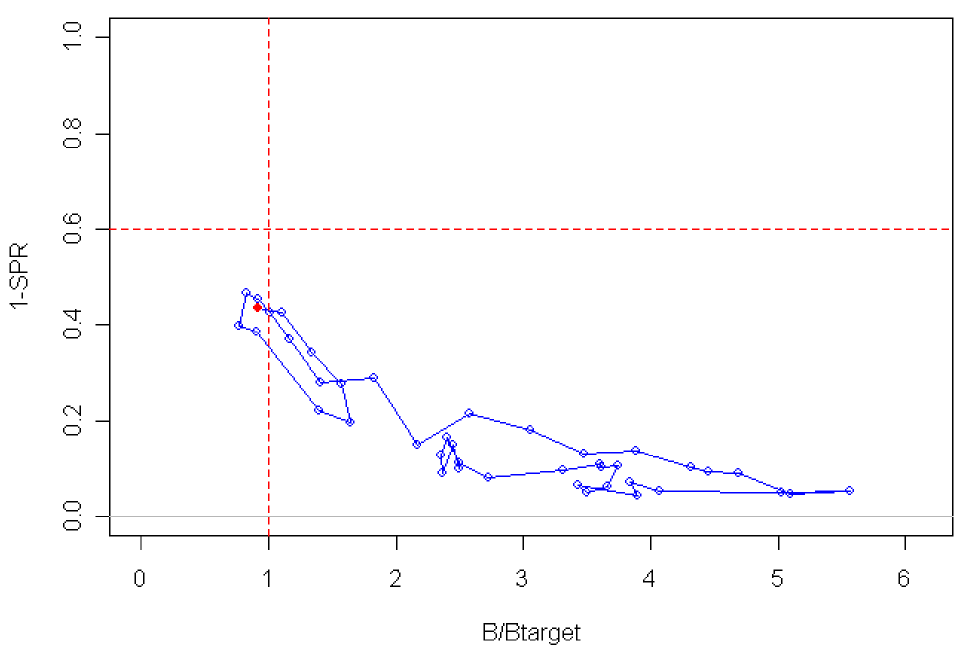

Figure f. Temporal pattern of estimated spawning potential ratio relative to the proxy target of 40% vs estimated spawning biomass relative to the proxy 40% level.

Management performance

Since implementation of the Magnuson Fisheries 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 quotas have been the primary management tool used to limit the catch of Pacific hake in both zones by foreign and domestic fisheries. The scientists from both countries have collaborated through the Technical Subcommittee of the Canada-US Groundfish Committee (TSC), and there has been informal agreement on the adoption of an annual fishing policy. During the 1990s, however, disagreement between the U.S. and Canada on the division of the acceptable biological catch (ABC) between the two countries led to quota overruns; 1991-1992 quotas summed to 128% of the ABC and quota overruns have averaged 114% from 1991-1999. Since 2000, total catches have been below coastwide ABCs. A recent treaty between the United States and Canada (2003), which awaits final signature, establishes U.S. and Canadian shares of the coastwide allowable biological catch at 73.88% and 26.12%, respectively.

Table e. Recent trend in Pacific hake management performance.

Year	Total landings (mt)	Coastwide (U.S. + Canada) OY (mt)	Coastwide (U.S. + Canada) ABC (mt)
1997	325,215	290,000	290,000
1998	320,619	290,000	290,000
1999	311,855	290,000	290,000
2000	230,819	290,000	290,000
2001	235,962	238,000	238,000
2002	182,883	162,000	208,000
2003	205,582	228,000	235,000
2004	334,721	501,073	514,441
2005	360,306	364,197	531,124
2006	359,901	364,842	661,680
2007	276,084	328,358	612,068

Unresolved problems and major uncertainties

The acoustic survey catchability, *q,* and selectivity remains uncertain and the model results are quite sensitive to assumed values. This is largely driven by an inconsistency in the acoustic survey biomass time series and age compositions. Age-composition data suggest a large build up of stock biomass in the mid-1980s, however the acoustic survey biomass time series is relatively flat since 1977. Efforts have been made in this assessment to integrate both the uncertainty in the acoustic survey's *q* and selectivity pattern.

Forecasts

Stochastic forecasts are generated assuming the maximum potential catch would be removed under 40:10 control rule for both the base and alternative models. Projections are based on relative F's corresponding to a coastwide catch allocation of 73.88% and 26.12% to the U.S. and Canada, respectively, with application of the 40-10 harvest control rule.

Table f. Three year stochastic projections of potential Pacific hake landings, spawning biomass and depletion assuming full coastwide catch is taken under the 40:10 rule. Three year catch streams are given for three arbitrary catches of 250,000, 300,000 (approximately status quo) and 400,000 mt. In addition, catch streams of the average 2008-2010 coastwide catches corresponding to the 0-25th, 25-75th and 75-100th percentile of the marginal posterior distribution of 2008 spawning depletion are also given.

Percentile[1] 2008 depletion	Forecast Year	Coastwide Catch (mt)	Spawning Biomass (millions, mt) [2] Posterior Interval 5th	25th	50th	75th	95th	Spawning Depletion (% unfished) [2] Posterior Interval 5th	25th	50th	75th	95th
	2008	414,193	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
25%	2009	432,862	0.757	1.062	1.430	1.885	3.424	0.278	0.368	0.470	0.571	0.891
	2010	522,299	0.670	1.083	1.609	2.250	4.369	0.244	0.372	0.512	0.673	1.236
	2011	-	0.571	1.111	1.740	2.608	5.204	0.210	0.377	0.546	0.789	1.570
	2008	656,604	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
50%	2009	675,032	0.765	1.009	1.321	1.720	3.199	0.281	0.349	0.427	0.517	0.814
	2010	751,936	0.712	0.994	1.365	1.895	3.631	0.257	0.339	0.432	0.578	1.049
	2011	-	0.685	1.005	1.417	2.056	3.878	0.240	0.337	0.451	0.631	1.192
	2008	1,092,911	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
75%	2009	1,341,489	0.455	0.763	1.129	1.592	3.132	0.169	0.262	0.369	0.482	0.803
	2010	1,502,207	0.103	0.423	0.926	1.574	3.683	0.037	0.148	0.298	0.469	1.046
	2011	-	0.019	0.270	0.716	1.562	4.187	0.006	0.092	0.230	0.477	1.238
	2008	250,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	250,000	0.951	1.299	1.748	2.727	9.203	0.351	0.446	0.557	0.718	1.102
	2010	250,000	1.050	1.536	2.122	3.511	10.202	0.380	0.516	0.670	0.897	1.397
	2011	-	1.164	1.780	2.485	4.201	10.813	0.412	0.593	0.778	1.037	1.793
	2008	300,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	300,000	0.807	1.112	1.481	1.935	3.473	0.297	0.385	0.485	0.586	0.907
	2010	300,000	0.776	1.189	1.715	2.355	4.476	0.283	0.410	0.543	0.710	1.259
	2011	-	0.765	1.308	1.936	2.801	5.401	0.280	0.441	0.609	0.854	1.634
	2008	400,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	400,000	0.763	1.068	1.436	1.891	3.430	0.280	0.370	0.471	0.573	0.893
	2010	400,000	0.690	1.104	1.629	2.271	4.390	0.251	0.379	0.518	0.680	1.241
	2011	-	0.644	1.184	1.814	2.681	5.277	0.235	0.401	0.569	0.812	1.591

[1] Coastwide catches for 2008-2010 represent the average from slicing the marginal posterior distribution of 2008 spawning depletion in 25th, 50th and 75t

[2] Posterior intervals are based on 1,000,000 draws from MCMC simulation.

Research and data needs

1) Evaluate the quantity and quality of biological data prior to 1988 from the Canadian fishery for use in developing length and conditional age at length compositions.
2) Evaluate whether modeling the distinct at-sea and shore based fisheries in the U.S. and Canada explain some lack of fit in the compositional data.
3) Evaluate a sex specific model and use of split-sex selectivity for both the U.S. and Canadian fishery and survey data.
4) Compare spatial distributions of hake across all years and between bottom trawl and acoustic surveys to estimate changes in catchability/availability across years. The two primary issues are related to the changing spatial distribution of the survey as well as the environmental factors that may be responsible for changes in the spatial distribution of hake and their influences on survey catchability and selectivity.
5) Initiate analysis of the acoustic survey data to determine variance estimates for application in the assessment model. The analysis would provide a first cut to define the appropriate CV for the weighting of the acoustic data and should incorporate uncertainties in spatial variability, sampling variability and target strength variability.
6) Develop an informed prior for the acoustic q. This could be done either with empirical experiments (particularly in off-years for the survey) or in a workshop format with technical experts. There is also the potential to explore putting the target strength estimation in the model directly. This prior should be used in the model when estimating the q parameter.
7) Review the acoustic data to assess whether there are spatial trends in the acoustic survey indices that are not being captured by the model. The analysis should include investigation of the migration (expansion/contraction) of the stock in relation to variation in environmental factors. This would account for potential lack of availability of older animals and how it affects the selectivity function.
8) Investigate aspects of the life history characteristics for Pacific hake and their possible effects on the interrelationship of growth rates and maturity at age. This should include additional data collection of maturity states and fecundity, as current information is limited.
9) Additional cross and double reads of otoliths prior to 2001 should be performed to determine the age-reading error properties of production ages.
10) Additional in situ measurements of target strength for hake are needed, particularly during daytime hours and at varying depths.

Table g. Summary of recent trends in Pacific hake exploitation and stock levels; all values reported at the beginning of the year.

Base Model	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Landings (1000s mt)	320.6	311.9	230.8	236.0	182.9	205.6	334.7	360.3	359.9	276.1	NA
ABC (1000s mt)	290	290	290	238	208	235	514	531	661	612	555
OY (1000s mt)											
SPR*	0.548	0.536	0.601	0.616	0.779	0.805	0.723	0.657	0.573	0.566	NA
Total biomass (millions mt)	2.29	2.08	1.90	1.80	4.42	4.18	3.89	3.15	2.69	2.05	2.49
Spawning biomass (millions mt)	1.06	0.96	0.88	1.05	1.62	1.90	1.83	1.55	1.28	1.07	1.10
~95% interval	0.794-1.336	0.687-1.236	0.596-1.169	0.677-1.42	1.028-2.222	1.186-2.611	1.113-2.542	0.889-2.218	0.665-1.892	0.472-1.663	0.419-1.775
Recruitment (billions)	1.898	18.151	0.030	1.374	0.035	1.809	0.414	6.065	3.676	3.556	3.575
~95% interval	1.377-2.616	12.905-25.529	0.012-0.073	0.944-1.998	0.015-0.081	1.157-2.83	0.236-0.728	3.371-10.91	0.604-22.365	0.586-21.588	0.573-14.359
Depletion	36.8%	33.2%	30.5%	36.2%	56.1%	65.5%	63.1%	53.6%	44.1%	36.8%	37.9%
~95% interval	-	-	-	-	-	-	-	-	-	23.7% - 50.1%	21.9% - 53.9%

Table h. Summary of Pacific hake reference points. Quantities based on the current growth and maturity schedules and are marked with an asterisk (*) and are not comparable to those based on unfished conditions.

Quantity	Estimate	~95% Confidence interval
Unfished spawning stock biomass (SB_0, millions mt)	2.89	1.56 - 2.50
Unfished 3+ biomass (millions, mt)	5.99	NA
Unfished recruitment (R_0, billions)	4.06	3.23 - 5.11
Reference points based on $SB_{40\%}$		
MSY Proxy Spawning Stock Biomass ($SB_{40\%}$ millions mt)	1.17	0.89 - 1.43
SPR resulting in $SB_{40\%}$ ($SPR_{SB40\%}$)	0.53	0.43 - 0.33
Exploitation rate resulting in $SB_{40\%}$	0.16	NA
Yield with $SPR_{SB40\%}$ at $SB_{40\%}$ (mt)	416,150	232,245 - 600,055
Reference points based on SPR proxy for MSY		
Spawning Stock Biomass at SPR (SB_{SPR})(millions mt)	0.81	0.42 - 1.9
$SPR_{MSY\text{-}proxy}$	0.40	NA
Exploitation rate corresponding to SPR	0.25	NA
Yield with $SPR_{MSY\text{-}proxy}$ at SB_{SPR} (mt)	470,910	253,115 - 688,705
Reference points based on estimated MSY values		
Spawning Stock Biomass at *MSY* (SB_{MSY}) (millions mt)	0.68	0.34 - 1.01
SPR_{MSY}	0.35	0.11 - 0.59
Exploitation Rate corresponding to SPR_{MSY}	0.26	NA
MSY (mt)	476,750	209,073 - 744,427

INTRODUCTION

The Joint US-Canada treaty on Pacific Hake was formally ratified by the United States as part of the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act. As of this writing the treaty has not been officially ratified by the Canadian Parliament. Under this treaty Pacific hake (a.k.a. Pacific whiting) stock assessments are to be prepared by the Hake Technical Working Group comprised of U.S. and Canadian scientists and reviewed by a Scientific Review Group (SRG), with memberships as appointed by both parties to the agreement. While these entities have not been formally established by either nation, the current assessment was cooperatively prepared by an ad hoc Technical Committee. The US and Canadian scientist met three times for the purposes of data exchange and discussion of major issues and modeling activity in preparation for the final review. As background, separate Canadian and U.S. assessments were submitted to each nation's assessment review process prior to 1997. In the past, this practice has resulted in differing yield options being forwarded to each country's managers for this single, yet shared trans-boundary fish stock. Multiple interpretations of Pacific hake status made it difficult to coordinate overall management policy. To address this problem, the working group agreed in 1997 to present scientific advice in a single collaborative assessment agreement officially formalized in 2003. To further advance the coordination of scientific advice on Pacific hake, this report was submitted to the Pacific Council's Stock Assessment review process for technical review in fulfillment of the agreement and to satisfy management responsibilities of both the U.S. Pacific Fisheries Management Council (PFMC). The Review Group meeting was held in Seattle, WA at the Northwest Fisheries Science Center, during Feb 11-14, 2008.

Stock Structure and Life History

Pacific hake (*Merluccius productus*), also referred to as Pacific whiting, is a codlike species distributed along the west coast of North America generally ranging from 25^0 N. to 51^0 N. latitude. It is among about a dozen other species of hakes from the genus, *Merluccidae*, which are distributed worldwide in both hemispheres of the Atlantic and Pacific Oceans and collectively constitute nearly two million mt of catch annually (Alheit and Pitcher 1995). 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 North Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California. Electrophoretic studies indicate that Strait of Georgia and the Puget Sound populations are genetically distinct from the coastal population (Utter 1971). 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 distinguished from the inshore populations by larger body size, seasonal migratory behavior, and a pattern of low median recruitment punctuated by extremely large year classes.

The coastal stock of Pacific hake typically ranges from the waters off southern California to Queen Charlotte Sound. 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 midwater 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 (age 5+), larger, and predominantly female hake exhibit the greatest northern migration each season. During El Niño events, 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)). Range extensions to the north also occur during El Niño conditions, as evidenced by reports of hake from southeast Alaska during these warm water years. Throughout the warm period experienced in 1990s, there have been changes in typical patterns of hake distribution: Spawning activity has been recorded north of California, and frequent reports of unusual numbers of juveniles from Oregon to British Columbia suggest that juvenile settlement patterns have also shifted northwards in the late 1990s (Benson et al. 2002, Phillips et al. 2007). Because of this shift, juveniles may be subjected to increased predation from cannibalism and to increased vulnerability to fishing mortality. Subsequently, La Nina conditions apparently caused a southward shift in the center of the stock’s distribution and a smaller portion of the population was found in Canadian waters in the 2001 survey.

Fisheries

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

Large-scale harvesting of Pacific hake in the U.S. zone began in 1966 when factory trawlers from the former Soviet Union began targeting Pacific hake. During the mid 1970's, factory trawlers from Poland, Federal Republic of Germany, the former German Democratic Republic and Bulgaria also participated in the fishery. During 1966-1979, the catch in U.S. waters averaged 137,000 t per year (Table 1). 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. In the late 1980's, joint-ventures involved fishing companies from Poland, Japan, former Soviet Union, Republic of Korea and the People’s Republic of China. In 1989, the U.S. fleet capacity had grown to a level sufficient to harvest the entire quota, and no foreign fishing was allowed. In contrast, Canada allocates a portion of the Pacific hake catch to joint-venture operations once shore-side capacity is filled.

Historically, the foreign and joint-venture fisheries produced fillets and 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. Previously, these vessels had engaged primarily in Alaskan pollock fisheries. The development of surimi production techniques for walleye pollock was expanded to include Pacific hake as a viable alternative. In 1991, the joint-venture fishery for Pacific hake ended because of the increased level of participation by domestic catcher-processors and mother ships, and the growth of shore-based processing capacity. Shore-based processors of Pacific hake had been constrained historically 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.

The sectors involved in the Pacific hake fishery in Canada exhibits a similar pattern, although phasing out of the foreign and joint-venture fisheries has lagged a few years relative to the U.S. Since 1968, more Pacific hake have been landed than any other species in the groundfish fishery on Canada's west coast (Table 1). 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. Since declaration of the 200-mile extended fishing zone in 1977, the Canadian fishery has been divided into shore-based, joint-venture, and foreign fisheries. In 1990, the foreign fishery was phased out, but the demand of Canadian shore-based processors remained below the available yield, thus the joint-venture fishery continued through 2002. Poland is the only country that participated in the 1998 joint-venture fishery. The majority of the shore-based landings of the coastal hake stock is processed into surimi, fillets, or mince by processing plants at Ucluelet, Port Alberni, and Delta, British Columbia. Small deliveries were made in 1998 to plants in Washington and Oregon. 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 are sufficient quantities of fish in proximity to processing plants.

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 have historically collaborated through the Technical Subcommittee of the Canada-U.S. Groundfish Committee (TSC), and there have been 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 acceptable biological catch (ABC) between U.S. and Canadian fisheries led to quota overruns; 1991-1992 quotas summed to 128% of the ABC, while the 1993-1999 combined quotas were 107% of the ABC on average. The 2002 and 2003 fishing year were somewhat different from years past in that the ABC of

Pacific hake was utilized at an average of 87%. In the Pacific hake agreement between the United States and Canada, 73.88% and 26.12%, respectively, of the coastwide allowable biological catch are to be allocated between the two countries. Furthermore, the agreement establishes a Joint Technical Committee to exchange data and conduct stock assessments, which will be reviewed by a Scientific Review Group.

United States

Prior to 1989, catches in the U.S. zone were substantially below the harvest guideline, but since 1989 have caught up to the harvest guideline with exceptions in 2000, 2001 and 2003 when 90%, 96% and 96% of the quota were taken, respectively. The total U.S. catch has not significantly exceeded the harvest guideline for the U.S. zone, indicating that in-season management procedures have been effective.

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 widow rockfish bycatch 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 1992-95, the U.S. fishery opened on April 15; however, in 1996 the opening date was advanced 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%).

Shortly after the 1997 allocation agreement was approved by the PFMC, fishing companies with factory trawler permits established the Pacific Whiting Conservation Cooperative (PWCC). The primary role of the PWCC is to allocate the factor trawler quota among its members. Anticipated benefits of the PWCC include 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 summer of 1998 and 2001, which since 2002 has become an ongoing collaboration with NMFS.

Overview of Recent Fishery and Management

United States

The coastwide acceptable biological catch (ABC) for 2004 was estimated to be 514,441 mt based on the F_{msy} proxy harvest rate of F40% applied to the model in which acoustic survey catchability (q) was assumed to be 1.0 (Helser et al. 2004). This was the largest ABC in recent years and reflected substantial increases in biomass (above 40% unfished biomass) due to the presence of the strong 1999 year-class. The final commercial U.S. optimum yield (OY) was set at 250,000 mt due to constraints imposed by bycatch of canary and widow rockfish in the hake fishery. The Makah tribe was allocated 32,500 mt in 2004. For the 2005 fishing season, the coastwide OY was estimated to be 364,197 mt, with 269,069 mt apportioned to the U.S. fishery. The 2005 OY was nearly 100% utilized. The coastwide 2006 ABC was estimated to be 661,680 mt (based on the q=1.0 model assumption), with a coastwide OY set at 364,842 mt. The U.S. fishery OY of 269,069 mt was fully utilized. For the 2007 fishing season the PFMC adopted the 612,068 mt ABC and coastwide OY of 328,358 mt. The coastwide OY, which was considerably below the ABC, was based on bycatch considerations. The 2007 U.S. OY for hake was 242,591 metric tons (mt). The Makah tribe was allocated 32,500 mt, the commercial fishery 208,091 mt, and research 2,000 mt. The shoreside sector has been allocated 87,398 mt while the catcher/processor and mothership fishery received 70,751 mt and 49,942 mt respectively.

The at-sea sector's distribution of catch in 2004 ranged slightly stronger northward with roughly 50% of the catch occurring north and south of Newport, Oregon (Fig. 2). The total at-sea sector harvested approximately 43% (90,200 mt) of the total U.S. catch of 210,400 mt. In 2005, at sea catches extended from south of Cape Blanco to Cape Flattery, with nearly even distribution north and south of Newport.

The shore-based sector harvested 46% (96,200 mt) of the total U.S. catch of 210,400 mt in 2004. As in previous years, the dominate ports were Newport (38,800 mt) followed by Westport (30,000 mt) and Astoria (16,000 mt). The 2005 shore-based fishery began on June 15 and ended on August 18, and utilized approximately 94% of the commercial optimum yield of 97,469 mt.

Since 1996, the Makah Indian Tribe has conducted a separate fishery in its "usual and accustomed fishing area." During the 2004 and 2005 fishing season, the distribution of Pacific hake provided favorable conditions to support the fishery in the Makah tribal fishing area, where the Makahs harvested approximately 95% (31,000 mt) of the Tribal allocation and 15% of total US catch in 2004. The 2005 Makah fishery, which began on May 1 and ended on August 15, utilized 35,000 mt, (100% of the 35,000 mt allocation).

The primary 2007 hake/whiting fishery began on June 15; however the fishery was closed to all fishing sectors on July 26, 2007 because at sea observer data indicated that the bycatch limit (220 mt) of widow rockfish had been exceeded in the non-tribal whiting fisheries. On November 28, 2007 6,000 mt of the 87,398 mt shore-based sectors was reapportioned to the catcher/processor sector and fishing continued in the early fall. The U.S. havested 84% of the 242,519 OY allocation.

Canada

DFO managers allow a 15% discrepancy between the quota and total catch. The quota may be exceeded by up to 15% in any given year, which is then 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 instance, the overage in 1998 (Table 2) is due to carry-over from 1997 when 9% of the quota was not taken. During 1999-2001 the PSARC groundfish subcommittee recommended to DFO managers yields based on F40% (40-10) option and Canadian managers adopted allowable catches prescribed at 30% of the coastwide ABC (Table 14; Dorn et al. 1999).

The all-nation catch in Canadian waters was 53,585 mt in 2001, up from only 22,401 mt in 2000 (Table 1). In 2000, the shore-based landings in the Canadian zone hit a record low since 1990 due to a decrease in availability. Catches in 2001 increased substantially over those of 2000 for both the Joint Venture and shore-based sectors over catches in 2000, but were still below recommended TAC. Total Canadian catches in 2002 and 2003 were 50,769 mt and 62,090 mt, respectively, and were harvested exclusively by the shore-side sector; constituting nearly 87% of the total allocation of that country. In 2004, the allowable catch in Canada was 26.14% of the coastwide ABC, approximately 134,000 mt. Catches were nearly split equally between the shore-based and joint venture sectors, totaling 124,000 mt. Canadian Pacific hake catches were fully utilized in the 2005 fishing season with 85,284 mt and 15,178 mt taken by the Domestic and Joint Venture fisheries, respectively. In 2006, the Joint Venture and Domestic fisheries harvested 13,700 mt and 80,000 mt, respectively. During the 2007 fishing Season, Canadian fisheries harvested 85% of the 85,373 mt national allocation with Joint Venture and Domestic sectors catching 7,000 mt and 65,000 mt, respectively.

ASSESSMENT

Modeling Approaches

Age-structured assessment models have been used to assess Pacific hake since the early 1980's. 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). Since 1989, a stock synthesis model that utilizes fishery catch-at-age data and acoustic survey estimates of population biomass and age composition has been the primary assessment method (Dorn and Methot, 1991). Dorn et al. (1999) converted the age-structured stock synthesis Pacific hake model to an age-structured model using AD model builder (Fournier 1996). AD model builder's post-convergence routines permit calculation of standard errors (or likelihood profiles) for any quantity of interest, allowing for a unified approach to the treatment of uncertainty in estimation and forward projection. Since 2001, Helser et al. (2001, 2003, 2004) have used the same ADMB modeling platform to assess the hake stock and examine important modifications and assumptions, including the time varying nature of the acoustic survey selectivity and catchability. The acoustic survey catchability coefficient (q) has been, and continues to be, one of the major sources of uncertainty in the model. Due to the lengthened acoustic survey biomass trends the assessment model was able to freely estimate the acoustic survey q. These estimates were substantially below the assumed value of q=1.0 from earlier assessments. The 2003 and 2004 assessment 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 hake population model was migrated to the Stock Synthesis modeling framework (SS2 Version 1.21, December, 2006) which was written by Dr. Richard Methot (Northwest Fisheries Science Center) in AD Model Builder (Helser et al. 2006). Conversion of the previous hake model into SS2 was guided by three principles: 1) the incorporation of less derived data, 2) explicit modeling of the underlying hake growth dynamics, and 3) achieving parsimony[2] in terms on model complexity. "Incorporating less derived data" entailed fitting observed data in their most elemental form. For instance, no pre-processing to convert length composition data to age composition data was performed. Also, the incorporation of conditional age-at-length data, through age-length keys for each fishery and survey, allowed explicit estimation of expected growth and dispersion and temporal variability about that expectation, all conditioned on selectivity. The primary goal was to achieve model parsimony without loss of performance in maximum likelihood estimation, and was assessed through a combination of diagnostics, convergence criteria and comparative analysis with MCMC integration. The current assessment implements the hake model in the newest version of SS2 (Ver. 2.00n). The model is updated with fishery data through 2007 and includes estimates of hake biomass and age-length compositions from the recently completed 2007 U.S.-Canada acoustic survey. The model also includes an aging error matrix using nearly 1,000 cross-read otoliths collected since 2001. Efforts have also been made to incorporate uncertainty in acoustic survey catchability coefficient q, the acoustic survey selectivity and natural Mortality, M, on ages 13-15+ though numerical integration using Markov Chain Monte Carlo simulation.

Data Sources

The data used in the stock assessment model included:

- Total catch from the U.S. and Canadian fisheries (1966-2007).

- Length compositions from the U.S. fishery (1975-2007) and Canadian fishery (1988-2007).

- Age compositions from the U.S. fishery (1973-1974) and Canadian fishery (1977-1987). These are the traditional age compositional data generated by applying

[2] Parsimony is a balance between the number of parameters needed to represent a complex state of nature and data quality/quantity to support accurate and precise estimation of those parameters.

fishery length compositions to an age-length key. Use of this approached was necessary to fill in gaps for those years in which biological samples could not be re-acquired from standard procedures.

- Conditional age-at-length compositions from the U.S. fishery (1975-2007) and Canadian fishery (1988-2007).

- Biomass indices, length compositions and conditional age-at-length composition data from the Joint US-Canadian acoustic/midwater trawl surveys (1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998, 2001, 2003, 2005, and 2007). It should be noted that this year's assessment re-incorporates the 1986 acoustic survey biomass estimate and compositional data which was previously removed upon recommendation by 2004 STAR review (the STAT argued that this was one of the few survey biomass estimates that provided contrast in the time series).

- NWFSC-PWCC midwater juvenile hake and rockfish surveys (2001-2006). A coastwide index of hake recruitment was generated based on data from both the SWFSC and NWFSC-PWCC surveys to account for recent northerly extension of hake recruitment along the coast.

- CalCOFI larval hake production index, 1951-2006. The data source was explored as a potential index of hake spawning stock biomass.

- Aging error matrix based on 1,000 cross-read otoliths

As in the previous hake model, the U.S. and Canadian fisheries were modeled separately. The model also used biological parameters to estimate spawning and population biomass to obtain predictions of fishery and survey biomass from the parameters estimated by the model. These parameters were:

- Proportion mature at length (not estimated in model).

- Population allometric growth relationship, as estimated from the acoustic survey (not estimated in model).

- Initial estimates of growth including CVs of length at age for the youngest and oldest fish (estimated in model).

- Natural mortality (*M,* not estimated in model).

Total catch

Table 1 lists the catch of Pacific hake for 1966-2007 by nation and fishery. Catches in U.S. waters for 1966-1980 are from Bailey et al. (1982). Prior to 1977, the at-sea catch was reported by foreign nationals without independent verification by observers. Bailey et al. (1982) suggest that the catch from 1968 to 1976 may have been under-reported because the apparent catch per vessel-day for the foreign fleet increased after observers were placed on foreign vessels in the late 1970's. For 1981-2007, the shore-based landings are from Pacific Fishery Information Network (PacFIN). Foreign and joint-venture catches for 1981-1990 and domestic at-sea catches for 1991-2007 are estimated by the NWFSC's At-Sea Hake Observer Program.

At-sea discards are included in the foreign, joint-venture, at-sea domestic catches in the U.S. zone. Discards have been recently estimated for the shore-based fishery but are nominal relative to the total fishery catch. The majority of vessels in the U.S. shore-based fishery operate under experimental fishing permits that require them to retain all catch and bycatch for sampling by plant observers. Canadian joint-venture catches are monitored by at-sea observers, which are placed on all processing vessels. 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. Catch data from Canadian JV and domestic fisheries were provided by Greg Workman (DFO, Pacific Biological Station, Nanaimo, B.C.).

Fishery-dependent Data

Since the SS2 model uses length compositions and conditional age-at-length compositions, a complete reconstruction of these data inputs was required. Biological information from the U.S. at-sea commercial Pacific hake fishery was extracted from the NORPAC database management system maintained at the Alaska Fisheries Science Center. A query of length, weight and age information yielded biological samples from the Foreign and Joint Venture fisheries from 1975-1990, and from the domestic at sea fishery from 1991-2007. Specifically these data included sex-specific length and age data collected at the haul level by observers, where random samples of fish lengths from a known sampled haul weight and otoliths are then collected on a length-stratified basis. Detailed sampling information including the numbers of hauls sampled, lengths collected, and otoliths aged in the Foreign, JV and domestic at-sea fisheries are presented in Table 2.

Biological samples from the U.S. shore-based fishery were collected by port samplers from ports with substantial landings of Pacific hake: primarily Newport, Astoria, Crescent City, and Westport, from 1991-2007. Port samplers routinely take one sample per offload or trip in the port consisting of 100 randomly selected fish for individual length and weight, and 20 random samples per offload for otolith extraction and subsequent aging. It should be noted that the sampling unit here is the trip rather than the haul as in the case of the at-sea fishery. 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 can not 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 were simply summed over hauls and trips for U.S. fishery length- and age-compositions; however each fishery was weighted according to the proportion of its catch.

The Canadian domestic shore-based fishery is subject to 10% observer coverage. On observed trips, an otolith sample is taken from the first haul of the trip with associated length information, followed by length samples on subsequent hauls. 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. Sampled weight of the catch from which biological information is collected must be inferred from year-specific length-weight relationships. Canadian domestic fishery biological samples were only available from 1996-2007, and detailed sampling information is presented in Table 3.

For the Canadian at-sea Joint Venture fishery, an observer aboard the factory ship records the codend weight for each codend transferred from companion catcher boats. However, length samples are only collected every second day of fishing operations, and an otolith sample is only collected once a week. Length and age samples are taken randomly from a given codend. Since sample weight 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. Length and age information was only available from the Joint Venture fishery from 1988-2007. As in the case with the U.S. at-sea fishery, the basic sampling unit in the Canadian Joint Venture fishery is assumed to be a haul. Detailed sampling information for the Canadian Joint Venture fishery is also presented in Table 3.

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

1) Count lengths (or ages) in each size (or age) bin (1 cm/year) for each haul in the at-sea fishery and for each trip in the shore-based fishery, generating "raw" frequency data.
2) Expand the raw frequencies from the haul or trip level to account for the catch weight sampled in each trip.
3) Expand the summed frequencies by fishery sector to account for the total landings.
4) Calculate sample sizes (number of samples and number of fish within sample) and normalize to proportions that sum to unity within each year.

To complete step (2), it was necessary to derive a multiplicative expansion factor for the observed raw length frequencies of the sample. This expansion factor was calculated for each sample corresponding to the ratio of the total catch weight in a haul or trip divided by the total sampled weight from which biological samples were taken within the haul or trip. In cases where there was not an estimated sample weight (more common in the Canadian domestic shore-based trips), a predicted weight of the sample was computed by applying a year-specific length-weight relationship to each length in the sample, then summing these weights. Anomalies that could emerge when very small numbers of fish lengths are collected from very large landings were avoided by constraining expansion factors to not exceed the 95^{th} percentile of all expansion factors calculated for each year and fishery. The expanded lengths (N at each length times the expansion factor for the sample) were then summed within each fishery sector, and then weighted a second time by the relative proportion of catches by fishery within each year and nation. Finally, the year-specific length frequencies were summed over fishery sector and normalized so that the sum of all lengths in a single year and nation was equal to unity.

Tables 4 and 5 provide a detailed sampling summary, by fishery and nation, including the number of unique samples (hauls in the JV fishery and trips in the domestic fishery) by year and other sampling metrics of the relative efficiency of sample effort. Ultimately, the total sample size (# samples) by year is the multinomial sample size included in the stock assessment model. In both the U.S. and Canada, at-sea biological samples are collected at the haul level while shore-based samples are collected at the trip level. Tables 4 and 5 provide comparisons of sampling levels relative to the total sector catches in each country. In recent U.S. fisheries, between 9% and 16% of all shore-based catch has been sampled, compared to 40% to 60% of the at-sea catch. In both cases, fraction sampled has increased over time. Between 2000 and 2007, a sample was taken, on average, once per 575 mt of hake caught in the shore-based fishery, compared to once per 45 mt of catch in the at-sea fishery. Sample sizes for conditional age-at-length compositions for the U.S. and Canadian fisheries are given in Tables 6 and 7, respectively.

U.S. fishery length and implied age compositions representing fish caught in both the at-sea and shore-based fisheries are shown in Figures 3-4 and Figure 5-6, respectively. Implied age compositions represent the proportions at age from collapsing the conditional age at length compositions over the length margin (appropriately weighted). It should be noted that there are some differences in the length compositions between the at sea and shore-based domestic fisheries, suggesting that future attempts should be made to model them separately. In general, the composite U.S. fishery length and age compositions confirm the well known pattern of year-class strengths, including the dominant 1980 and 1984 and secondary 1970, 1977 and 1999 year classes moving through the size structure (Figure 4). The most recent length and age compositional data from the 2007 U.S. fishery also indicate the presence of a 2003 and 2005 year class. These relationships suggest that the sizes of hake, which are vulnerable to the U.S. fishery, have changed over time, possibly due to growth, selectivity or both. This is particularly evident with the appearance of larger fish before 1990 and a shift to smaller fish between 1995 and 2000. These features are explored in the population dynamics model.

As with the U.S. fleet sectors, differences in length compositions between the Canadian Joint-venture and domestic fleets among some of the years warrant exploration of fitting the fisheries separately. This, however, was not done in this assessment due to time limitations. The composite Canadian fishery length compositions (Figures 7 and 8) and age compositions (Figures 9 and 10) indicate that the Canadian fleets exploit larger and presumably older hake. A particularly interesting feature of these length compositions is that the Canadian fleet prosecuted a seemingly fast growing 1994 year class of hake in 1995 (age 1), 1996 (age 2) and subsequent years. It is unclear whether this is due to size- vs. age-based selectivity; however, it is well known that larger (and older) hake migrate further northward annually (Dorn, 1995). In recent years the 1999 year class has dominated the catch of the Canadian fleets. As in the U.S. fishery, Canadian length compositions show some temporal pattern in the range of fish exploited by the fishery (Figure 8).

U.S. and Canadian fishery conditional age-at-length compositions constitute the bulk of compositional data in this assessment and provide information on recruitment strength, growth and growth variability. As such the model is actually fitting the conditional age-at-length compositions, but fits are shown to the "implied" age compositions (fits are simply collapsed in the margin of proportions at age) for convenience. Since age-composition data used in the old hake assessment extended further back in time than the conditional age-at-length data generated here, the older data were also included in the assessment model to augment information on recruitment earlier in the time series (U.S. fishery = 1973-1974, Canadian fishery=1977-1987).

Triennial Shelf Trawl Survey

The Alaska Fisheries Science Center has conducted a triennial bottom trawl survey along the west coast of North America between 1977 and 2001 (Wilkins et al. 1998). In 2003, the Northwest Fisheries Science Center took responsibility for the triennial bottom trawl survey. Despite similar seasonal timing of the two surveys, the 2003 survey differed in size/horsepower of the chartered fishing vessels and bottom trawl gear used. For this reason, the continuity of the shelf survey remains to be evaluated. In addition, the presence of significant densities of hake both offshore and to the north of the area covered by the trawl survey limits the usefulness of this survey to assess the hake population. Moreover, bottom trawl used in the survey is limited in its effectiveness at catching mid-water schooling hake. For these reasons the triennial shelf trawl survey is presently not used in the assessment. However, age composition data from this survey are used, in conjunction with age composition data from the acoustic survey, to evaluate the selectivity pattern associated with the acoustic survey external to the SS2 model. Results of this analysis are described below.

Acoustic Survey (Biomass, length and age composition)

Integrated acoustic and trawl surveys are used to assess the distribution, abundance and biology of coastal Pacific hake, *Merluccius productus*, along the west coasts of the United States and Canada (Fleischer et al. 2005). The Pacific Biological Station (PBS) of the Canadian Department of Fisheries and Oceans (DFO) has conducted annual surveys along the Canadian west coast since 1990. From 1977-2001, surveys in U.S. waters were conducted triennially by Alaska Fisheries Science Center (AFSC). The triennial surveys in 1995, 1998, and 2001 were carried out jointly by AFSC and PBS. 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). Following the transfer, the survey was scheduled on a biennial basis, with joint acoustic surveys conducted by FRAM and PBS in 2003, 2005 and 2007.

The 2007 survey was conducted jointly by U.S. and Canadian science teams aboard the NOAA vessel *Miller Freeman* from 20 June to 19 August, spanning the continental slope and shelf areas the length of the West Coast from south of Monterey California (35.7º N) to the Dixon Entrance area (54.8º N). A total of 96 line transects, generally oriented east-west and spaced at 10 or 20 nm intervals, were completed (Figure 11). During the 2007 acoustic survey, aggregations of coastal Pacific hake were detected as far south as 37º N (Monterey Bay) and extending nearly continuously to the furthest northerly area surveyed at Dixon Entrance. Areas of prominent concentrations of hake included the waters off Point Arena (ca. 39º N) and north of Cape Mendocino, California (ca. 41º N), in the area south of Heceta Bank, Oregon (ca. 44º N). North of the U.S. border, hake which are typically present in the acoustic survey off Vancouver Island, were relatively sparse during the 2007 acoustic survey. Diffuse concentrations were found north of Vancouver Island within waters of the Queen Charlotte Sound (ca. 51º N) and north to Dixon Strait. Mid-water and bottom trawls, deployed to verify size and species composition and collect biological information (i.e., age composition, sex), found that smaller individuals - age-2 fish - were prevalent in the southern portion of their range, but the coastal Pacific hake stock continued to be dominated by representatives of the 1999 year-class (age 8) throughout most of their range, except for the occurrence of numbers of larger Pacific hake in the north.

Pacific hake distribution can be highly variable based on backscatter information from the acoustic survey such and northward migration patterns have been proposed to be 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 (Figure 12). The 1998 acoustic survey stands out and shows an extremely northward occurrence that is thought to be tied to the strong 1997-1998 El Nino. In contrast, the distribution of hake during the 2001 survey was very compressed into the lower latitudes off the coast of Oregon and Northern California.

As with the fishery data, acoustic survey length and conditional age compositions were used to reconstruct the age structure of the hake population. In general, biological samples taken by midwater trawls were post-stratified based on geographic proximity and similarity in size composition. Estimates of numbers (or biomass) of hake at length (or age) for individual cells were summed for each transect to derive a coast-wide estimate. Details of this procedure can be found in Fleischer et al. (2005). Each sample was given equal weight without regard to the total catch weight. The composite length frequency was then used for characterizing the hake distribution along each particular transect and was the basis for predicting the expected backscattering cross section for Pacific hake based on the fish size-target strength relationship $TS_{db} = 20\log L - 68$ (Traynor 1996.). New target strength work (Henderson and Horne 2007), based on in situ and ex situ measurements, suggests a regression intercept of 4-6 dB lower than that of Traynor. A lower intercept to the TS-to-length regression suggests that an individual hake reflects 2.5-4 times less acoustic energy, implying considerably more biomass than that of Traynor's equation. Both estimates of the TS-to-length regression use night time in situ measurements and hake may have different behavior characteristics than during the daytime. The acoustic survey is conducted during the daytime. The current biomass estimates continue to be based on that of the Traynor's TS-to-length regression, which has been used historically to interpret the acoustic survey data. More careful and accurate *in situ* measurements on hake TS need to be collected *during daytime* when the survey acoustic data are collected, in addition to the investigation of , the depth dependence of the hake TS. In either case, uncertainty in the TS regression represents another source of uncertainty that is not accounted for in the survey biomass estimates.

Acoustic survey sampling information including the number of hauls, numbers of length taken and hake aged are provided in Tables 8 and 9. The 2007 acoustic survey size composition shows a dominant peak at 48 cm indicating the persistence of the 1999 year class in the population, and a secondary peak around 33 cm suggests the potential of a 2005 year class (Figures 13-14). Age compositions shown in Figure 15-16 confirm the presence of the strong 1999 year class and potentially a moderate to strong 2005 year class. Size and age compositions from the previous acoustic surveys also confirm the dominant 1980 and 1984 year classes present in the mid-1980s to early 1990s. Proportions at age are given in Figures 15 and 16, and conditional age-at-length proportions are shown in Figure 17.

Based on estimates from the acoustic survey, Pacific hake biomass declined by 31% from 1.8 million mt in 2003 to 1.26 million mt in 2005 (Table 10). The 2007 biomass estimate of 879,000 mt declined another 30% from 2005. In general, acoustic survey estimates of biomass indicate that the hake population has varied with little trend from the time of the first survey in 1977 to the most recent in 2007 (Figure 14). Estimates of variability have been calculated since the 2003 survey based on the Jolly-Hampton estimator (1989) with CVs on the order of 25%. This takes spatial variability of the acoustic backscatter into account but leaves other sources of observation error, including sampling variability (haul to haul variation in size/age) and target strength, unaccounted for. Error bars shown around point estimates of biomass are not estimated but rather assumed based on reliability of the survey in a given year and are used as input in SS2 (CV=0.5 1977-1989, CV=0.25 1992-2005.

Considerable discussion on assessment uncertainty continues to center on the acoustic survey in both the catchability coefficient, q, and the asymptotic vs. dome-shaped selectivity. Dome-shaped selectivity implies a greater proportion of older hake in the population than observed in the survey. Reasons for dome-shaped selectivity could be due to a number of factors including net avoidance of older hake and differential distribution of older fish near the bottom or at deeper depths. This was further investigated by comparing the numbers at age in both the acoustic and bottom trawl surveys during 1977-2001, in which data spatially and temporally overlapped. Hake catches (in number) taken from mid-water and near-bottom hauls in the acoustic survey and from bottom hauls in the triennial bottom trawl survey were summed by each age, and assumed to be representative of the underlying population age structure. These were then compared to the catch in numbers at age taken from hauls in the acoustic survey. Results indicate empirical support of an acoustic survey selectivity that is dome-shaped (Figures 19 and 20). A comparison of the ratio of acoustic survey numbers at age to the sum of the acoustic and triennial bottom trawl survey numbers at age (normalized to have a peak of unity), indicate that only 2 out of the nine years have asymptotic-like selectivity patterns. The remaining nine years show curves that peak at about ages 5-7, decline between 0.2-0.9 at ages 11-13, and further decline between <0.1-0.7 at ages 14-15+. For ages 14-15+, the mean is about 0.5 (when normalized) for all years. The weight of evidence suggests dome-shaped selectivity, although the results are not definitive.

The acoustic survey catchability coefficient, q, has historically been quite uncertain. This parameter globally scales population biomass higher if q is lower and lower if q is higher. Early assessments that used the acoustic survey in age-structure assessments (Dorn et al. 1999) asserted q=1.0 and treated the parameter as a fixed quantity (In fact ABCs and OYs until 2003 have been predicated upon that assumption). Helser et al. (2004) conducted a likelihood profile over the value of q as well as estimated it freely in the model, and found values of q in the range of 0.38 to 0.6, depending on model structure. In general, the best fit to the data is achieved when q is estimated to be low; however, low q's for an acoustic survey has been met with some resistance. Since 2005 assessments have presented two models with differing q's in order to bracket the range of uncertainty in the acoustic survey catchability coefficient, q. As discussed below, this assessment attempts to integrate out the uncertainty in q while incorporating uncertainty in the shape of the acoustic survey selectivity curve.

Aging Error

With the transfer of the task to age Pacific hake to the Northwest Fisheries Science Center in 2001, an effort was made to cross-calibrate age reader agreement. Cross-calibration was performed on a total of 900 otoliths collected during 2001-2007 and exchanged between the Cooperative Aging Project (Northwest Fisheries Science Center, NWFSC) and Department of Fisheries and Oceans (DFO). Overall agreement between NWFSC and DFO was 50%, and for ages assigned that were aged within one and two years, the agreement was 76% and 86%, respectively. As expected, agreement among all three labs, NWFSC, DFO and AFSC, was greater for younger fish than for older fish. The results of the cross-calibration were somewhat better than the 2001 comparisons between NWFSC and DFO but poorer than the1998 comparisons between AFSC and DFO. It should be noted that agreement between two age readers at NWFSC was 77%, with 88% agreement on aging within one year. Agreement between NWFSC readers for ages 3-4 and ages 5-7 was 82% and 40%, respectively, with similar results obtained between the NWFSC and DFO labs. When there was no age agreement between the three labs, the NWFSC tended to assign older ages to samples than DFO. Additional comparisons are needed to further calibrate ageing criteria between agencies.

Age-reading error was quantified for use in the stock assessment model according to the maximum likelihood method of Punt et al. (In Press). This method estimates bias and precision of the observed age from the "true" age assuming unbias samples in the observed data. There were insufficient samples to estimate bias; however, precision was estimated and quantified as the standard deviation of observed age from true age. Figure 19 shows the relationship of the standard deviation as a function of true age and suggests that aging imprecision increases as a nonlinear function of true age. This age error matrix (CAP + DFO) was applied to the model for 2001-2007. A similar relationship was estimated, with similar results, for individual age reads by AFSC, based on a large sample of calibration reads between "testers" and production readers. Since 20% of all pre-2001 samples read by AFSC were based on "resolved age" (consensus obtained between a production reader and "tester"), we assumed an aging error twice as precise as that obtained from the recent otolith cross reads (Figure 21). Further research is needed to derive an imprecision matrix based on the statistical properties of production resolved ages.

Pre-recruit surveys

NOAA's Southwest Fisheries Science Center (SWFSC) has conducted annual surveys since 1983 to estimate the relative abundance of pelagic juvenile rockfish off central California coast (36.50°–38.33°N). The survey was designed to measure the annual relative abundance of pelagic juvenile rockfishes (*Sebastes* spp.), but also captured YOY Pacific hake (Sakuma et al. 2006). Standardized 15 min midwater trawls with the headrope set at a depth of 30 m were conducted at a series of standard stations with a 9.5 mm mesh liner. The survey was expanded substantially in 2004 to cover a much larger spatial area (i.e., from San Diego to Point Delgada: 32.75°–40.00° N). Since 1999, the NWFSC and Pacific Whiting Conservation Cooperative (PWCC), in coordination with the SWFSC Rockfish survey have conducted an expanded survey to improve targeting of juvenile hake and rockfish. The NWFSC-PWCC pre-recruit survey uses a midwater 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 from 50 m to 700 m bottom depth seaward with hauls taken from bottom depths of 50, 100, 200, 300, and 500 m at each transect. Since 2001, side-by-side comparisons were made between the vessels used for the NWFSC-PWCC and SWFSC survey.

In an effort to obtain a more comprehensive coastwide survey of hake recruitment, a Delta-GLM was applied to catch data from both the SCL and PWCC-NWFSC midwater trawl data. The Delta-GLM approach is a type of mixture distribution analysis which models zero and non-zero information from catch data separately (Pennington 1983, Stefansson 1996). Specifically a logistic regression, which assumes a binomial error model, is used to model the proportion positive, while a lognormal error model is used to model the non-zero catches given a positive catch. The forms of the binomial and lognormal GLMs are:

$$p_i = \log\left[\frac{\pi_{ij}}{(1-\pi_{ij})}\right] = m + \tau_i + S_j + l_k + (S \cdot l_{jk})$$

$$c_i = g(\mu_{ij}) = m + \tau_i + S_j + l_k + (S \cdot l_{jk})$$

where: m is the model intercept, τ is the year effect, S is the survey effect, l is the latitude (seven discrete 1 degree latitude bins) effect. The survey effect accounts for potential differences between the NWFSC-PWCC survey and SWFSC survey catch data while the latitudinal effect attempts to capture changes in relative abundance of young-of-year hake. In particular, between

2001 and 2004, peak relative abundance shifted from approximately 38 to 42 degrees latitude. An index of abundance is obtained by taking the product of the inverse link of the year effects for each GLM. Variances were obtained using a numerical procedure in which a Monte Carlo approach (based on 10,000 replicates) was used by taking replicate draws from multivariate normal distributions of the MLE estimates of the mean parameter vector and the variance-covariance matrices.

Trends in the coastwide index and associated 95% intervals are shown in Figure 22 and Table 11a. While the coastwide index does include SWFSC data, the trends in hake recruitment between the coastwide and SWFSC index are comparable for the years of overlap, from 2001 to 2006. Specifically, both indices show large values in 2004 compared to the surrounding years, followed by very low values in 2005 and 2006. Given the brevity of the coastwide time series, it is difficult to judge how the magnitudes of the values taken from 2001 to 2006 compare on a historical basis. Details of the data used for this analysis are given in Table 11b.

CalCOFI Ichthyoplankton Survey

Pacific hake larvae have been routinely collected in the CalCOFI survey (Lo 2007). The survey, which began in 1949, was conducted annually until 1966 and then triennially until 1984. Survey coverage was generally restricted to between San Diego and Point Conception. Beginning in 1985, the survey was resumed annually and coverage, in some years, extended northwards to San Francisco. Lo (2007) has developed a time series of hake larval production, which may be useful for indexing spawning stock biomass. However, recent northward extension of pre-recruit densities suggested by Phillips et al. (2007) may indicate that hake spawn in areas to the north of the CalCOFI survey area. Despite this limitation, we investigated the usefulness of this survey to index the spawning stock biomass of the hake population.

Figure 23 shows a plot of the natural logarithm of hake spawning stock biomass (Helser and Martell. 2007) to the natural logarithm of the daily hake larval production index (Lo 2007) for data between 1966 and 2007. The plot shows a generally positive correlation ($r = 0.53$) between the larval production index and spawning stock biomass; however, the variability is quite large. Although coefficients of variation vary considerably over the time series, the average, CV=0.52, was assumed constant for modeling. The daily larval production was assumed to index the spawning stock biomass at the beginning of each year and the catchability coefficient, q, was estimated both as a linear and nonlinear function (power term on the proportionality) of spawning biomass. Model results given in Figure 23 show the fit to the observed larval production index and illustrate that the larval production index as a measure of spawning biomass has little influence on the fit. While the input CV is 0.52, the resulting root mean square error (RMSE, measure of error between the expected value and observed index) calculated from this index is 2.00. nearly 3*x* higher than the acoustic survey biomass index (RMSE=0.59). The larval production index may be of limited utility as an index of spawning biomass since the model would simply ignore it, due to the large variance, in favor of the other data sources such as the acoustic survey biomass, which are relatively more precise. Therefore, further efforts to include the larval production index in the model were not conducted. However, virgin spawning biomass, external to the SS2 model, was derived as a "ball park" estimate based on a predictive relationship between spawning biomass and larval production index (Figure 23). For this exercise, an estimate of unfished spawning biomass (SB_{zero}) was obtained by taking the bias-corrected, back-transformed predicted spawning biomass, based on the average larval production index between 1951-1965, a period prior to heavy exploitation. Unfished spawning biomass was estimated to be roughly 2.0 million mt. This estimate is highly uncertain given the prediction intervals (0.54 million mt - 3.8 million mt), but it does provide a check for results from the SS2 model.

Biological Parameters

Growth

There is considerable variability in the length-at-age data collected during the acoustic surveys since 1977. The process governing variation in growth may include effects from size-selective fishing, changes in size selectivity over time, and variation in growth rates over time. In order to explore alternative specifications for hake growth within SS2, we fit alternative growth models to the length-at-age data collected in the acoustic surveys (assuming size-selectivity in the acoustic surveys has been constant over time). The first of these models was a simple time-varying growth model, where the growth coefficient (k) was allowed to vary over time. This assumed that all extant cohorts are subject to time varying changes in the metabolic rates (presumably associated with changes in available food). This version of the growth model was implemented in the current assessment in Stock Synthesis 2 (SS2). The second growth model assumed that growth is density-dependent. That is, the density of each cohort determines the overall growth rate and each cohort has its own asymptotic length. The third model was similar to the second model; however, in this case we assumed the growth coefficient (k) to be cohort specific. Details of this analysis are given in Helser et al. (2006).

Temporal variability in hake growth is shown in Figures 24 and 25 in terms of observed lengths at age from the acoustic survey from 1977-2005. Of the three alternative growth models, the model with cohort specific l_2 (asymptotic size, SS2 parameterization of the von Bertalanffy growth model) values explains more of the variation in the length-age data than the time varying k model and cohort k model (Figure 24). In particular, cohort based L2 begins relatively high (> 55 cm) prior to 1980 (Figure 24) and then appears to decline rapidly as the very large 1980 and 1984 year class grow. Expected size at age, based on the cohort based L2 parameter, is above the expected size for the other models in the 1977, 1980, and 1983 survey data. Likewise, cohort based k declines rapidly between the mid 1970s and mid 1980s (Figure 24). It should be noted that these cohort-based models do not assume the cumulative affects of size-selective fisheries. A similar exploratory growth analysis was conducted on other sources of age data including the acoustic survey (1977-2007), AFSC triennial bottom trawl survey (1977-2003), and the U.S. at sea hake fishery (1973-2006). In particular, a hierarchical von Bertalanffy growth model was fit separately to each data source which treated cohort as a random linear effect with the growth coefficients, L_∞ and k. The scale parameter, $t_{0,}$ was estimated as the mean fixed effect. Markov Chain Monte Carlo simulation in WinBUGs (Bayesian inference Using Gibbs Sampling, Thomas et al. 1992; Spiegelhalter et al. 1999) was used to estimate the marginal posterior density of the cohort specific L_∞ and k parameters, which were plotted sequentially by cohort (Figure 25). The results illustrate striking consistency in the change in L_∞ and k parameters over time (by cohort) from each data source and confirm the observations described above.

A final analysis was conducted, using the same hierarchical model, to investigate differences in sex specific growth of hake. A plot of the bivariate posterior density of 1,000 MCMC samples of L_∞ and k reveal that female hake grow to a significantly larger asymptotic size (L_∞) but at as slower rate (k) than males (Figure 26). While the present model does not model hake by sex, future work should consider a separate sex model that may account for differential fishery selectivity by sex. To properly represent the cumulative effects of size-selective fisheries in this approach, the cohort-based growth model should be integrated into the assessment model itself. This would provide a fruitful area of research for improving SS2. In this case it would not be necessary to use the conditional MLE for the numbers at age; this information could be provided from the stock assessment model itself. Since this feature is not currently implemented in SS2, blocks were created aggregating various years in which it was anticipated the cohort affects on growth would be manifested (See *Model Selection and Evaluation* below).

Size/Age at Maturity

The fraction mature by size was estimated using data from Dorn and Saunders (1997) with a logistic regression. 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. Maturity in hake probably varies both as a function of length and age, however, for the purposes of parameterizing SS2 the logistic regression model was fit as a function of length. Maturity proportions by length are shown in Figure 27. Less then 10% of the fish smaller than 32 cm are mature, while 100% maturity is achieved by 45 cm.

Natural mortality

The natural mortality currently used for Pacific hake stock assessment and population modeling is 0.23 per year. This estimate was obtained by tracking the decline in abundance of a year class from one triennial acoustic survey to the next (Dorn et. al 1994). Pacific hake longevity data, natural mortality rates reported for Merluciids in general, and previously published estimates of 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). We also considered Hoenig's (1983) method for estimating natural mortality (M), assuming a maximum age of 22 (attributing a single observation at age 25 to ageing error or anomaly), 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 -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 undoubtedly somewhere in between these two extremes (while not addressing the bias question). 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 about 0.2 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 (note that SS2 does not currently allow for priors in log-normal space). The fixed value of M which is used in the current model (0.23) is about two standard errors from Hoenig's point estimate (0.193), while still being far less than the model estimate when M is free constrained by either of the above priors (> 0.30 in all three cases).

Model description

This assessment used the Stock Synthesis modeling framework written by Dr. Richard Methot at the NWFSC (SS2 Version 2.00n, Methot 1989). The Stock Synthesis application provides a general framework for modeling fish stocks that permits the population dynamics to vary in complexity, in response to the quantity and quality of available data. In this regard, both complex and simple models were explored as part of this assessment. The Pacific hake population is assumed to be a single coastwide stock along the Pacific coast of the United States and Canada. As in the previous model, sexes are combined in the current model in representing the underlying dynamics and in all data sources where this was possible: growth and fishery and survey size/age compositions. The accumulator age for the internal dynamics of the population was set at 15 years, well beyond the expectation of asymptotic growth. The length structure ranged from 20 cm to 70 cm. The years explicitly modeled were 1966-2007 (last year of available data). Initial population conditions were assumed to be in equilibrium prior to the first year of the model. No initial fishing mortality was estimated and the spawning biomass was assumed equal to Bzero in 1966, preceding the advent of the distant water fleets during the mid-to-late 1960s. The level of hake removals prior to 1966 is unknown, but there were no directed commercial fisheries for hake until the arrival of foreign fleets in the mid to late 1960s.

The following narrative of the model structure is accompanied by the detailed parameter specifications and assumptions found in Table 12. The assessment model includes two national fisheries: US and Canadian trawl fisheries. Arguably, the U.S. at-sea and shore-based fisheries, as well as the Canadian JV and domestic fisheries could be modeled separately for reasons mentioned above. However, in this assessment each nation's fleets were combined and implicitly assumed to have the same selectivity patterns. The selectivity curves for the acoustic survey and the U.S. and Canadian fisheries were assumed to be dome-shaped and modeled as a function of age using the double logistic function (option 19 in SS2). These fishery selectivity curves were also allowed to vary over time to account for temporal changes in fishery operations (distant water fleets, domestic fleets, etc.) and shifts in selectivity as the fishery focused exploitation on abundant cohorts.

The wealth of conditional age-at-length data from the commercial fleets and acoustic survey provided a great deal of flexibility in modeling potential changes in growth curves over time. The comparative analysis used a 'random walk' approach to growth, but it was felt that this approach might be over-parameterized since empirical examination of the growth parameters outside the model suggested a pattern of discrete changes between multi-year periods. Preserving some degree of temporal variability was clearly warranted, since specifying growth as time-invariant resulted in a decline of roughly 1,000 likelihood units in the objective function, relative to the random-walk structure. Through an iterative process of gradually increasing the size of adjacent-year blocks and examining residuals, a block structure was developed that sacrificed little in the value of the objective function and seemed consistent with empirical observations. Two blocks were used for the L2 parameter, 1966-1983 and 1984-2007, which allowed the model to account for the larger asymptotic fish size and the general prevalence of larger fish observed during the early period. Three blocks were used to partition the growth parameter k: 1966-1980, 1981-1986, and 1987-2007. The middle period was intended to allow the model to accommodate the slightly smaller body size of age 4-6 year old fish during those years. The temporal structure of hake growth in terms of the expected size at age is (Figure 24) characterized as an early period from 1966 to the early 1980s where expected maximum size (i.e., L2) is high relative to the subsequent period from the mid 1980s to 2007, with a decline in growth rates (i.e., smaller expected size at age for ages 4-6) during the early-to-mid 1980s. In the most recent block, 1987-2007, growth returns to near baseline rates but the expected maximum size is lower.

In modeling temporal changes in fishery selectivity, we employed the same approach and developed a block structure that seemed consistent with the empirical data. In particular, both the U.S. and Canadian fisheries consisted of four discrete temporal blocks. For the U.S. fishery, separate selectivity functions (for both the ascending and descending limb) were estimated for the periods: 1966-1983, 1984-1992, 1993-2000, and 2001-2007. Selectivity functions for the Canadian fishery (ascending limb only allowed to vary through time) were estimated for the periods: 1966-1994, 1995-2000, 2001-2002, and 2003-2007.

For the base case model, as well as the previous models, instantaneous natural mortality (M) is assumed to be time-independent and equal to 0.23 y^{-1}, and allowed to increase on ages 13-15+. A prior distribution was used on the offset parameter as specified in Table 12. We also conducted a profile likelihood over values of M. The stock-recruitment function was a Beverton-Holt parameterization, with the log of mean unexploited recruitment estimated. When freely estimated, the steepness parameter is close to the upper limit of 1.0, thus implying that recruitment is independent of the level of spawning biomass. However, for this assessment a beta prior for steepness was developed 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. Year-specific recruitment deviations were initially estimated from 1967-2007 but revised based upon inspection of the standard deviation of the deviations. This structure was based upon inspection of year-specific standard deviations relative to the input value of $sigma_R$.

The constraint and bias correction standard deviation, $sigma_R$, is treated as a fixed quantity in SS2. Typically, the value is derived through an iterative process of adjusting the input value corresponding to the minimal difference between the root mean squared error (RMSE) of the predicted recruitment deviations and the input value. This ensures that the approximate bias-correction term will be appropriately and internally consistent for predicted recruitments estimated in the model and projected forward in time. Initial model runs began with the value used in the 2007 hake model: $sigma_R$ = 1.13. In addition, input sample sizes were iterated by examining the relationship between effective sample size estimated in the model and the observed input sample sizes.

Maturity of Pacific hake was assumed to have a logistic functional form, increasing sigmoidally to an asymptote as a function of size (Figure 28). Fecundity (spawning output) was assumed to be a function only of mass and equivalent in form to the maturity-at-length relationship (Figure 28). Individual growth was modeled for combined sexes and based on the von Bertalanffy growth function. All von Bertalanffy growth parameters, including the growth coefficient k, length at minimum age, length at maximum age (15 years old), CVs of size at age, as well as time blocks describing changes in some parameters, were estimated within the model. The explicit temporal parameterization is shown in Table 12.

Multinomial sample sizes for the length composition and conditional age at length data used in this assessment are based on the number of hauls or trips sampled for the commercial at sea and shore-based fisheries, respectively, and the number of tows in the research surveys. Sample sizes for conditional age-at-length data were taken from the number of fish aged. Standard deviations from the survey indices were not adjusted, as the RMSE from preliminary model runs were consistent with the mean of the input standard deviations. The base case model employed equal emphasis factors (lambdas=1.0) for each likelihood component.

Modeling Results

Model Transition

This assessment transitioned to the newest version of Stock Synthesis (SS2 ver.2.00n) and therefore, a comparison was performed to evaluate differences in model results, if any, from the last assessment (Helser and Martell 2007) in SS2 ver.1.23e using the exact same model structure and data through 2006. The model structure employs temporal variation in growth and fishery selectivity as described earlier, but the reader is directed to Helser and Martell (2007) for specific details. Figure 29 shows estimated trends in spawning biomass and relative depletion from 1966 to 2007. Ver.2.00n of SS2 resulted in slightly lower initial spawning biomass prior to

1984 than compared to ver.1.23e, but both have very similar trends in stock biomass overall. Unfished spawning biomass dropped from 3.56 to 3.21 million mt. A detailed comparison of model output shows slightly lower estimates of mean size at ages 0-3 which are attributable to the new way in which SS2 extrapolates means size as a linear function below the first age specified for growth estimation in the model. Despite the slight differences in spawning biomass between versions, the relative depletion is nearly identical at roughly 32% of unfished biomass in 2007. These results were satisfactory as to warrant a version update of the model.

The model using SS2 ver.2.00n was then updated with data from the 2007 fishery and 2007 acoustic survey. Again, the trend in spawning biomass and relative depletion were quite similar, except that unfished spawning biomass in 1966 was lower (2.97 million mt) and 2007 relative depletion dropped from 32% to 25% (Figure 29). The difference in relative depletion was attributable to the fact that recruitment in 2004, which was predicted by the coast-wide pre-recruit index to be larger than any from 2001-2006 (see Figure 22), did not in fact materialize based on the newest 2007 fishery and acoustic survey data (evident as age 3 hake in the 2007 acoustic survey). This weaker than expected year class translated into less biomass and therefore lower relative depletion. However, recruitment in 2005, which was predicted to be the second lowest between 2001-2006 based on the coast-wide pre-recruit index, appears to be a considerably larger than average based on the 2007 fishery and acoustic survey data (Figure 15). The resulting RMSE for the pre-recruit survey has more than doubled (SE=1.45) since the last assessment and calls into question the utility of the index to reliably predict recruitments that are not well informed by other data in the model.

The final series of model runs focused on comparison of the double normal selectivity curve for the acoustic survey and the double logistic form used in the last assessment, implementation of the aging error matrix (imprecision but not bias), and tuning the input to output sample variances. The purpose of using an age-reading error matrix (imprecision matrix) is to generate the model's expectation of cohort sizes so that there is some probability of assigning an age other than the true age in order to better match the observed age-composition data. Implementing the aging error matrix did in fact improve the model fits to the age-composition data. As a result, the expected cohort sizes were sharpened, with large year-classes increasing in size and smaller year classes reduced. The effect on the model result was a reduction in the estimate of logRzero, which translated into a lower estimate of Bzero (from approximately 3 million mt to 2.4 million mt), and increase in 2008 relative depletion from 25% to 31% with an increase in the strength of the 1999 year class (Figure 29). Transitioning to the double normal curve for acoustic survey selectivity gave results nearly identical to those obtained with the double logistic curve. The model including ageing error and the double-normal selectivity specification, which is generally consistent with the model structure and assumptions from the 2007 assessment (i.e. q = 1.0), served as the basis for additional model selection and evaluation.

Model selection and evaluation

As previously mentioned, acoustic survey catchability, *q,* and selectivity have been viewed as the principal axes of uncertainty in the hake assessment for a number of years. We explored this uncertainty by conducting likelihood profiles for five different values of the final (age-15) acoustic survey selectivity (final selex = 0.2, 0.4, 0.6, 0.8, 1.0) within five acoustic survey catchability values (*q* = 0.2, 0.4, 0.6, 0.8, 1.0) within five different values of natural mortality (M = 0.21, 0.22, 0.23, 0.24, 0.25). The final selectivity (final selex) defines the degree of curvature in the descending limb of the selectivity curve. Figure 30 illustrates the results of this analysis and shows the response surface of differences in total log likelihood, as well as corresponding estimates of Bzero and 2008 relative depletion, as a function of M, acoustic survey final selectivity and survey catchability. Figure 31 shows the difference in likelihood of the individual data components (size and age compositions) for M=0.23 and Figure 32 shows the difference in likelihood of the acoustic survey biomass index for all values of M profiled against.

The relative difference in total log likelihood (smaller differences imply better fit to the data) changes far more dramatically with changes in final acoustic survey selectivity than with changes in survey catchability; dropping by as much as 400 likelihood units from a curve which is asymptotic to one which is highly dome-shaped. This pattern is consistent over all values of survey catchability included in the profile, suggesting that better model fits are achieved when the selectivity curve is dome-shaped no matter which value of survey q is used. In contrast, the difference in total log likelihood changes very little as a function of survey catchability when profiled against lower values of final selectivity, but suggest better model fits to higher values of q when selectivity is assumed asymptotic. Finally, the response surface of difference in total log likelihood is conserved over the profiled values of natural mortality, but does suggest better model fit with a higher value of M.

While the likelihood profiles suggest that model results are more sensitive to the shape of the selectivity curve than to survey *q* in terms of differences in total likelihood, estimates of Bzero and 2008 relative depletion appears to be sensitive to final selectivity, and perhaps even more so to survey *q*. Using results with M=0.23 to illustrate, Bzero ranges from over 3.5 million mt at low *q* and dome-shaped selectivity to less than 1.0 million mt at high values of *q* and asymptotic selectivity. Correspondingly, relative depletion in 2008 ranges from nearly 80%-100% of unfished biomass at low values of survey *q* to less than 30% under high values of *q*.

These results point to some degree of confounding between survey selectivity, q and M, however, all the individual data components (except perhaps those of the Canadian age compositions) suggest better model fits to a dome-shaped selectivity pattern and lower or intermediate values of survey *q*. Nevertheless, uncertainty regarding the true values of both survey *q* and final selectivity propagates substantial uncertainty upon our understanding of Bzero and the level of depletion.

In the present assessment we attempt to capture the uncertainty associated with the acoustic survey selectivity while at the same time allowing for uncertainty in the survey catchability coefficient, *q*. We initially proposed a base model with two alternatives where the model is fit using the double normal curve (pattern 20) for the acoustic survey selectivity that specifies a range of curvature for the descending limb; final selectivity at age 15+ equals 0.3, 0.5 and 0.7. The two parameters that defined the shape of the ascending limb of the curve were freely estimated as was the acoustic survey catchability coefficient, *q*, for each descending limb selectivity pattern. During the STAR review, February 11-12, 2008, the review panel expressed concern that this approach overstated the uncertainty in model results (95% of 2008 depletion from the two extreme models ranged from 17.5% to 78.2%). As such an alternative model formulation was proposed in which the acoustic survey selectivity curve (both ascending and descending portions) and survey catchability coefficient, *q,* are freely estimated, and that M on older ages, 13-15+, is also estimated with a mildly informative prior ($M_{13\text{-}15+}$ ~ N (0.0.8), Table 12). The STAT agreed with this approach as a better means of quantifying uncertainty and to fully integrate model results using Markov Chain Monte Carlo simulation, described later under *Model Uncertainty*.

The acoustic survey selectivity was estimated freely but was time invariant. The estimated selectivity curves are shown in Figure 34 with parameter estimates and asymptotic standard deviations in Table 13. The shapes of the selectivity curves for both the U.S. and Canadian fisheries appear to be quite reasonable, even with the apparent temporal shifts in the curves. The U.S. fishery selectivity curves show substantial temporal variation in both the ascending and descending limbs. As might be expected, U.S. fishery selectivity increased on the younger aged fish (ages 3 and 4) as the dominant 1980 and 1984 year classes became vulnerable to exploitation during the mid 1980s to early 1990s. As these cohorts grew into the older age structure and persisted in the fishable stock U.S. fishery selectivity increased on the older ages, seen as an increase in the descending curve in 1993-2006. Canadian fishery selectivity curves also show variability through time (it should be noted that Canadian fishery selectivity curves on older fish were assumed to be the same throughout). As is the case with the U.S., changes in ascending-limb selectivity appear to be associated with availability of a specific year class and its exploitation by the Canadian fleets, which can be observed in the exploitation of the 1994 year class during1995-2000.

Model fits to size-composition data are shown as predicted length frequency distributions, effective vs. observed sample sizes, and Pearson residual plots, and are illustrated separately for the U.S. fishery (Figures 35-37), Canadian fishery (Figures 38-40) and acoustic survey (Figures 41-43). In general, model fits to the U.S. fishery length-frequency distributions show reasonable predictions given the observed data (Figure 35). Predictions seem to be consistent with the observed length compositions in terms of hitting the modes of the distribution and range of sizes exploited. Comparison of observed and calculated effective sample sizes for U.S. fishery length frequencies show no clear relationship, but generally indicate that model fits are as good as expected given the input sample sizes and length frequency data (Figure 66). It should be noted that the input samples sizes shown in Figure 36 for the U.S. length and length-at-age compositions have already been iteratively tuned to 0.3 and 0.5, respectively, of their original input sizes. Some lack of fit does appear to be evident in the U.S. fishery length compositions, but this is generally restricted to the largest sizes, especially in the earlier years (Figure 37).

The model fit the Canadian fishery length composition data slightly less well than the U.S. fishery, but this might not be surprising given the fewer years of data (Figure 38). Predicted length distributions were on the mode for most years with the exception of 2000, 2001, and 2002, suggesting a pool of larger hake was exploited during those years than predicted by the model. The model was also not able to accommodate well the catches of smaller hake in 1995-1998. This suggests that hake spawned in Canadian waters in 1994 and were exploited by the Canadian fleet as young fish. Benson et al. (2002) confirm this pattern of spawning in Canadian waters. This pattern has not been observed in the Canadian fishery during any other period. Despite the lack of fit created by these anomalies, overall the model fit these data as well as expected given the observed data and input sample sizes (Figure 39). Canadian size- or age-composition data did not require iterative re-scaling of input sample sizes. Pearson residuals of length compositions data also illustrate the apparent lack of fit in the mid-1990s and early 2000s (Figure 40).

Predicted lengths for the acoustic survey were also generally on the modes with the observed size compositions. But in a number of years (1980, 1995, and 2005) the model was unable to effectively reproduce the observed bi-modal structure (Figure 41). Comparison of effective vs. input sample sizes suggest that the model fit these data as well as expected, given the observed data and input sample sizes (Figure 42). Figure 33 illustrates model lack of fit, consistent with the model's inability to reproduce the bi-modal structure of the observed size compositions. The 1999 year class in 2007 is fully selected and thus the model fits the modal structure of the size composition well. In contrast, the 2005 year class, evident as 31 cm fish in the 2007 size compositions, is not fit particularly well as these fish are not fully selected to the survey, and the model appears to be splitting the difference in an attempt to fit both a 2003 and 2005 year class.

Given the assumption of age-based selectivity for the fisheries and the volume of conditional age-at-length data, the model generally fits the age data better than the length-composition data. Fits to the implied age compositions and Pearson residual plots are illustrated separately for the U.S. fishery (Figures 44-45), Canadian fishery (Figures 46-47) and acoustic survey (Figures 48-49). Results indicate that the model fit the data as well as expected, given the data and sample sizes (Figure 36, Figure 39, and Figure 42). As with the U.S. fishery length compositions, the U.S. fishery age-composition sample sizes were iterated to 30% of the original input sample sizes. The Canadian and acoustic survey conditional age-at-length compositions were unmodified. The model fit the U.S. fishery age composition (implied) data relatively well, particularly for the series of years that were dominated by the large 1980, 1984, and 1999 year classes. For instance, throughout the early 1980s and 1990s the predicted fits match the age structure of the population as the dominant 1980 and 1984 year class moved through the population (Figure 44). Similarly, the model fits to the observed age compositions since 2003 are particularly good during the time period in which the U.S. fishery has exploited the 1999 year class. During the mid-1990s to early 2000s, when the age compositions lacked any strong year class, the model fits are not as good. However, Pearson residuals for the U.S. fishery do not appear to present any pathologic patterns (Figure 45). Model fits to the Canadian fishery age composition data (Figure 46) show similar patterns and quality as those for the U.S. fishery. In general, the predicted age compositions matched the observed data relatively well during those years when the compositions were dominated by the 1980, 1984 and 1999 year classes. As with the U.S. fishery, Pearson residuals for the Canadian age composition data do not show any evident patterns (Figure 47). Model predictions of the acoustic survey age compositions again show a similar pattern to that illustrated for the U.S. and Canadian fisheries, although fits appear slightly worse (Figure 48). In particular, the model over-estimates the observed size of the 1999 year class between 2001 and 2005 and slightly over estimates the observed strength of the 2005 year class in 2007. Acoustic survey Pearson residuals for the age composition data are shown in Figure 49 and a pattern of negative (under fit) residuals are evident in 2001 and 2003.

The model's fit to the acoustic survey biomass time series seems reasonable given the error structure assumed for the index (Figure 50). Biomass estimates since 1992 are assumed to have less error (CV=0.25) than pre-1992 (CV=0.5) data. During all survey years, the predicted biomasses are within asymptotic 95% confidence intervals, with model fits generally better to the post-1992 survey indices. Prior to 1992, the predicted survey biomass is above the observed data, which is not unexpected given the assumed variance and the influence of other data (compositional data) informing the level of biomass during the mid 1980s. The predicted vs. observed acoustic biomass estimates generally show a linear pattern, and calculated RMSE was approximately 0.58.

Assessment Model Results

The predicted time series of hake recruitments, as well as recruitment uncertainty, recruitment deviations from the S-R curve, and yearly estimates of variability are shown in Figure 51. The model estimated very large year classes in 1980 and 1984, with secondary recruitment events in 1970, 1973 and 1977. The 1999 year class was the single most dominant cohort since the late 1980s, and is estimated to be the second largest since 1966. Evidence of an above-average 2005 year class is also present in the data, however its magnitude is subject to greater uncertainty than estimates for most year classes, due to the limited opportunities for observing it. Uncertainty in recruitment can be substantial as shown by asymptotic 95% confidence intervals (Figure 51). Based on the assumption of log-normal error about the mean log recruitment, uncertainty increases with the magnitude of recruitment. Recruitment to age 0 before 1967 is assumed to be equal to mean recruitment, while recruitment from 1967 to 2005 is estimated from the data. Age-0 recruitment in 2005 is predicted to be slightly above average as informed by both the U.S. fishery data and acoustic survey age compositions. This year class was previously predicted to be weak, based on the 2005 coast-wide pre-recruit survey. Furthermore, the 2004 year class that was predicted by the coast-wide pre-recruit survey to be much stronger than indicated in the current assessment. Model results indicate that the coast-wide pre-recruit survey has no better predictive capability (RMSE=1.5) than average recruitment (assumed RMSE=1.13) generated from the S-R curve. The calculated RMSE of recruitment has increased over estimates from last year's assessment, principally due to the increased variability introduced by addition of age-reading error. Except for the actual magnitude of estimated recruitments, the patterns in recruitment deviations and uncertainty are qualitatively the same under the base and alternative models.

Summary of Pacific hake population time trends in 3+ biomass, recruitment, spawning biomass, relative depletion, spawning potential ratio (SPR) and fishery performance are shown in Figures 52-54 for the base. Summary Pacific hake biomass (age 3+) under unfished conditions (< 1966) was estimated to be 5.9 million mt (Table 14). Summary biomass increased briefly during the mid-1970s, as the 1970 and 1973 year classes recruited, then declined briefly until 1980 (Figure 52, Table 14). Summary biomass increased again to the highest level in the time series in 1983 as the very large 1977 and 1980 classes entered the population (Figure 52, Table 14). The hake population then experienced a long period of decline as fishing increased and few large recruitment events occurred between 1985 and 2001. Summary biomass increased by more than 150% between 2001 and 2002 due to recruitment of the 1999 year class, but has subsequently declined in the face of generally poor recruitments since.

Pacific hake spawning biomass trend is similar to that for summary biomass (Figure 53, Table 14). Spawning biomass in 1966 (unfished conditions) was estimated to be 2.89 million mt. It is worth noting that this estimate is quite close to the 2.0 million mt estimate generated from the CalCOFI larval production index. Spawning biomass declined rapidly after peaking in 1984 (6.5 million mt) to the lowest point in the time series in 2000 (882 thousand mt), followed subsequently by a brief increase to 1.0 million mt in 2003. In 2008 (beginning of the year), spawning biomass is estimated to be 1.1 million mt, and is at 37.9 % (~95% CI range from 21.9% to 53.9%; Figure 53, Table 14) of the unfished level. Approximate asymptotic intervals about the MLE for spawning biomass and recruitment for the entire times series are given in Table 15.

Reference points (biomass and exploitation rate)

Because of temporal changes in growth, there are two types of reference points reported in this assessment: those based on the assumed population parameters at the beginning of the modeled time period and those based on the most recent time period in a 'forward projection' mode of calculation. All strictly biological reference points (e.g., unexploited spawning biomass) are calculated based on the unexploited conditions at the start of the model, whereas management quantities (MSY, SB_{msy}, etc.) are based on the current growth and maturity schedules and are marked throughout this document with an asterisk (*).

Given the current life history parameters and long term exploitation patterns, the fishing mortality that reduces the spawning potential of the stock to 40% of the unfished level is referred to as F40%, which is the default Pacific Fishery Management Council proxy for F_{MSY} for Pacific hake. Similarly, the proxy for B_{MSY} is spawning biomass corresponding to 40% of the unfished stock size (B40%). Unexploited equilibrium Pacific hake spawning biomass (SB_{zero}) from the base model was estimated to be 2.9 million mt (~ 95% confidence interval: 2.23 – 3.56 million mt), with a mean expected recruitment of 4.06 billion age-0 hake (~ 95% confidence interval:

3.23 – 5.11). Associated management reference points for target and critical biomass levels for the base model based on $SB_{40\%}$ proxy are 1.16 million mt (B40%) and 0.72 million mt (B25%), respectively. The MSY-proxy harvest amount (F40%) under the base model was estimated to be 470,910* mt (~ 95% confidence interval: 253,115 - 688,705 mt). The spawning stock biomass that produces the MSY-proxy catch amount under the base model was estimated to be 0.81 million* mt (confidence interval is 0.42 - 1.90)* million mt given current life history parameters.

The full exploitation history under the base and alternative models is portrayed graphically in Figure 54, which plot for each year the calculated spawning potential ratio (1-SPR) and spawning biomass level (B) relative to their corresponding targets, F40% and B40%, respectively. As indicated in Figure 54, the estimated spawning potential ratio for Pacific hake has generally been above both the 40% proxy target MSY and B_{MSY} level in all but one of the assessed years. During the last decade both target reference points have gradually declined as stock biomass decreased under moderately high removals. While SPR has been above proxy target of 40% for Pacific hake, the biomass relative to the B40 reference target dropped briefly below the target in recent years.

Harvest projections

Stochastic forecasts were generated assuming the maximum potential catch would be removed under the 40:10 harvest control rule. Projections were based on the relative F contribution from the U.S. and Canadian fishery commensurate with the 73.88% and 26.12% coast wide national catch allocation to the U.S. and Canada, respectively, as specified in the Treaty. Table 16 presents 3-year stochastic projections using catch streams which correspond to the 2008-2010 average catches by slicing the marginal posterior density of 2008 spawning depletion at the 25th, 50th and 75th percentiles. The results of the MCMC posterior sample were combined with the forecasted 2008-2010 catch streams and results summarized as posterior intervals of spawning biomass and spawning depletion. Spawning biomass is expected to increase slightly or stay relatively constant over the next three years if coastwide catches are taken consistent with the 25% and 50% of 2008 spawning depletion. In the extreme case, where coastwide catches are taken from the upper 75% percentile of 2008 spawning depletion, forecasted spawning biomass will decline from 1.3 million mt in 2008 to 716,000 mt in 2010. Consequently, spawning depletion will decline to greater than a 50% probability of being less than the minimum spawning threshold of 25% unfished. Alternative coastwide constant catch scenarios of 250,000, 300,000 (roughly status quo) and 400,000 mt for 2008-2010 are also presented in Table 16. In each case, spawning stock biomass and relative spawning depletion is projected to increase.

Uncertainty and reliability

Uncertainty in current stock size and other state variables were explored using a Markov Chain Monte Carlo (MCMC) simulation in AD model builder. Although MCMC has been used mostly in Bayesian applications, it can also be used to obtain likelihood-based confidence regions (Punt and Hilborn 1997). It has the advantage of producing the true marginal likelihood (or marginal distributions) of the parameter, rather than the conditional mode, as with the likelihood profile. For the base case, low and high alternative models, we ran the MCMC routine in ADMB drawing 1,000,000 samples in which one in every 1000th sample was saved to reduce autocorrelation in the chain sequence. Results of the MCMC simulation were evaluated for nonconvergence to the target posterior distribution as prescribed in Gelman et al. (2004). The final samples from the MCMC were used to develop the probability distributions of the marginal posterior of management quantities and were compared to MLE asymptotic estimates of uncertainty.

Convergence diagnostics of selected parameters from the MCMC simulation provided no evidence for lack of convergence in the base model, in either the primary estimated parameters (Figure 55) or derived quantities such as spawning stock biomass and recruitment (Figure 56). In nearly all cases, parameter autocorrelation was less than +/- 0.15. Furthermore, most of the primary parameters or derived variables have a Geweke statistic of less than +/- 1.96 indicating stationarity of the parameter mean. Finally, parameters passed the Heidelberger-Welch statistic test. If this test is passed, the retained sample is deemed to estimate the posterior mean with acceptable precision, while failure implies that a longer MCMC run is needed to increase the accuracy of the posterior estimates for the given variable. Based on the above diagnostic tests the retained MCMC sample appears acceptable for use in characterizing the uncertainty (distribution) of state variables.

Results of the Markov Chain Monte Carlo simulation show the uncertainty in 2008 female spawning biomass and relative spawning depletion (Figure 57). Based on MCMC results there is 50% probability that 2008 spawning biomass is 1.3 million mt, with a corresponding 50% probability that relative spawning depletion is 42.6%. There is less than a .5% probability that 2009 spawning depletion is below minimum biomass threshold of 25% Bzero and a 35% probability of being below 40% Bzero. It should be noted that the MPD (median posterior density) from MCMC simulation of 2008 spawning biomass (1.3 million mt) is slightly greater than the MLE (1.1 million mt) and that MPD relative spawning depletion in 2008 is 42.6% compared to the MLE of 37.9%. This is largely due to the non-symmetric nature of the posterior distributions of state variables from MCMC integration.

A risk analysis was conducted to evaluate the outcomes associated with a range of 2008-2010 catch scenarios. Performance measures included the probability that 2009 SPR is less than the $SPR_{40\%}$ target, the probability of spawning stock biomass declining between 2008 and 2009, and the probability that 2009 spawning stock biomass is below the target and threshold spawning biomass level of 40% and 25% unfished, respectively. Arbitrary 2008-2010 catch streams ranging from 200,000 to 1,400,000 mt were used to forecast stock outcomes and MCMC implemented to calculate risk and posterior intervals. Results or the risk analysis are shown in Figure 58, and show that with respect to the fishing rate target there is a 50% probability that the 2009 SPR will be below the SPR40% target with a catch of 647,000 mt, and a 25% probability with a coastwide catch of 512,000 mt. The probability of 2009 spawning biomass falling into the precautionary zone, less than 40% unfished, remains relatively low (less than 40%) for a range of coastwide catch below 550,000 mt.

Finally a retrospective analysis was conducted by systematically removing the terminal years' data sequentially for six years and re-running the model. Results of this analysis show trends in spawning stock biomass, recruitment to age-0 and spawning depletion in Figure 59. Little to mild retrospective bias is seen when comparing the model results in terms of spawning depletion, which suggests that addition of data year after year may revise the overall scale of biomass (through changes in recruitment) in concert with virgin and ending year biomass levels. Overall recruitment strength seems to be generally revised downward through time by sequentially adding new data. The parameters which affect population scale, most notably acoustic survey catchability q, are shown in Figure 60 and illustrate how these estimates are retrospectively revised.

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Table 1. Annual catches of Pacific hake (1,000 t) in U.S. and Canadian management zones by foreign, joint venture (JV), domestic at-sea, domestic shore-based, and tribal fisheries, 1966-2007.

	U.S.						Canada				U.S. and
			Domestic								Canada
Year	Foreign	JV	At-sea	Shore	Tribal	Total	Foreign	JV	Shore	Total	total
1966	137.000	0.000	0.000	0.000	0.000	137.000	0.700	0.000	0.000	0.700	137.700
1967	168.699	0.000	0.000	8.963	0.000	177.662	36.713	0.000	0.000	36.713	214.375
1968	60.660	0.000	0.000	0.159	0.000	60.819	61.361	0.000	0.000	61.361	122.180
1969	86.187	0.000	0.000	0.093	0.000	86.280	93.851	0.000	0.000	93.851	180.131
1970	159.509	0.000	0.000	0.066	0.000	159.575	75.009	0.000	0.000	75.009	234.584
1971	126.485	0.000	0.000	1.428	0.000	127.913	26.699	0.000	0.000	26.699	154.612
1972	74.093	0.000	0.000	0.040	0.000	74.133	43.413	0.000	0.000	43.413	117.546
1973	147.441	0.000	0.000	0.072	0.000	147.513	15.125	0.000	0.001	15.126	162.639
1974	194.108	0.000	0.000	0.001	0.000	194.109	17.146	0.000	0.004	17.150	211.259
1975	205.654	0.000	0.000	0.002	0.000	205.656	15.704	0.000	0.000	15.704	221.360
1976	231.331	0.000	0.000	0.218	0.000	231.549	5.972	0.000	0.000	5.972	237.521
1977	127.013	0.000	0.000	0.489	0.000	127.502	5.191	0.000	0.000	5.191	132.693
1978	96.827	0.856	0.000	0.689	0.000	98.372	3.453	1.814	0.000	5.267	103.639
1979	114.909	8.834	0.000	0.937	0.000	124.680	7.900	4.233	0.302	12.435	137.115
1980	44.023	27.537	0.000	0.792	0.000	72.352	5.273	12.214	0.097	17.584	89.936
1981	70.365	43.556	0.000	0.839	0.000	114.760	3.919	17.159	3.283	24.361	139.121
1982	7.089	67.464	0.000	1.024	0.000	75.577	12.479	19.676	0.002	32.157	107.734
1983	0.000	72.100	0.000	1.050	0.000	73.150	13.117	27.657	0.000	40.774	113.924
1984	14.722	78.889	0.000	2.721	0.000	96.332	13.203	28.906	0.000	42.109	138.441
1985	49.853	31.692	0.000	3.894	0.000	85.439	10.533	13.237	1.192	24.962	110.401
1986	69.861	81.640	0.000	3.463	0.000	154.964	23.743	30.136	1.774	55.653	210.617
1987	49.656	105.997	0.000	4.795	0.000	160.448	21.453	48.076	4.170	73.699	234.147
1988	18.041	135.781	0.000	6.876	0.000	160.698	38.084	49.243	0.830	88.157	248.855
1989	0.000	203.578	0.000	7.418	0.000	210.996	29.753	62.618	2.563	94.934	305.930
1990	0.000	170.972	4.713	8.115	0.000	183.800	3.814	68.313	4.022	76.149	259.949
1991	0.000	0.000	196.905	20.600	0.000	217.505	5.605	68.133	16.178	89.916	307.421
1992	0.000	0.000	152.449	56.127	0.000	208.576	0.000	68.779	20.048	88.827	297.403
1993	0.000	0.000	99.103	42.119	0.000	141.222	0.000	46.422	12.355	58.777	199.999
1994	0.000	0.000	179.073	73.656	0.000	252.729	0.000	85.162	23.782	108.944	361.673
1995	0.000	0.000	102.624	74.965	0.000	177.589	0.000	26.191	46.193	72.384	249.973
1996	0.000	0.000	112.776	85.127	14.999	212.902	0.000	66.779	26.395	93.174	306.076
1997	0.000	0.000	121.173	87.410	24.840	233.423	0.000	42.565	49.227	91.792	325.215
1998	0.000	0.000	120.452	87.856	24.509	232.817	0.000	39.728	48.074	87.802	320.619
1999	0.000	0.000	115.259	83.419	25.844	224.522	0.000	17.201	70.132	87.333	311.855
2000	0.000	0.000	116.090	85.828	6.500	208.418	0.960	15.059	6.382	22.401	230.819
2001	0.000	0.000	102.129	73.474	6.774	182.377	0.000	21.650	31.935	53.585	235.962
2002	0.000	0.000	63.258	45.708	23.148	132.114	0.000	0.000	50.769	50.769	182.883
2003	0.000	0.000	67.473	51.256	24.763	143.492	0.000	0.000	62.090	62.090	205.582
2004	0.000	0.000	90.258	89.381	30.845	210.484	0.000	58.892	65.345	124.237	334.721
2005	0.000	0.000	150.400	74.147	35.297	259.844	0.000	15.178	85.284	100.462	360.306
2006	0.000	0.000	137.564	97.230	35.469	270.263	0.000	13.751	80.011	93.762	364.025
2007	0.000	0.000	107.489	66.640	29.850	203.979	0.000	6.780	65.325	72.105	276.084
Average 1966-2007						163.179				55.797	218.977

Table 2. U.S. fishery sampling information by sector showing the number of hauls (or trips), number of lengths and number of ages taken by year. Sample sizes shown are the number of hauls or trips where length samples were taken.

U.S. At-sea fishery length samples				U.S. Shore-based fishery			
Year	No. Hauls	No. Lengths	No. Aged	Year	No. Trips	No. Lengths	No. Aged
1973	-	-	-	1973	-	-	-
1974	-	-	-	1974	-	-	-
1975	13	486	332	1975	-	-	-
1976	249	48,433	4,077	1976	-	-	-
1977	1,071	140,338	7,693	1977	-	-	-
1978	1,135	122,531	5,926	1978	-	-	-
1979	1,539	170,951	3,132	1979	-	-	-
1980	811	101,528	4,442	1980	-	-	-
1981	1,093	135,333	4,273	1981	-	-	-
1982	1,142	169,525	4,601	1982	-	-	-
1983	1,069	163,992	3,219	1983	-	-	-
1984	2,035	237,004	3,300	1984	-	-	-
1985	2,061	259,583	2,450	1985	-	-	-
1986	3,878	467,932	3,136	1986	-	-	-
1987	3,406	428,732	3,185	1987	-	-	-
1988	3,035	412,277	3,214	1988	-	-	-
1989	2,581	354,890	3,041	1989	-	-	-
1990	2,039	260,998	3,112	1990	-	-	-
1991	800	94,685	1,333	1991	17	1,273	934
1992	787	72,294	2,175	1992	49	3,152	1,062
1993	406	31,887	1,196	1993	36	1,919	845
1994	569	41,143	1,775	1994	80	4,939	1,457
1995	413	29,035	690	1995	57	3,388	1,441
1996	510	32,133	1,333	1996	47	3,330	1,123
1997	614	47,863	1,147	1997	67	4,272	1,759
1998	740	47,511	1,158	1998	63	3,979	2,021
1999	2,176	49,192	1,047	1999	92	4,280	1,452
2000	2,118	48,153	1,257	2000	81	2,490	1,314
2001	2,133	48,426	2,111	2001	106	4,290	1,983
2002	1,727	39,485	1,695	2002	94	3,890	1,582
2003	1,814	37,772	1,761	2003	101	3,866	1,561
2004	2,668	57,014	1,875	2004	129	7,170	1,440
2005	2,956	62,944	2,451	2005	108	6,166	1,160
2006	2,824	58,094	2,058	2006	156	8,974	1,547
2007	2,810	57,817	2,058	2006	126	7,035	1,398

Table 3. Canadian fishery sampling information by sector showing the number of hauls (or trips), number of lengths and number of ages taken by year. Sample sizes shown are the number of hauls or trips where length samples were taken.

	Canadian JV fishery samples				Canadian shore-based fishery samples		
Year	No. Hauls	No. Lengths	No. Aged	Year	No. Trips	No. Lengths	No. Aged
1988	231	75,767	1,557	1988	-	-	-
1989	261	56,202	1,353	1989	-	-	-
1990	171	33,312	1,024	1990	-	-	-
1991	632	97,205	1,057	1991	-	-	-
1992	429	60,391	1,786	1992	-	-	-
1993	500	70,522	1,228	1993	-	-	-
1994	875	122,871	2,196	1994	-	-	-
1995	183	20,552	1,747	1995	-	-	-
1996	813	99,228	1,526	1996	6	449	0
1997	414	16,957	1,430	1997	302	42,296	150
1998	468	45,117	1,113	1998	238	29,850	454
1999	66	8,663	812	1999	314	42,119	1,568
2000	375	45,946	1,536	2000	19	2,151	0
2001	284	26,817	1,424	2001	121	14,937	111
2002	-	-	-	2002	186	13,611	1,831
2003	-	-	-	2003	345	24,898	1,386
2004	595	60,025	1,102	2004	124	7,716	1,581
2005	58	5,206	292	2005	240	17,252	1,415
2006	98	9,417	334	2007	203	15,576	1,170
2007	47	4,050	0	2007	120	8,991	965

Table 4. U.S. fishery sampling summary by sector showing number of samples, total sampled weight, total fishery weight, and sampling intensity given as the percent of total catch weight sampled and catch weight per sample taken.

	U.S. At-sea sampling (foreign, JV, domestic)					U.S. Shore-based fishery sampling				
Year	No. Hauls	Sampled weight (mt)	Total fishery landings (mt)	% total weight Sampled	Weight (mt) per sample	No. Trips	Sampled weight (mt)	Total fishery landings (mt)	% total weight Sampled	Weight (mt) per sample
1975	13	47	205,654	0.02%	15,820	-	-	-	-	-
1976	249	4,165	231,331	1.80%	929	-	-	-	-	-
1977	1,071	4,239	127,013	3.34%	119	-	-	-	-	-
1978	1,135	4,769	97,683	4.88%	86	-	-	-	-	-
1979	1,539	6,797	123,743	5.49%	80	-	-	-	-	-
1980	811	10,074	71,560	14.08%	88	-	-	-	-	-
1981	1,093	9,846	113,921	8.64%	104	-	-	-	-	-
1982	1,142	23,956	74,553	32.13%	65	-	-	-	-	-
1983	1,069	27,110	72,100	37.60%	67	-	-	-	-	-
1984	2,035	13,603	93,611	14.53%	46	-	-	-	-	-
1985	2,061	11,842	81,545	14.52%	40	-	-	-	-	-
1986	3,878	24,602	151,501	16.24%	39	-	-	-	-	-
1987	3,406	22,349	155,653	14.36%	46	-	-	-	-	-
1988	3,035	21,499	153,822	13.98%	51	-	-	-	-	-
1989	2,581	20,560	203,578	10.10%	79	-	-	-	-	-
1990	2,039	16,264	175,685	9.26%	86	-	-	-	-	-
1991	800	15,833	196,905	8.04%	246	17	683	20,600	3.32%	1,212
1992	787	17,781	152,449	11.66%	194	49	1,964	56,127	3.50%	1,145
1993	406	11,306	99,103	11.41%	244	36	1,619	42,119	3.84%	1,170
1994	569	13,959	179,073	7.80%	315	80	4,461	73,656	6.06%	921
1995	413	9,833	102,624	9.58%	248	57	3,224	74,965	4.30%	1,315
1996	510	13,813	112,776	12.25%	221	47	3,036	85,127	3.57%	1,811
1997	614	17,264	121,173	14.25%	197	67	4,670	87,410	5.34%	1,305
1998	740	17,370	120,452	14.42%	163	63	4,231	87,856	4.82%	1,395
1999	2,176	47,541	115,259	41.25%	53	92	6,740	83,419	8.08%	907
2000	2,118	48,482	116,090	41.76%	55	81	7,735	85,828	9.01%	1,060
2001	2,133	43,459	102,129	42.55%	48	106	8,524	73,474	11.60%	693
2002	1,727	37,252	63,258	58.89%	37	94	7,089	45,708	15.51%	486
2003	1,814	38,067	67,473	56.42%	37	101	7,676	55,335	13.87%	548
2004	2,668	53,411	90,258	59.18%	34	129	10,918	96,229	11.35%	746
2005	2,956	66,356	150,400	44.12%	51	108	8,997	85,914	10.47%	796
2006	2,824	60,435	97,403	62.05%	34	156	13,646	115,980	11.77%	743
2007	2,810	64,230	107,489	59.75%	38	126	12,231	72,663	16.83%	577

Table 5. Canadian fishery sampling summary by sector showing number of samples, total sampled weight, total fishery weight, and sampling intensity given as the percent of total catch weight sampled and catch weight per sample taken.

	Canadian JV fishery sampling					Canadian Shore-based fishery sampling				
Year	No. Hauls	Sampled weight (mt)	Total fishery landings (mt)	% total weight Sampled	Weight (mt) per sample	No. Trips	Sampled weight (mt)	Total fishery landings (mt)	% total weight Sampled	Weight (mt) per sample
1988	231	4,184	49,243	8.50%	213	-	-	-	-	-
1989	261	4,679	62,618	7.47%	240	-	-	-	-	-
1990	171	3,396	68,313	4.97%	399	-	-	-	-	-
1991	632	13,054	68,133	19.16%	108	-	-	-	-	-
1992	429	8,901	68,779	12.94%	160	-	-	-	-	-
1993	500	8,929	46,422	19.23%	93	-	-	-	-	-
1994	875	15,387	85,162	18.07%	97	-	-	-	-	-
1995	183	3,770	26,191	14.39%	143	-	-	-	-	-
1996	813	14,863	66,779	22.26%	82	6	21,297	26,395	80.69%	4399
1997	414	8,325	42,565	19.56%	103	302	44,802	49,227	91.01%	163
1998	468	9,638	39,728	24.26%	85	238	45,982	48,074	95.65%	202
1999	66	1,970	17,201	11.45%	261	314	66,700	70,132	95.11%	223
2000	375	6,557	15,059	43.54%	40	19	5,791	6,382	90.74%	336
2001	284	6,072	21,650	28.05%	76	121	30,852	31,935	96.61%	264
2002	-	-	-	-	-	186	49,189	50,769	96.89%	273
2003	-	-	-	-	-	345	61,110	62,090	98.42%	180
2004	595	14,620	58,892	24.83%	99	124	58,624	65,345	89.71%	527
2005	58	1,630	15,178	10.74%	262	240	67,242	85,284	78.84%	355
2006	126	2,702	13,715	19.70%	109	203	14,555	80,011	18.19%	394
2007	47	1,043	6,780	15.38%	144	122	4,049	65,325	6.20%	535

Table 6. U.S. fishery sample sizes for conditional age at length. Sample size shown by year and length bin represent the sum of the total number of hauls (in the at-sea fishery) and trips (in the shore-based fishery) contributing age information to each 1 cm length category.

	Year samples were taken														
Length	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
20			1		1	1	5								
21			1	2		3	9								
22		1		2		2	13								
23	1	1		4		1	23								
24	1	1		4		2	25	2				1			
25	1	3		10	1	1	29	5							
26	2	1		10	2		40	11	1		1			1	
27	2	4		9	2	1	34	9		1					
28	1	5		14	4	1	22	12			1				
29	3	4		7	10	1	21	18	6		2	1		1	2
30	5	4		4	21	1	16	37	10		1	5			3
31	3	6	2	2	27		12	38	11	3	3	8		1	9
32	5	8			30	3	6	52	23	1	3	19		2	15
33	2	9	4		46	4	9	62	23	2	3	22	3	2	15
34	4	10	5		33	9	12	66	35	6	2	49	6	3	8
35	4	7	12		24	19	16	62	39	12	1	41	16	3	10
36	5	13	28	3	17	38	28	55	51	25	1	42	29	3	13
37	5	23	56	7	19	66	49	59	55	41	2	40	60	15	9
38	3	26	71	17	12	74	59	48	62	72	7	39	79	56	17
39	2	45	99	51	11	84	78	50	58	112	16	36	88	101	40
40	6	58	114	88	17	89	94	62	62	121	43	51	97	129	79
41	10	53	146	129	25	83	84	66	69	135	78	85	104	141	120
42	9	55	141	176	36	93	85	86	77	125	107	114	112	141	129
43	9	56	160	171	44	88	88	94	72	112	121	119	121	145	125
44	10	54	160	158	65	100	101	99	69	93	124	110	117	153	127
45	8	47	147	165	72	111	101	100	69	82	115	113	113	152	125
46	9	47	142	148	74	114	107	99	75	83	101	105	106	150	130
47	7	39	132	144	84	96	114	103	74	74	79	100	102	137	133
48	10	42	128	154	83	90	122	111	70	67	63	83	92	123	118
49	8	44	136	143	76	85	122	116	69	66	58	67	83	81	98
50	4	57	123	147	83	90	105	101	71	50	52	77	59	68	74
51	5	62	135	156	89	87	113	112	59	49	25	59	40	45	49
52	6	60	140	184	85	92	107	100	66	43	24	51	31	34	40
53		69	146	178	86	94	116	106	66	28	17	52	18	22	35
54	2	64	147	186	78	105	96	104	61	20	15	44	14	15	27
55	4	58	161	176	70	102	80	86	57	11	11	27	8	14	14
56		67	139	156	66	102	65	85	44	5	3	31	5	8	15
57	1	65	131	115	58	102	56	81	32	5	4	24	5	13	8
58	1	62	94	103	41	88	39	48	32	4	3	11	3	11	8
59	2	57	95	60	47	52	34	53	17	7		11	2	4	7
60	1	56	73	60	22	60	36	37	22	2	1	7	5	6	3
61		48	60	45	26	39	30	28	15		1	8	3	5	6
62		45	52	41	16	27	20	17	9	4		7	6	1	
63		30	46	27	12	25	20	21	12	4		3	1		3
64		36	42	26	8	26	16	21	6	2		6	2	4	1
65		33	23	18	13	19	8	18	6	1		5	3	3	1
66		33	17	14	11	12	10	9	4			6	1	4	2
67		33	15	18	6	11	10	10	4	1		4	2		
68	1	28	18	13	8	9	5	6	5	2	1	3	3	2	4
69	1	25	17	10	4	7	7	6	1	3		4	1	3	
70		71	62	60	16	14	15	14	12	9		25	5	12	4

Table 6. continued.

	Year samples were taken																	
Length	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
20		2				1											1	4
21		2															1	
22		1															1	1
23		1															2	1
24																	4	
25																	6	
26																	7	1
27			1									1					11	3
28	2		2								2						11	6
29	6		5							2	2						10	8
30	5	1	6		1		1			8	3	6					9	11
31	15	2	8	4			6			8	3	7	1		1		7	17
32	22	5	5	1		1	9		2	9	2	15					14	39
33	24	13	3	5	1		17		4	19	1	19				1	28	41
34	45	23	4	5		1	23	1	1	29	2	28	1			2	51	41
35	51	32	3	17	3		30	1	5	41	2	32	2			4	96	57
36	76	33	6	31	9		30	7	13	38	6	50	11	2			107	45
37	84	39	22	42	19	2	23	16	17	41	18	55	19	2	1	2	128	49
38	94	37	23	45	42	4	27	32	30	54	16	61	45	6	7	3	187	60
39	98	46	58	49	64	2	33	47	36	60	24	56	80	25	23	6	275	42
40	104	50	66	44	70	6	38	59	50	53	36	61	113	61	45	25	298	46
41	95	55	78	38	66	18	35	77	56	59	43	97	128	133	90	49	328	72
42	96	59	84	50	73	31	36	83	73	49	56	100	117	199	133	125	248	126
43	93	58	82	57	81	33	50	84	97	77	85	100	100	227	216	242	187	155
44	91	54	81	64	99	38	65	70	102	70	86	112	85	203	227	309	112	235
45	82	53	81	65	99	37	73	71	90	84	89	121	63	156	225	318	72	319
46	88	53	81	63	98	36	74	57	77	63	106	136	53	106	177	267	45	332
47	82	47	84	58	95	39	72	53	51	63	120	136	61	67	105	199	18	315
48	84	48	84	62	90	38	64	41	43	47	100	153	65	49	79	114	8	259
49	73	44	82	46	91	37	59	28	25	31	95	118	74	33	39	72	2	173
50	72	36	73	30	63	33	47	27	17	17	75	86	76	33	26	46	8	124
51	74	18	59	22	34	25	30	21	7	13	55	59	68	17	8	31	3	74
52	58	9	39	9	25	23	29	11	3	9	34	50	55	15	12	9	6	53
53	43	6	35	4	15	13	10	11	3	6	17	37	48	5	5	11	4	31
54	34	6	26	7	13	10	12	5	2	3	17	34	38	7	3	6	1	19
55	20	7	20	6	8	8	7	1	4		9	10	27	4	2	3	2	14
56	15	2	15	1	4	6	4	3	1		12	8	17	3	2	4	1	9
57	14	3	15	2	5	4	1	1		3	4	11	13		2	3	1	16
58	14	2	9		6	6	3	1	1	2	3	1	7		2	1	2	4
59	11	3	9	1	2	3	3	1	1		5	2	4	1	1	2	1	6
60	14		7		3	1	1	1		1	4	4	4		2		3	6
61	15	3	5	2	1	1	2	1		2	2	1	2			1	2	2
62	9	3	5		1	2	2		1	1	4		3		1		5	1
63	9	3	2		1	1	1	1			1		1					5
64	8		3		1		1						2					1
65	8	2	2		2		1		1		2	1	1	1				1
66	8	5	2					1					1			1		1
67	6	2			1		1								1			
68	6	2	2		1											1		
69	7	1		1	1													
70	20	8	6	1	3	1	2	2					1					4

Table 7. Canadian fishery sample sizes for conditional age at length. Sample size shown by year and length bin represent the sum of the total number of hauls (in the joint venture fishery) and trips (in the shore-based domestic fishery) contributing age information to each 1 cm length category.

	Year samples were taken																			
Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
20											1									1
21												1								
22												1								
23								1				2								
24								2												
25								2												
26								1				2								
27								1												
28								1			1									
29												1					1			
30												1					1			
31									2			3	1	1						
32									2			5				2	1			
33							1	1	3			10				2	1			
34						1			3		1	7	1				2			1
35	1						1		4			10	3				1			2
36						1	1		8		4	16	4			1	1			
37	1				1		1		9		8	17	5		1		2			
38	1		2		1				12	1	10	19	6				2	2		1
39	3		3	1	2				7	7	17	26	5				3		1	1
40	4	2	3	1	3	5			8	10	18	27	9			1	11	1	2	4
41	4	5	4	1	9	10	6	1	6	17	19	30	13	1		3	20	3	5	7
42	4	6	5	3	15	14	10	6	14	21	25	35	14	3		11	26	12	13	13
43	5	6	6	6	22	17	20	11	15	22	24	36	14	4	8	14	31	17	16	15
44	5	6	4	14	27	17	24	18	22	22	25	35	17	6	3	14	32	19	41	19
45	5	6	4	16	29	18	28	21	24	23	25	37	16	11	5	15	32	20	51	24
46	5	6	4	16	29	18	29	21	24	23	25	38	18	15	11	15	32	20	73	26
47	5	6	4	16	29	18	30	21	24	23	25	38	19	18	15	15	32	20	82	29
48	5	6	4	16	29	18	31	21	24	23	23	34	19	20	22	15	31	19	81	30
49	5	6	4	16	29	18	30	21	23	22	21	35	19	20	24	15	31	17	71	33
50	5	6	5	16	27	17	28	21	23	22	22	31	20	20	25	15	31	12	70	31
51	5	6	5	16	28	13	28	21	22	18	17	27	18	20	26	13	27	12	59	23
52	5	6	6	13	16	12	27	17	17	18	8	22	16	20	26	13	18	2	45	23
53	5	6	4	13	15	4	23	17	11	14	8	14	17	19	26	11	17	5	24	17
54	5	4	5	8	12	5	18	14	12	9	6	11	15	18	26	11	13	7	26	21
55	4	5	3	4	7	1	21	11	4	5	2	9	9	19	26	9	11	6	10	10
56	4	4	4	8	4		12	7	7	2	2	6	10	17	25	7	5	4	12	12
57	4	4	4	3	4		9	5	7	3	3	2	6	17	25	6	7	2	6	9
58	4	3	3	5	4	5	6	9	6		2	4	6	17	21	8	3	2	6	12
59	3	2	4	3	1		8	6	1	1	1	4	8	12	13	5	1	1	7	8
60	3	2	3	2	3		6	4	4	1		1	4	9	18	5	5		7	6
61	2	1	2	2			5	4	4			1	4	7	12	3	2	1	6	2
62	1	3	4	2	1		3	1	1			1		4	12	1	1			4
63	1	3	4		2		2	2			1		2	2	7	1	2		1	2
64	1	2	2	1			3	3		1		1	1	2	2	1		1	2	3
65	1	1	2				5	1	2					3	1	1	1	1	2	2
66		1	1	1			1	1	1			2	1	1	2		1		1	2
67		2	2					1					1	2	1					
68				1					1	1					1	1	1			3
69			1	1				1									1			1
70	1	4	1	1	1		2	1					1						1	2

Table 8. Acoustic survey sampling information showing the number of hauls, number of lengths measured and number of aged by year.

Year	No. hauls	No. lengths	No. aged
1977	85	11,695	4,262
1980	49	8,296	2,952
1983	35	8,614	1,327
1986	43	12,702	2,074
1989	22	5,606	1,730
1992	43	15,852	2,184
1995	69	22,896	2,118
1998	84	33,347	2,417
2001	49	16,442	2,536
2003	71	19,357	3,007
2005	49	13,644	1,905
2007	130	15,756	2,915

Table 9. Acoustic survey sample sizes for conditional age at length. Sample sizes shown by year and length bin represent the sum of the total number of hauls contributing age information to each 1 cm length category.

	Number hauls by length and year											
Length	1977	1980	1983	1986	1989	1992	1995	1998	2001	2003	2005	2007
24						2		1				3
25						2		3		1		2
26	1					2		2				4
27					1	4		4	2			7
28	1					2	2	10		1	1	8
29	1	1		2		5	1	13			1	15
30	1			3		7	2	16	3	2	4	17
31	2			6		7	4	20	8	2	6	18
32	3			8		8	9	23	14	4	7	17
33	4		2	8	1	8	13	23	17	4	10	20
34	3	4	4	9	3	8	15	31	20	8	8	20
35	9	7	3	9	4	7	21	31	20	8	10	16
36	14	9	5	11	6	6	20	30	20	8	9	15
37	16	10	7	8	8	6	17	36	17	9	10	13
38	14	12	8	10	7	5	14	39	13	14	8	11
39	17	10	9	5	9	8	6	50	10	14	10	10
40	20	12	13	6	10	7	11	44	17	29	6	16
41	22	11	11	12	15	10	15	55	14	43	22	14
42	24	10	11	21	20	24	26	62	18	56	28	27
43	29	12	9	21	20	28	40	66	22	55	36	36
44	34	13	13	20	20	36	45	64	17	59	41	38
45	40	16	12	21	20	38	49	57	29	61	42	43
46	41	18	13	21	20	39	53	49	29	53	41	44
47	45	19	12	17	18	37	50	51	30	55	39	54
48	48	21	13	18	16	34	47	46	30	43	32	49
49	48	24	12	16	16	30	38	31	28	41	27	46
50	45	22	12	16	10	22	27	22	27	32	23	37
51	47	22	11	16	8	18	17	9	25	28	12	30
52	46	21	10	11	9	14	14	5	26	24	12	22
53	44	19	9	13	6	6	10	6	24	19	9	22
54	40	18	8	8	5	3	7	4	25	12	5	12
55	38	17	6	9	2	4	5	2	18	12	3	12
56	31	19	5	4	2	5	6	2	13	7	5	6
57	33	16	7	4		4	3	3	10	6	2	6
58	27	11	2	3	3	3	5	5	10	5	1	7
59	19	14	3	3	2	1	2		7	3	1	5
60	18	7	1	4	2	1	2	1	8	6		6
61	16	4	2	3		1	1	2	5	2		3
62	11	3	2	2		2	4		3	5		
63	11	2	1		1	3	2		2			
64	10	2		3	1		1		4	2	1	4
65	8	3	1	1	1		2		3	2	1	
66	8	2	1				2		2	2		2
67	8	2		1			2		1	2		
68	7	4		1					2		1	
69	4	3	1	1	1		1	1	4	2	1	
70	7	3		1	2		3		4	6	6	2

Table 10. Acoustic survey estimates of Pacific whiting biomass and age composition. Surveys in 1995 and 1998 were cooperative surveys between AFSC and DFO. Biomass and age composition for 1977-89 were adjusted as described in Dorn (1996) to account for changes in target strength, depth and geographic coverage. Biomass estimates at 20 log l - 68 in 1992 and 1995 are from Wilson and Guttormson (1997). The biomass in 1995 includes 27,251 t of Pacific whiting found by the DFO survey vessel W.E. Ricker in Queen Charlotte Sound. (This estimate was obtained from 43,200 t, the biomass at -35 dB/kg multiplied by 0.631, a conversion factor from -35 dB/kg to 20 log l - 68 for the U.S. survey north of 50°30' N lat.). In 1992, 1995, and 1998, 20,702 t, 30,032 t, and 8,034 t of age-1 fish respectively is not included in the total survey biomass. In 2001-2005 no age one fish were captured in survey trawls. Estimates of biomass and numbers at age from 1977-1992 include revised based on year-specific deep-water and northern expansion factors (Helser et al. 2004).

	Total biomass at 20 log L - 68						Number at age (million)									
Year	(1,000 mt)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1977	1915	0.24	151.94	144.57	902.04	82.60	115.79	1001.86	138.13	102.08	58.53	54.82	28.54	10.61	2.79	3.46
1980	2115	0.00	16.18	1971.21	190.90	115.65	94.42	417.83	154.83	333.21	133.62	78.76	13.26	22.81	4.75	3.49
1983	1647	0.00	1.10	3254.35	107.83	32.62	428.59	68.59	47.27	33.71	92.68	21.86	25.80	26.90	4.32	0.00
1986	2857	0.00	4555.66	119.65	21.04	148.80	2004.57	215.71	171.63	225.45	27.33	28.72	2.08	10.85	3.49	0.00
1989	1238	0.00	411.82	141.76	31.19	1276.32	28.43	10.08	18.30	435.18	22.95	1.75	43.08	0.00	0.00	1.76
1992	2169	230.71	318.37	42.50	246.38	630.74	77.96	31.61	1541.82	46.68	28.08	14.14	533.23	27.13	0.00	28.42
1995	1385	316.41	880.52	117.80	32.62	575.90	26.58	88.78	403.38	5.90	0.00	429.34	0.96	17.42	0.00	130.39
1998	1185	98.31	414.33	460.41	386.81	481.76	34.52	135.59	215.61	26.41	39.14	120.27	7.68	4.92	104.47	29.19
2001	737	0.00	1471.36	185.56	109.35	117.25	54.26	54.03	29.41	17.11	12.03	5.07	4.48	8.73	0.83	3.10
2003	1840	5.19	99.78	84.88	2146.50	366.87	92.55	201.22	133.09	73.54	74.67	24.06	14.18	14.63	10.33	14.12
2005	1265	8.65	601.86	61.02	180.86	129.98	1210.46	132.12	45.07	61.09	34.83	28.17	11.90	6.11	0.81	4.35
2007	879	38.27	849.10	48.34	202.04	22.86	81.75	51.65	575.01	59.95	26.72	26.16	14.25	12.07	5.51	7.79

Table 11a. Hake pre-recruit (age-0 fish) indices from the SWFSC Santa Cruz midwater trawl juvenile groundfish survey (estimates are based on log-transformed hake catch per tow in numbers from Monterey outside stratum only, Sakuma and Ralston 1997) and the coast-wide survey which includes data from the PWCC/NMFS and SWFSC Santa Cruz surveys.

	SWFSC Santa Cruz hake pre-recruit index			Coast-wide survey SWFSC/PWCC/NMFS hake pre-recruit index				
Year	log(numbers)	S.E	Antilog (bias corrected)	Year	Catch per tow	S.D.	CV	S.E. (log space)
1986	2.989	0.552	18.87	1986	-	-	-	-
1987	6.691	0.537	803.92	1987	-	-	-	-
1988	5.294	0.507	198.17	1988	-	-	-	-
1989	2.232	0.526	8.32	1989	-	-	-	-
1990	3.778	0.526	42.72	1990	-	-	-	-
1991	4.187	0.535	64.81	1991	-	-	-	-
1992	2.797	0.540	15.39	1992	-	-	-	-
1993	7.266	0.522	1,430.09	1993	-	-	-	-
1994	3.661	0.523	37.90	1994	-	-	-	-
1995	2.131	0.523	7.43	1995	-	-	-	-
1996	4.929	0.536	137.21	1996	-	-	-	-
1997	3.011	0.556	19.31	1997	-	-	-	-
1998	1.716	0.539	4.56	1998	-	-	-	-
1999	4.724	0.534	111.66	1999	-	-	-	-
2000	2.819	0.541	15.75	2000	-	-	-	-
2001	3.637	0.526	36.99	2001	9.490	4.629	0.488	0.462
2002	2.347	0.558	9.45	2002	6.429	3.414	0.531	0.498
2003	0.733	0.526	1.08	2003	6.648	3.266	0.491	0.465
2004	4.771	0.526	117.05	2004	19.228	7.882	0.410	0.394
2005	0.540	0.511	0.72	2005	3.271	2.169	0.663	0.604
2006	0.409	0.509	0.51	2006	1.411	0.844	0.598	0.553

Table 11b. Basic data used to develop a coast-wide hake pre-recruit index based on SWFSC Santa Cruz midwater groundfish trawl and PWCC/NMFS midwater trawl surveys. These data include total number of zero and non-zero tows, mean and variance of log(catch numbers) of all and all non-zero tows for each year from 2001-2006 and eight latitudinal strata.

Basic catch data: Tows with zero and non-zero catches

	2001		2002		2003		2004		2005		2006	
Latitudinal Stratum	Num zero	Num pos.	Num zero	Num pos.	Num zero	Num pos.	Num zero	Num pos.	Num zero	Num pos.	Num zero	Num pos.
35	5	8	5	10	9	3	15	33	25	30	36	32
36	11	32	20	25	27	19	15	30	40	12	34	9
37	10	38	10	27	29	30	12	47	50	4	41	4
38	2	24	2	22	4	28	4	28	26	5	22	29
39	2	8	1	9	1	9	1	14	14	7	8	17
40	3	11	0	10	2	9	5	10	4	7	3	13
41	6	6	3	7	2	9	0	10	1	9	1	9
42	26	2	28	2	6	26	26	35	27	40	25	43
All	65	129	69	112	80	133	78	207	187	114	170	156
Proportion positive		0.66		0.62		0.62		0.73		0.38		0.48

Mean and variance of log catch numbers (all hauls)

	2001		2002		2003		2004		2005		2006	
Latitudinal Stratum	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var
35	2.827	8.061	1.818	3.339	0.851	3.544	1.682	2.773	2.495	7.678	0.769	1.387
36	2.504	4.261	1.554	4.419	0.845	1.803	2.746	6.641	0.218	0.449	0.435	1.146
37	2.658	4.430	1.771	2.924	0.995	2.763	3.091	6.521	0.013	0.009	0.111	0.261
38	2.753	5.230	3.493	4.534	2.520	4.509	4.046	7.502	0.103	0.109	0.919	1.448
39	2.073	2.854	4.817	4.904	3.587	3.834	6.098	6.520	0.411	0.710	1.908	3.159
40	2.144	3.414	1.881	0.948	2.674	6.913	2.385	5.379	1.346	1.811	2.417	2.746
41	0.860	1.005	1.326	1.197	5.493	10.601	5.185	12.953	4.288	7.031	1.954	0.724
42	0.069	0.135	0.065	0.126	2.391	6.698	1.631	6.707	1.787	4.887	1.230	1.380
All	2.096	4.525	1.816	4.294	1.834	5.407	2.789	7.534	1.125	4.151	0.958	1.720

Mean and variance of log catch numbers (non-zero hauls)

	2001		2002		2003		2004		2005		2006	
Latitudinal Stratum	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var
35	4.594	4.542	2.727	2.440	3.404	6.460	2.447	2.143	4.574	4.460	1.635	1.537
36	3.365	2.783	2.798	4.477	2.045	1.916	4.119	4.225	0.947	1.329	2.077	2.177
37	3.358	3.216	2.427	2.396	1.956	3.579	3.880	5.094	0.173	0.120	1.253	1.924
38	2.982	4.971	3.810	3.699	2.880	4.101	4.624	5.843	0.636	0.397	1.616	1.419
39	2.591	2.135	5.352	2.294	3.986	2.526	6.534	3.957	1.233	1.185	2.806	2.061
40	2.728	2.684	1.881	0.948	3.269	6.456	3.578	3.627	2.115	1.122	2.975	1.635
41	1.719	0.438	1.894	0.539	6.714	4.031	5.185	12.953	4.765	5.356	2.171	0.284
42	0.973	1.893	0.973	1.893	2.942	6.617	2.842	8.291	2.993	4.567	1.945	0.777
All	3.152	3.468	2.935	3.650	2.937	5.420	3.839	6.333	2.969	5.494	2.003	1.501

Table 12. Parameter assumptions and model configuration of Stock Synthesis II (Ver. 2.00n) for Pacific hake.

Parameter	**Number Estimated**	**Bounds (low,high)**	**Prior (Mean, SD)**
Natural Mortality			
base (ages 0-12)	-	NA	Fixed at 0.23
ages 13-15+ (exponential offset)	1	(-3,3)	~N(0,0.8)
Stock and recruitment			
Ln(Rzero)	1	(11,30)	~N(15,99)
Steepness	1	(.2,1.0)	~*Beta* (.77,113)
Sigma R (based on 1967-2005 R devs)	-	NA	Fixed at 1.131
Ln(Recruitment deviations): 1967-2005	39	(-15,15)	~Ln(N(0.Sigma R))
Catchability			
Ln(Acoustic survey)	1	(-5,5)	~N(0,99)
Selectivity			
US Fishery (double logistic):			
Base Period block: 1966 - 1983			
Ascending inflection (ln trans.)	1	(1,10)	~N(3,99)
Ascending slope	1	(0.001,10)	~N(2.5,99)
Descending inflection (ln trans.)	1	(1,20)	~N(12,99)
Descending slope	1	(0.001,10)	~N(1.0,99)
Temporal blocks for all: 1984-1992, 1993-2000, 2001-2007	12	same as above	same as above
Canadian Fishery (double logistic):			
Base Period block: 1966 - 1994			
Ascending inflection (ln trans.)	1	(1,20)	~N(3,99)
Ascending slope	1	(0.001,10)	~N(1.0,99)
Descending inflection (ln trans.)	1	(1,40)	~N(13,99)
Descending slope	1	(0.001,10)	~N(1.0,99)
Temporal blocks for ascending infl and slp: 1995-2000, 2001-2002, 2003-2007	6	same as above	same as above
Acoustic Survey (double normal):			
Peak age	1	(2,15)	~N(8,99)
Top (logistic)	-	(-9,3)	fixed at -1.5
Ascending width	1	(0,9)	~N(3,99)
Descending width	-	(-5,9)	fixed at 2.75
Final selectivity (logistic)	-	(-5,6)	~N(0,99)
Individual growth			
Sex combined:			
Length at age min (age 2)	1	(10,40)	~N(33,99)
base period Lmax 1966-1983	1	(30,70)	~N(53,99)
blocks for Lmax: 1984-2005	1	(30,70)	~N(53,99)
base period von Bertalanffy K, 1966-1980 and 1987-2005	1	(0.1,0.7)	~N(0.3,99)
blocks for von Bertalanffy K, 1981-1986	1	(0.1,0.7)	~N(0.3,99)
CV of length at age min	1	(0.01,0.35)	~N(0.1,99)
CV of length at age max	-	NA	fixed at 0

Table 13. Maximum likelihood model parameter estimates with asymptotic standard deviations from Stock Synthesis II (Ver. 2.00n) applied to Pacific hake.

Parameter	MLE	Asympt. SD
Natural mortality		
M (ages 13-15+, exp offset from 0.23)	0.927	0.064
Stock and recruitment		
Ln(Rzero)	15.214	0.117
steepness *h*	0.744	0.168
Catchability		
Ln(Acoustic survey)	-0.787	0.193
Selectivity		
US Fishery (double logistic):		
Base Period block: 1966 - 1983		
Ascending inflection (ln trans.)	3.944	0.166
Ascending slope	1.036	0.079
Descending inflection (ln trans.)	11.862	0.148
Descending slope	0.828	0.050
Block 1984 - 1992		
Ascending inflection (ln trans.)	2.262	0.110
Ascending slope	4.888	1.934
Descending inflection (ln trans.)	12.414	0.191
Descending slope	0.814	0.063
Block 1993- 2000		
Ascending inflection (ln trans.)	3.975	0.181
Ascending slope	0.975	0.082
Descending inflection (ln trans.)	13.522	0.363
Descending slope	0.525	0.082
Block 2001- 2007		
Ascending inflection (ln trans.)	2.655	0.056
Ascending slope	3.585	0.266
Descending inflection (ln trans.)	9.630	1.052
Descending slope	0.337	0.050
Canadian Fishery (double logistic):		
Base Period block: 1966 - 1994		
Ascending inflection (ln trans.)	5.405	0.169
Ascending slope	1.259	0.096
Descending inflection (ln trans.)	12.322	0.364
Descending slope	0.602	0.073
Base Period block: 1995 - 2000		
Ascending inflection (ln trans.)	5.244	0.478
Ascending slope	0.555	0.069
Base Period block: 2001 - 2002		
Ascending inflection (ln trans.)	3.700	0.109
Ascending slope	6.864	1.227
Base Period block: 2003 - 2007		
Ascending inflection (ln trans.)	4.534	0.115
Ascending slope	1.993	0.192
Acoustic Survey (double normal):		
Peak age	6.546	0.447
Ascending width	3.070	0.207
Final selectivity (logistic)*	-1.265	0.163
Growth Parameters:		
Length at age min (Lmin, age 2)	32.730	0.085
Base period Lmax, 1966-1983	52.952	0.086
Block for Lmax: 1984-2007	50.013	0.057
Base period K, 1966-1980, 1987-2007	0.342	0.003
Blocks for K: 1981-1986	0.222	0.004
CV of length at age min	0.072	0.000

Table 14. Time series of estimated 3+ biomass, spawning biomass, recruitment, and utilization from 1966-2008 for Pacific hake using Stock Synthesis II (Ver. 2.00n). U.S. and Canadian exploitation rate is the catch in biomass divided by the vulnerable biomass at the start of the year. Population (3+) and spawning biomass is in millions of tons at the start of the year. Recruitment is given in billions of age-0 fish.

	3+ Population	Spawning	Age 0	Depletion		Exploitation Rate	
Year	biomass (mt)	biomass (mt)	Recruits	% Bzero	U.S. exploitation rate	Canada exploitation rate	Total
1966	5.990	2.897	4.062	100.00%	3.44%	0.02%	3.46%
1967	5.861	2.833	5.669	97.82%	4.57%	1.21%	5.78%
1968	5.680	2.745	5.993	94.75%	1.62%	2.12%	3.74%
1969	5.615	2.733	5.563	94.36%	2.31%	3.29%	5.60%
1970	5.801	2.787	16.640	96.23%	4.23%	2.68%	6.92%
1971	6.036	2.886	5.140	99.62%	3.31%	0.97%	4.28%
1972	6.290	3.160	2.908	109.09%	1.72%	1.49%	3.21%
1973	8.541	3.836	11.689	132.41%	2.97%	0.47%	3.45%
1974	8.812	4.171	2.576	143.98%	3.44%	0.47%	3.91%
1975	8.379	4.188	4.274	144.58%	3.32%	0.37%	3.69%
1976	9.335	4.344	2.306	149.96%	3.65%	0.12%	3.77%
1977	8.718	4.245	20.312	146.54%	2.02%	0.11%	2.13%
1978	8.352	4.051	2.094	139.86%	1.61%	0.11%	1.72%
1979	7.637	3.980	3.554	137.39%	2.07%	0.26%	2.32%
1980	10.110	4.508	47.524	155.63%	1.21%	0.38%	1.60%
1981	9.375	4.445	0.506	153.46%	1.90%	0.55%	2.45%
1982	8.646	4.712	0.316	162.66%	1.11%	0.69%	1.80%
1983	15.063	5.828	0.845	201.20%	0.95%	0.80%	1.75%
1984	14.274	6.450	21.910	222.65%	0.77%	0.75%	1.53%
1985	12.402	5.912	0.100	204.10%	0.80%	0.39%	1.19%
1986	10.620	5.433	0.761	187.54%	1.61%	0.76%	2.36%
1987	12.092	5.165	6.019	178.31%	1.51%	1.04%	2.55%
1988	10.659	5.003	2.439	172.72%	1.75%	1.41%	3.16%
1989	9.146	4.506	0.410	155.55%	2.72%	1.67%	4.39%
1990	8.476	4.024	3.450	138.92%	2.65%	1.47%	4.12%
1991	7.418	3.545	1.103	122.39%	3.79%	2.04%	5.83%
1992	6.022	2.979	0.402	102.85%	4.68%	2.50%	7.17%
1993	5.262	2.508	2.725	86.58%	3.96%	2.05%	6.01%
1994	4.412	2.125	3.088	73.35%	8.84%	4.81%	13.65%
1995	3.290	1.638	2.288	56.54%	8.13%	3.68%	11.81%
1996	2.802	1.343	2.375	46.35%	11.76%	5.68%	17.44%
1997	2.553	1.179	2.268	40.70%	15.16%	6.66%	21.82%
1998	2.291	1.065	1.898	36.76%	16.86%	7.30%	24.16%
1999	2.079	0.961	18.151	33.19%	17.45%	7.91%	25.36%
2000	1.905	0.882	0.030	30.46%	17.07%	2.14%	19.21%
2001	1.798	1.048	1.374	36.19%	10.87%	4.36%	15.24%
2002	4.425	1.625	0.035	56.10%	3.65%	4.23%	7.87%
2003	4.182	1.898	1.809	65.54%	3.75%	3.67%	7.42%
2004	3.887	1.827	0.414	63.09%	6.39%	4.61%	11.00%
2005	3.149	1.554	6.065	53.64%	9.89%	3.83%	13.72%
2006	2.687	1.279	3.676	44.14%	13.92%	4.54%	18.46%
2007	2.046	1.067	3.556	36.85%	14.19%	4.79%	18.98%
2008	2.490	1.097	3.575	37.87%	-	-	-
2007 5% - 95% Asymptotic Interval				36.85%	23.7% - 50.1%		
2008 5% - 95% Asymptotic Interval				37.87%	21.9% - 53.9%		

Table 15. Estimates of uncertainty as expressed by asymptotic 95% confidence intervals of spawning biomass and recruitment to age-0 for Pacific hake based on the Stock Synthesis model (ver2.00n). Deviations from log mean recruitment were estimated between 1967-2005 and values given for 2006-2008 represent mean recruitment from the stock recruitment curve.

	Spawning biomass (millions, mt)			Recruitment to Age-0 (billions)		
		Asymptotic interval			Asymptotic interval	
Year	MLE	5%	95%	MLE	5%	95%
1966	2.897	2.234	3.559	4.062	3.230	5.108
1967	2.833	2.171	3.496	5.669	4.317	7.444
1968	2.745	2.082	3.407	5.993	4.627	7.762
1969	2.733	2.065	3.402	5.563	4.282	7.227
1970	2.787	2.090	3.485	16.640	12.917	21.437
1971	2.886	2.144	3.628	5.140	3.970	6.656
1972	3.160	2.339	3.981	2.908	2.244	3.769
1973	3.836	2.842	4.829	11.689	9.173	14.894
1974	4.171	3.085	5.256	2.576	2.006	3.309
1975	4.188	3.085	5.291	4.274	3.354	5.446
1976	4.344	3.198	5.490	2.306	1.794	2.965
1977	4.245	3.117	5.372	20.312	16.342	25.246
1978	4.051	2.979	5.123	2.094	1.633	2.684
1979	3.980	2.943	5.016	3.554	2.831	4.461
1980	4.508	3.385	5.632	47.524	39.072	57.804
1981	4.445	3.358	5.532	0.506	0.348	0.737
1982	4.712	3.592	5.831	0.316	0.222	0.451
1983	5.828	4.523	7.133	0.845	0.658	1.085
1984	6.450	5.053	7.846	21.910	18.552	25.876
1985	5.912	4.644	7.180	0.100	0.056	0.179
1986	5.433	4.286	6.579	0.761	0.619	0.936
1987	5.165	4.095	6.235	6.019	5.219	6.941
1988	5.003	3.991	6.015	2.439	2.112	2.817
1989	4.506	3.600	5.412	0.410	0.335	0.501
1990	4.024	3.219	4.829	3.450	3.013	3.950
1991	3.545	2.840	4.250	1.103	0.936	1.301
1992	2.979	2.382	3.576	0.402	0.322	0.502
1993	2.508	2.002	3.014	2.725	2.269	3.271
1994	2.125	1.697	2.553	3.088	2.508	3.803
1995	1.638	1.293	1.982	2.288	1.801	2.907
1996	1.343	1.054	1.631	2.375	1.813	3.111
1997	1.179	0.908	1.450	2.268	1.691	3.043
1998	1.065	0.794	1.336	1.898	1.377	2.616
1999	0.961	0.687	1.236	18.151	12.905	25.529
2000	0.882	0.596	1.169	0.030	0.012	0.073
2001	1.048	0.677	1.420	1.374	0.944	1.998
2002	1.625	1.028	2.222	0.035	0.015	0.081
2003	1.898	1.186	2.611	1.809	1.157	2.830
2004	1.827	1.113	2.542	0.414	0.236	0.728
2005	1.554	0.889	2.218	6.065	3.371	10.910
2006	1.279	0.665	1.892	3.676	0.604	22.365
2007	1.067	0.472	1.663	3.556	0.586	21.588
2008	1.097	0.419	1.775	3.575	0.573	22.317

Table 16. Three year stochastic projections of potential Pacific hake landings, spawning biomass and depletion assuming full coastwide catch is taken under the 40:10 rule. Coastwide catches for 2008-2010 represent the average from slicing the marginal posterior distribution of 2008 spawning depletion into 25th, 50th and 75th percentiles. Posterior intervals on spawning biomass and spawning depletion are based on 1,000,000 draws from MCMC simulation.

Percentile[1]			Spawning Biomass (millions, mt) [2]					Spawning Depletion (% unfished) [2]				
2008	Forecast	Coastwide	Posterior Interval					Posterior Interval				
depletion	Year	Catch (mt)	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
	2008	414,193	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
25%	2009	432,862	0.757	1.062	1.430	1.885	3.424	0.278	0.368	0.470	0.571	0.891
	2010	522,299	0.670	1.083	1.609	2.250	4.369	0.244	0.372	0.512	0.673	1.236
	2011	-	0.571	1.111	1.740	2.608	5.204	0.210	0.377	0.546	0.789	1.570
	2008	656,604	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
50%	2009	675,032	0.765	1.009	1.321	1.720	3.199	0.281	0.349	0.427	0.517	0.814
	2010	751,936	0.712	0.994	1.365	1.895	3.631	0.257	0.339	0.432	0.578	1.049
	2011	-	0.685	1.005	1.417	2.056	3.878	0.240	0.337	0.451	0.631	1.192
	2008	1,092,911	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
75%	2009	1,341,489	0.455	0.763	1.129	1.592	3.132	0.169	0.262	0.369	0.482	0.803
	2010	1,502,207	0.103	0.423	0.926	1.574	3.683	0.037	0.148	0.298	0.469	1.046
	2011	-	0.019	0.270	0.716	1.562	4.187	0.006	0.092	0.230	0.477	1.238
	2008	250,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	250,000	0.951	1.299	1.748	2.727	9.203	0.351	0.446	0.557	0.718	1.102
	2010	250,000	1.050	1.536	2.122	3.511	10.202	0.380	0.516	0.670	0.897	1.397
	2011	-	1.164	1.780	2.485	4.201	10.813	0.412	0.593	0.778	1.037	1.793
	2008	300,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	300,000	0.807	1.112	1.481	1.935	3.473	0.297	0.385	0.485	0.586	0.907
	2010	300,000	0.776	1.189	1.715	2.355	4.476	0.283	0.410	0.543	0.710	1.259
	2011	-	0.765	1.308	1.936	2.801	5.401	0.280	0.441	0.609	0.854	1.634
	2008	400,000	0.776	1.006	1.302	1.645	2.565	0.293	0.359	0.426	0.499	0.632
	2009	400,000	0.763	1.068	1.436	1.891	3.430	0.280	0.370	0.471	0.573	0.893
	2010	400,000	0.690	1.104	1.629	2.271	4.390	0.251	0.379	0.518	0.680	1.241
	2011	-	0.644	1.184	1.814	2.681	5.277	0.235	0.401	0.569	0.812	1.591

[1] Coastwide catches for 2008-2010 represent the average from slicing the marginal posterior distribution of 2008 spawning depletion in 25th, 50th and 75t

[2] Posterior intervals are based on 1,000,000 draws from MCMC simulation.

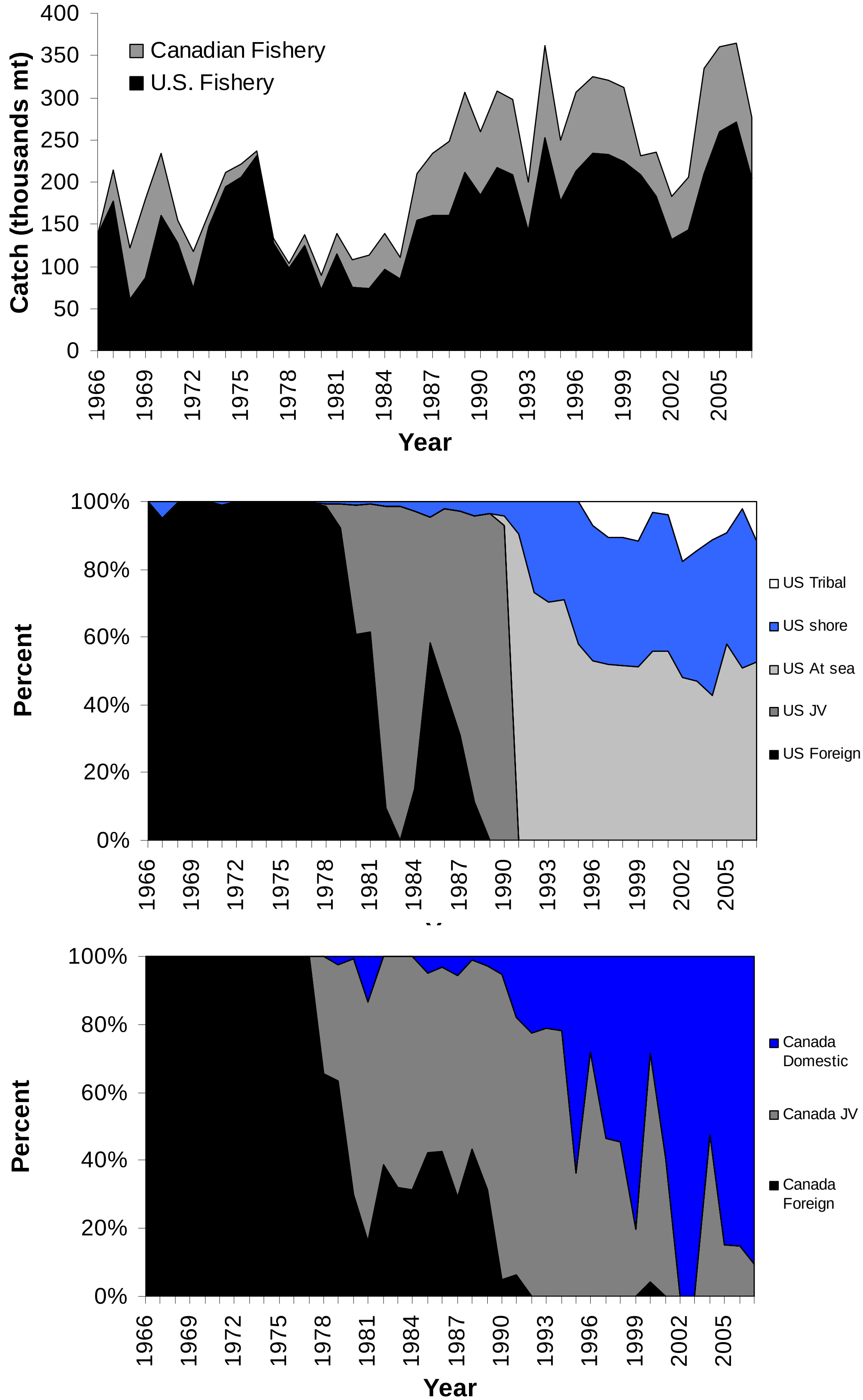


Figure 1. Pacific hake catches by fishery and national fishing sector, 1966-2007.

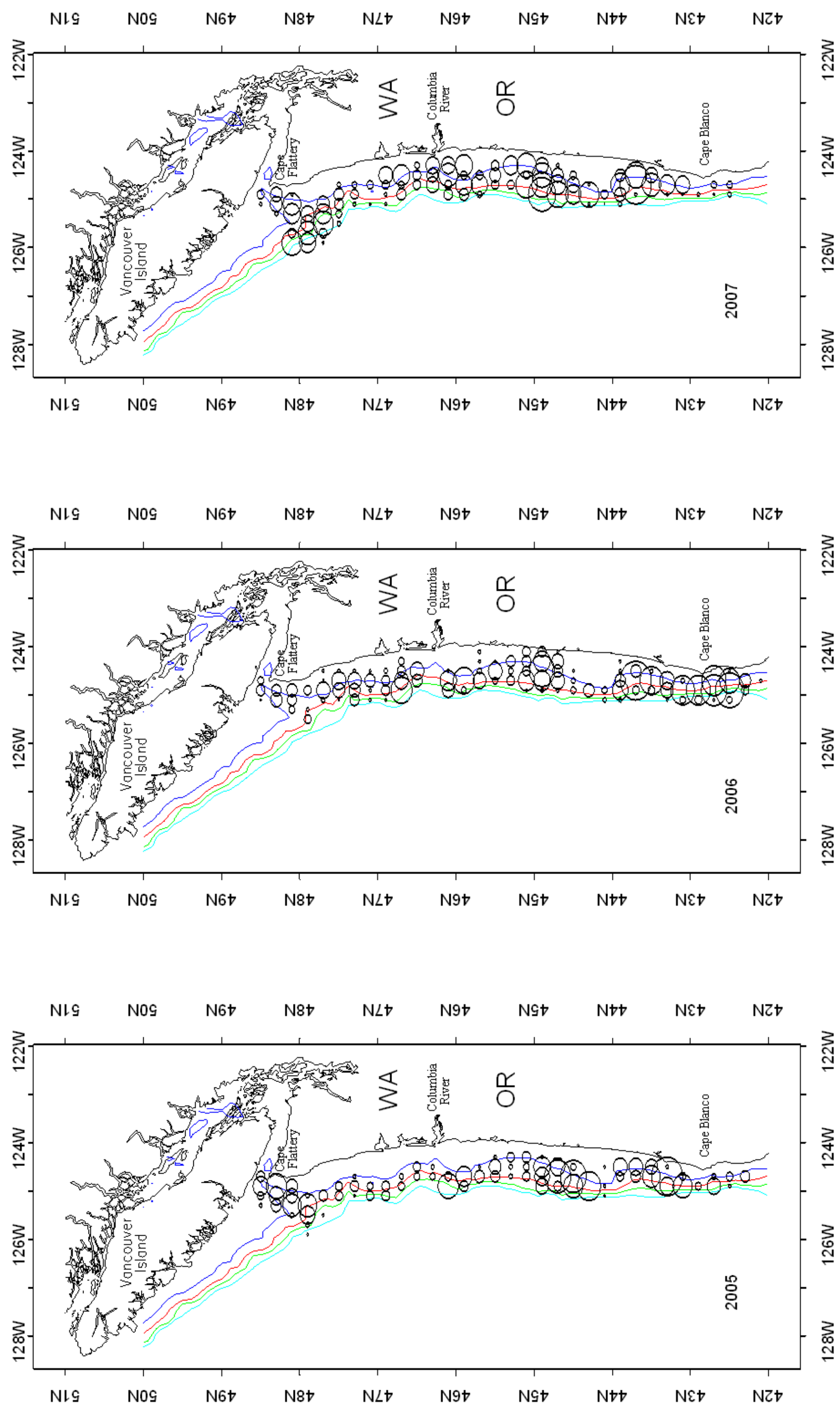


Figure 2. Distribution of at sea Pacific hake catches off the coast of the U.S. in 2005 (bottom), 2006 (middle) and 2007 (top).

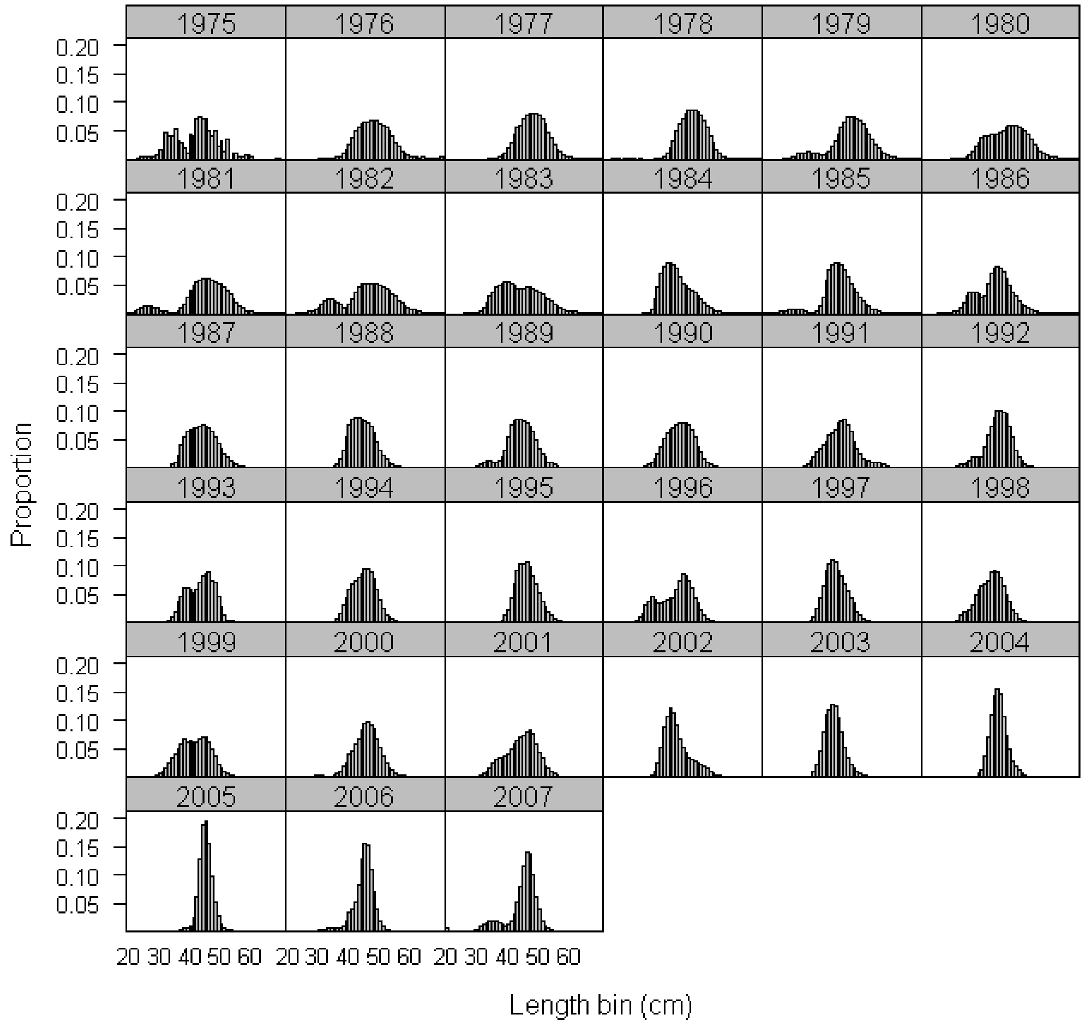


Figure 3. Plot of composite U.S. fishery size compositions of Pacific hake from fisheries operating off the west coast of the U.S., 1975-2007.

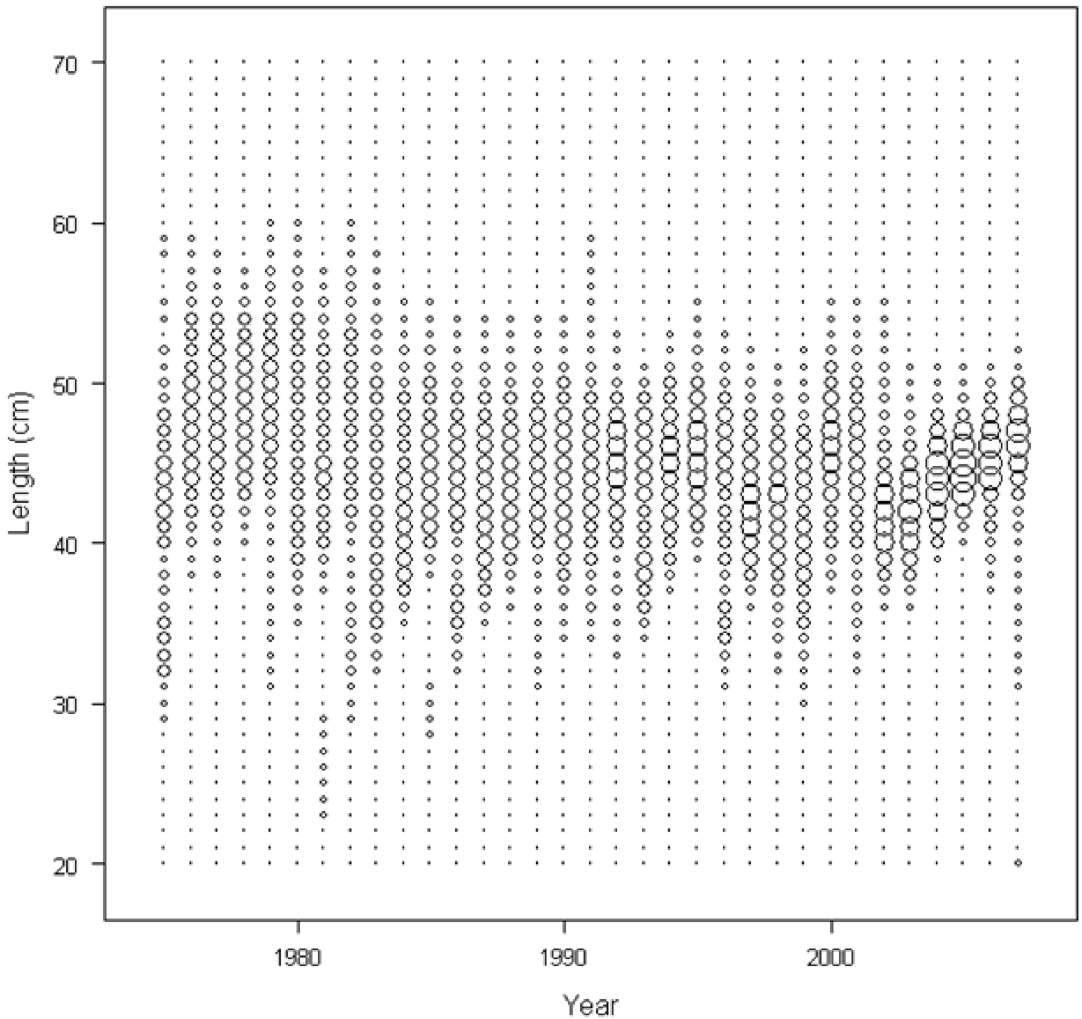


Figure 4. Composite U.S. fishery size compositions of Pacific hake from all fisheries operating off the west coast of the U.S., 1975-2007. Diameter of circles are proportional by year.

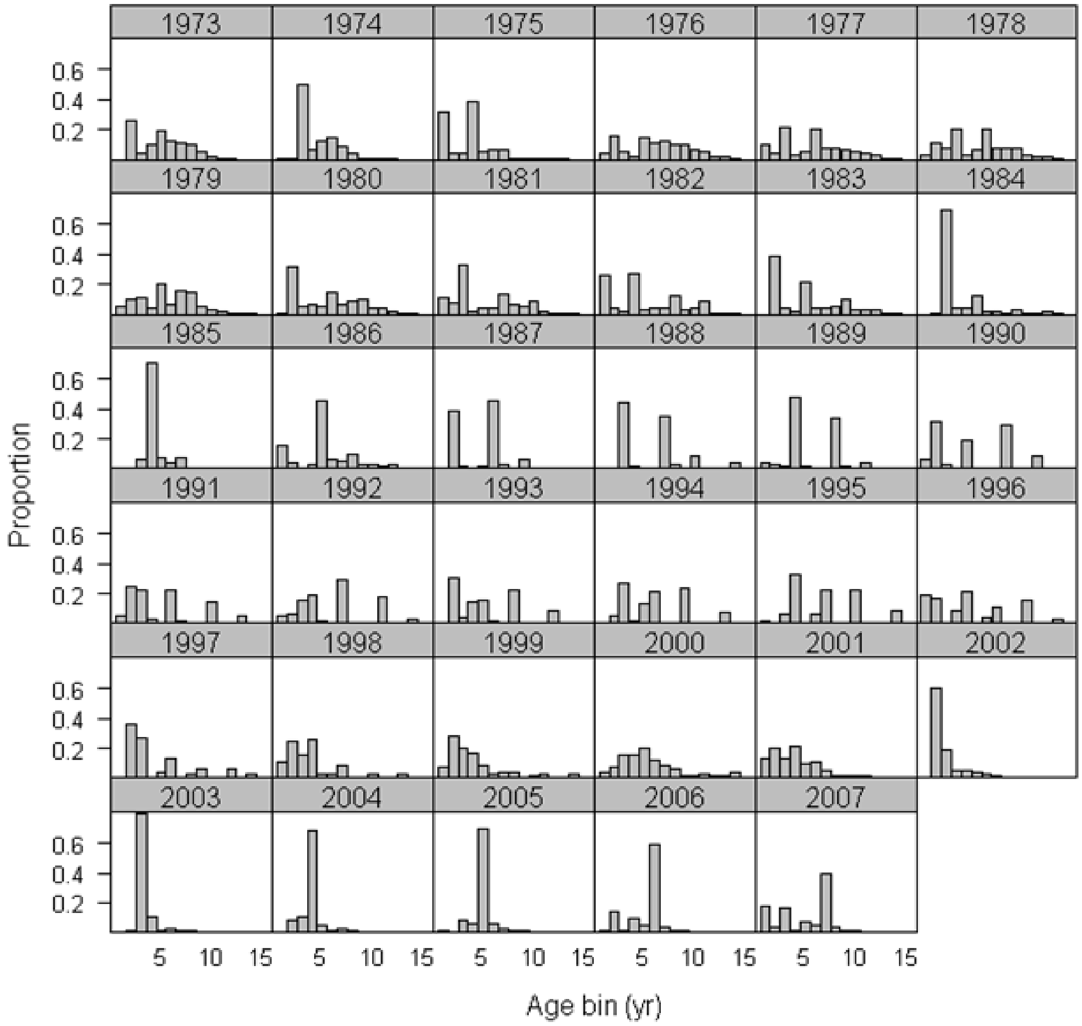


Figure 5. Plot of composite U.S. fishery age compositions of Pacific hake from fisheries operating off the west coast of the U.S., 1973-2007.

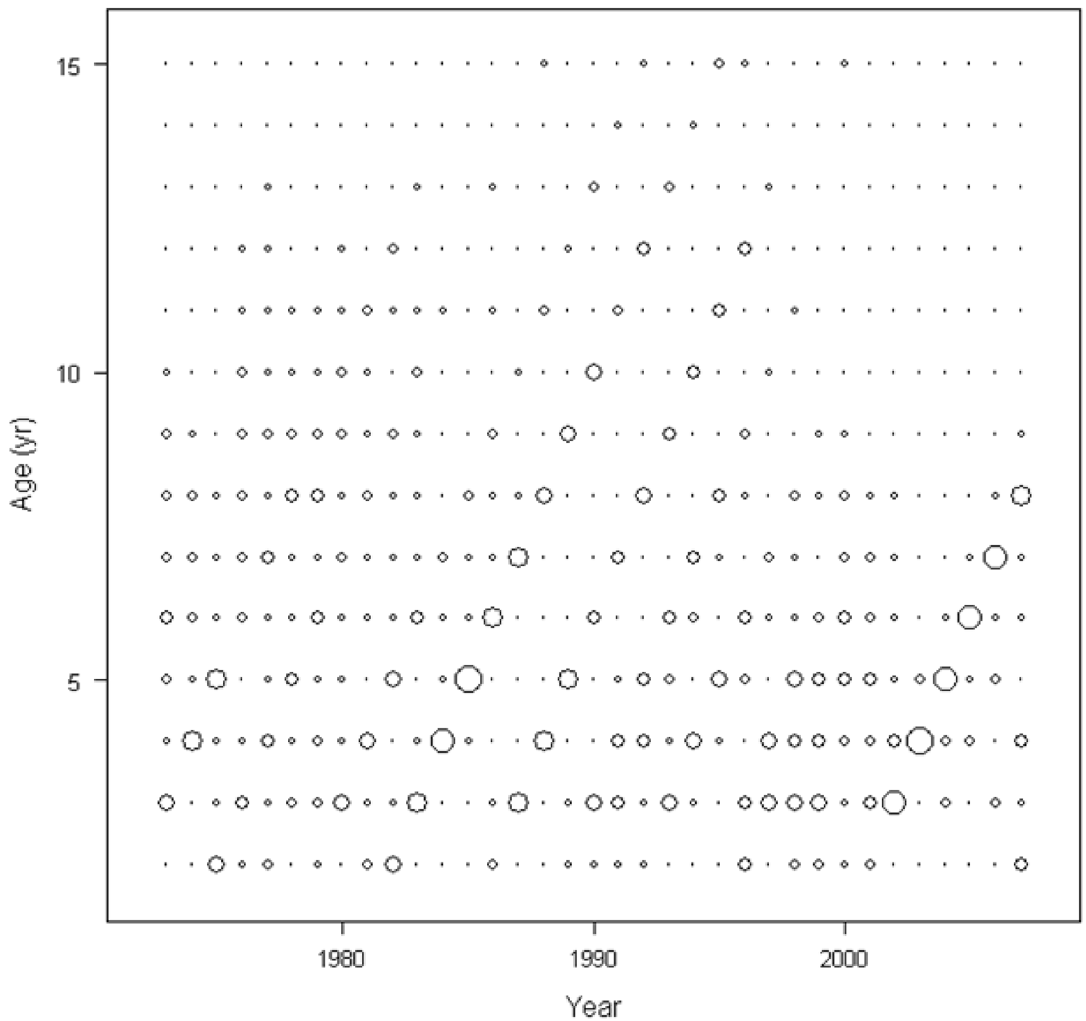


Figure 6. Age compositions of Pacific hake from the U.S. fishery, 1973-2007. Diameter of circles are proportional by year.

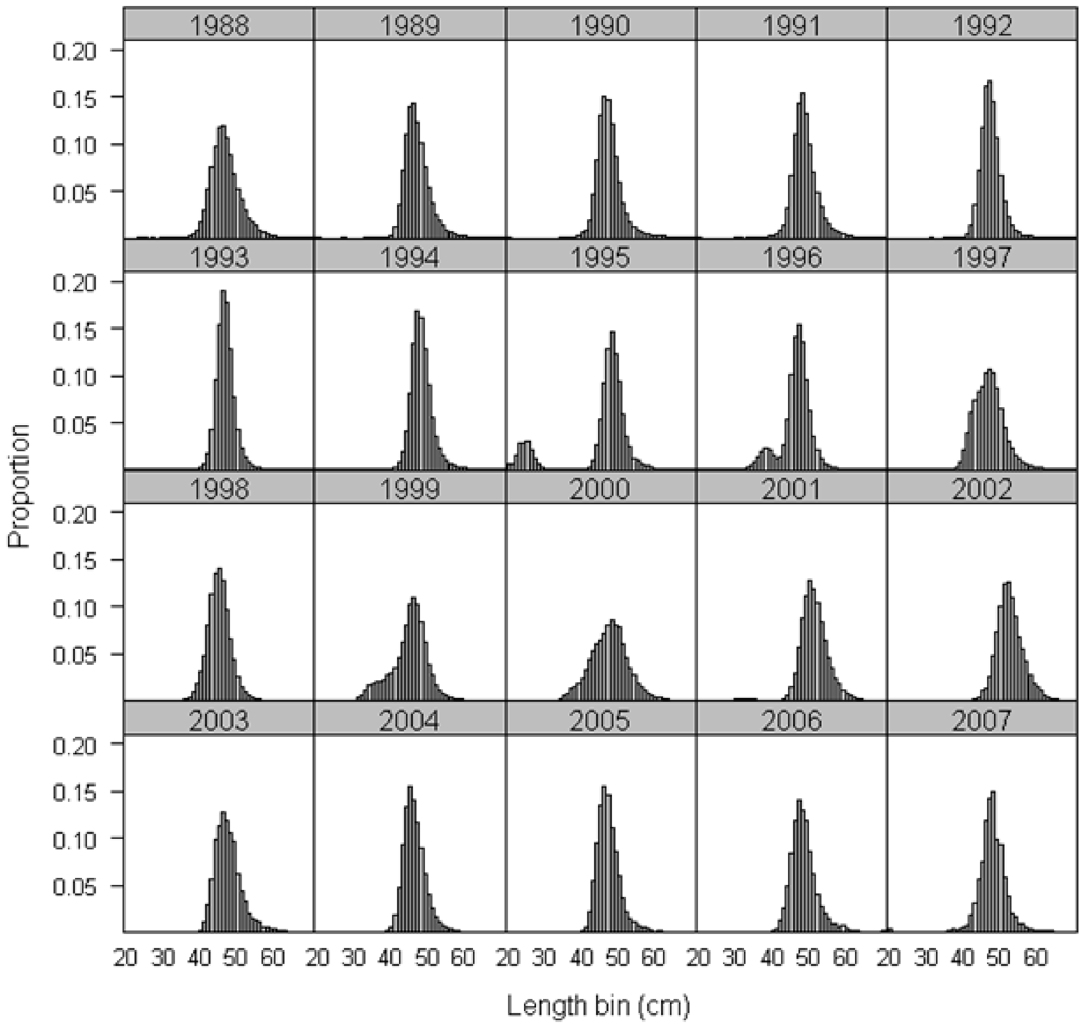


Figure 7. Plot of composite Canadian fishery size compositions of Pacific hake from fisheries operating off the west coast of the U.S., 1975-2007.

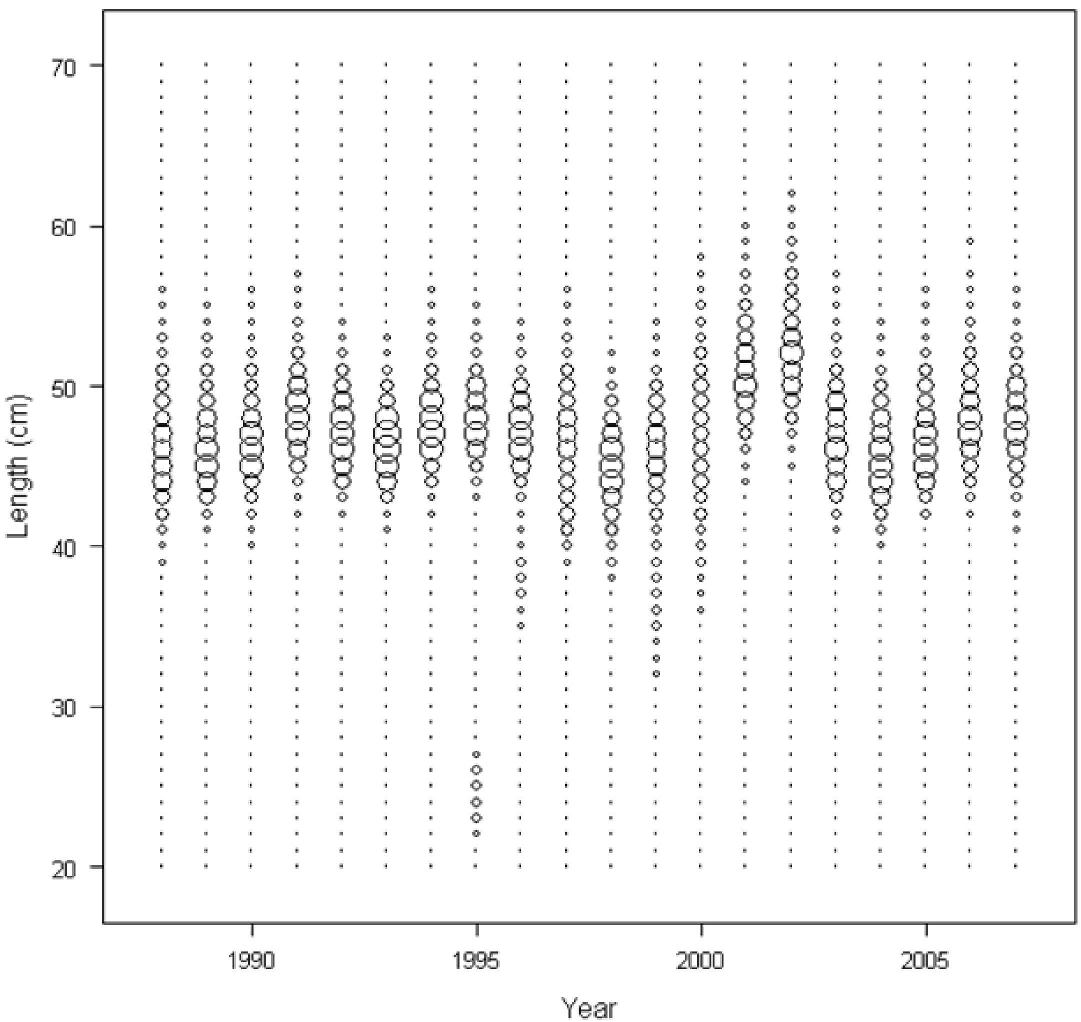


Figure 8. Size compositions of Pacific hake from the Canadian fishery, 1988-2007. Diameter of circles are proportional by year.

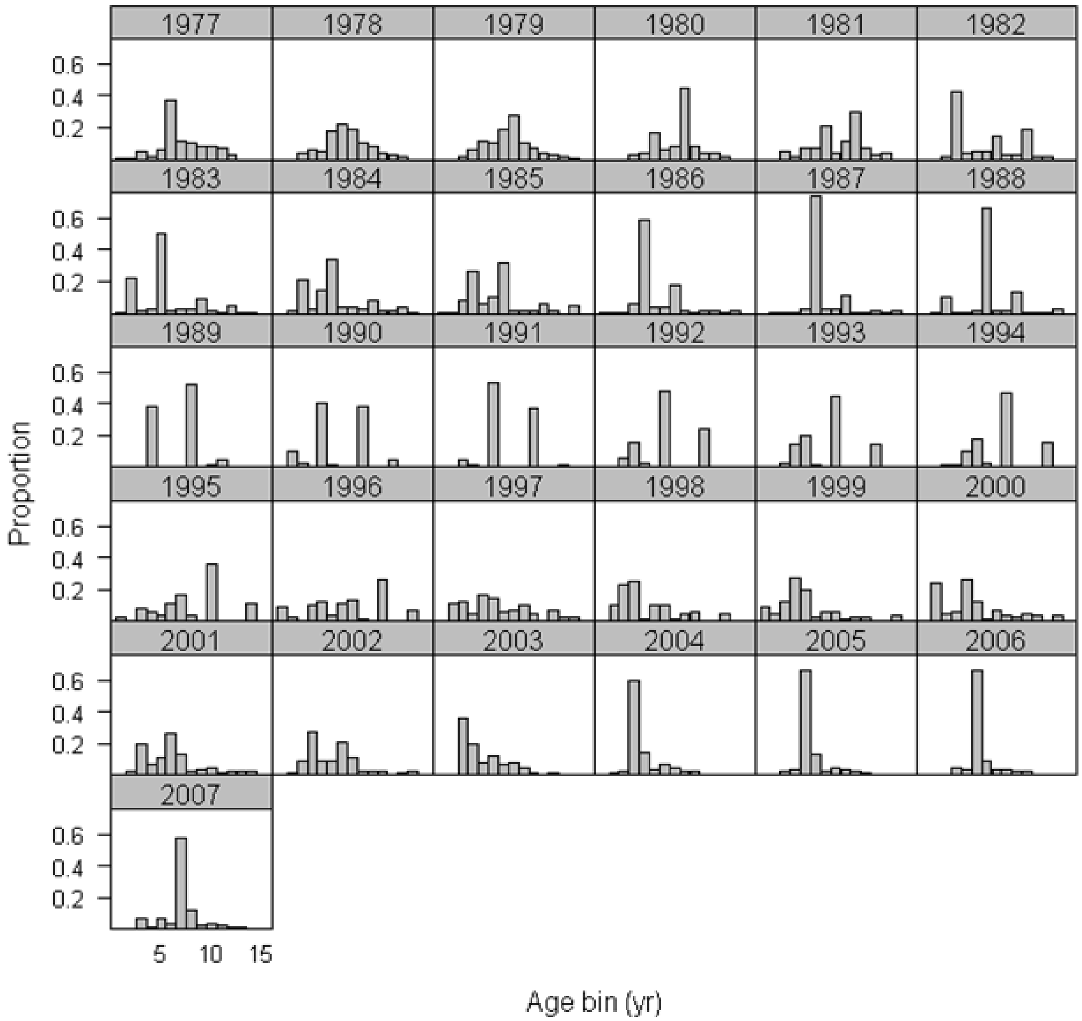


Figure 9. Plot of composite Canadian fishery age compositions of Pacific hake from fisheries operating off the west coast of the Canada., 1977-2007.

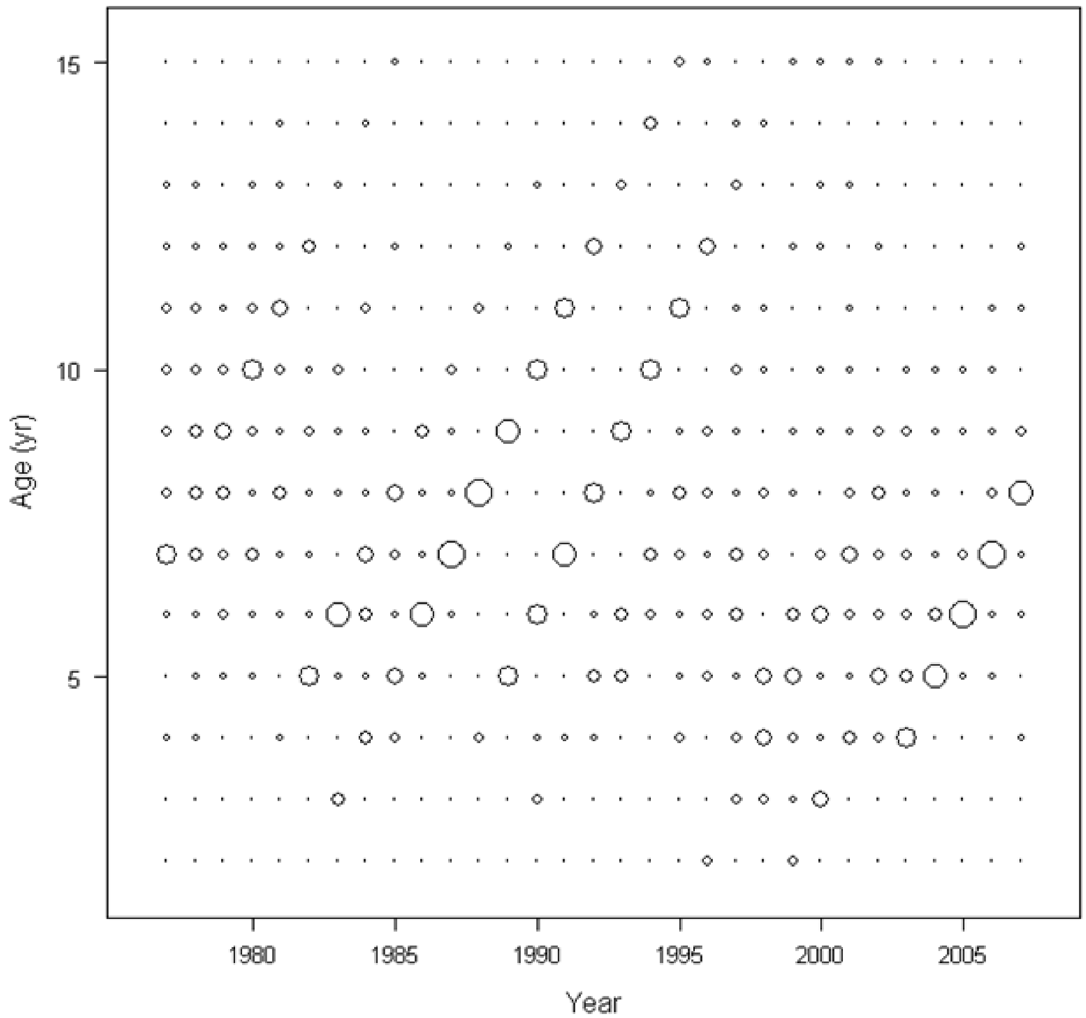


Figure 10. Age compositions of Pacific hake from the Canadian fishery, 1977-2007. Diameter of circles are proportional by year.

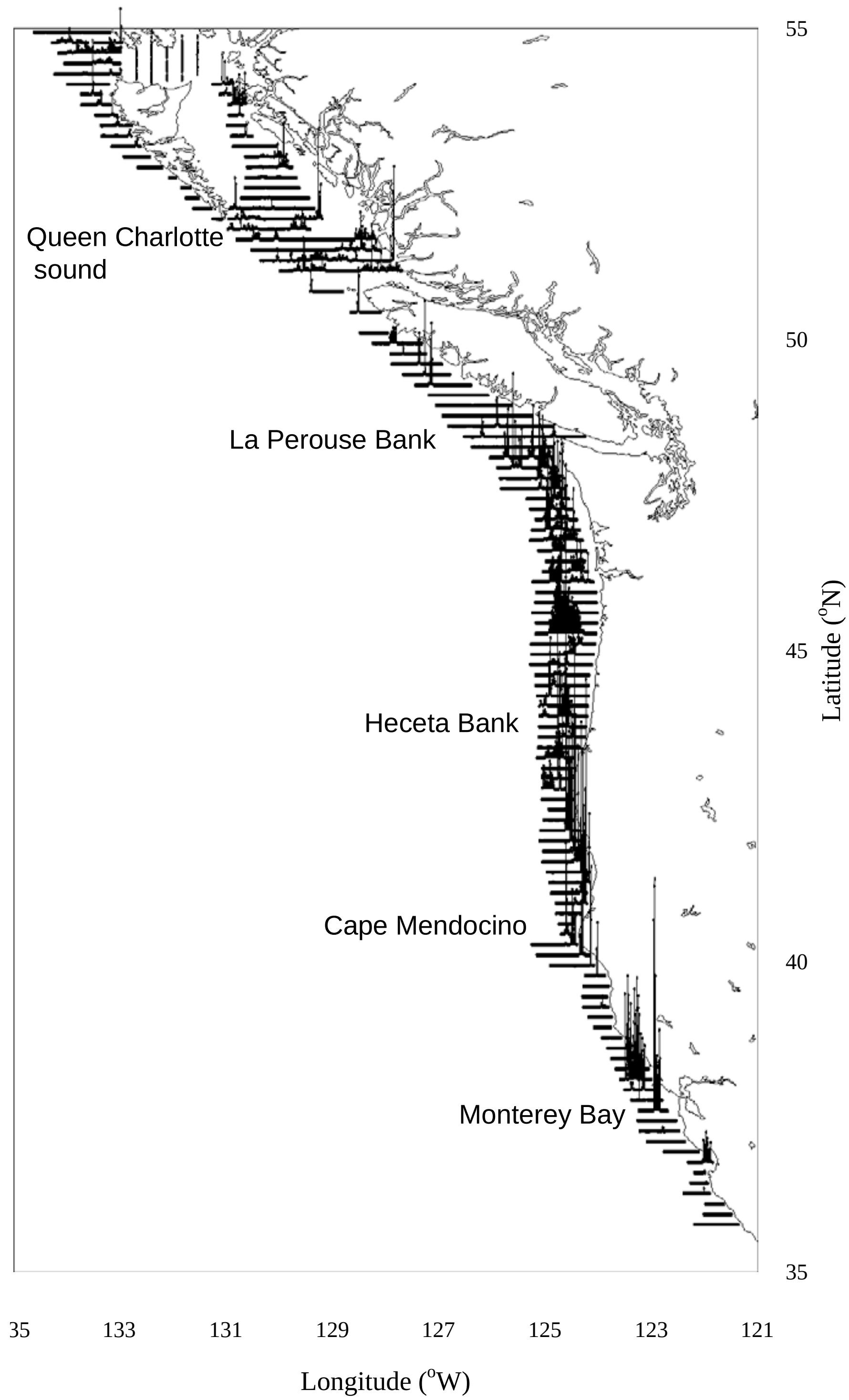


Figure 11. Line transects and occurrence of acoustic area backscattering attributable to Pacific hake in the 2007 joint US-Canada acoustic survey. Diameter of circles is proportional to measured backscatter levels.

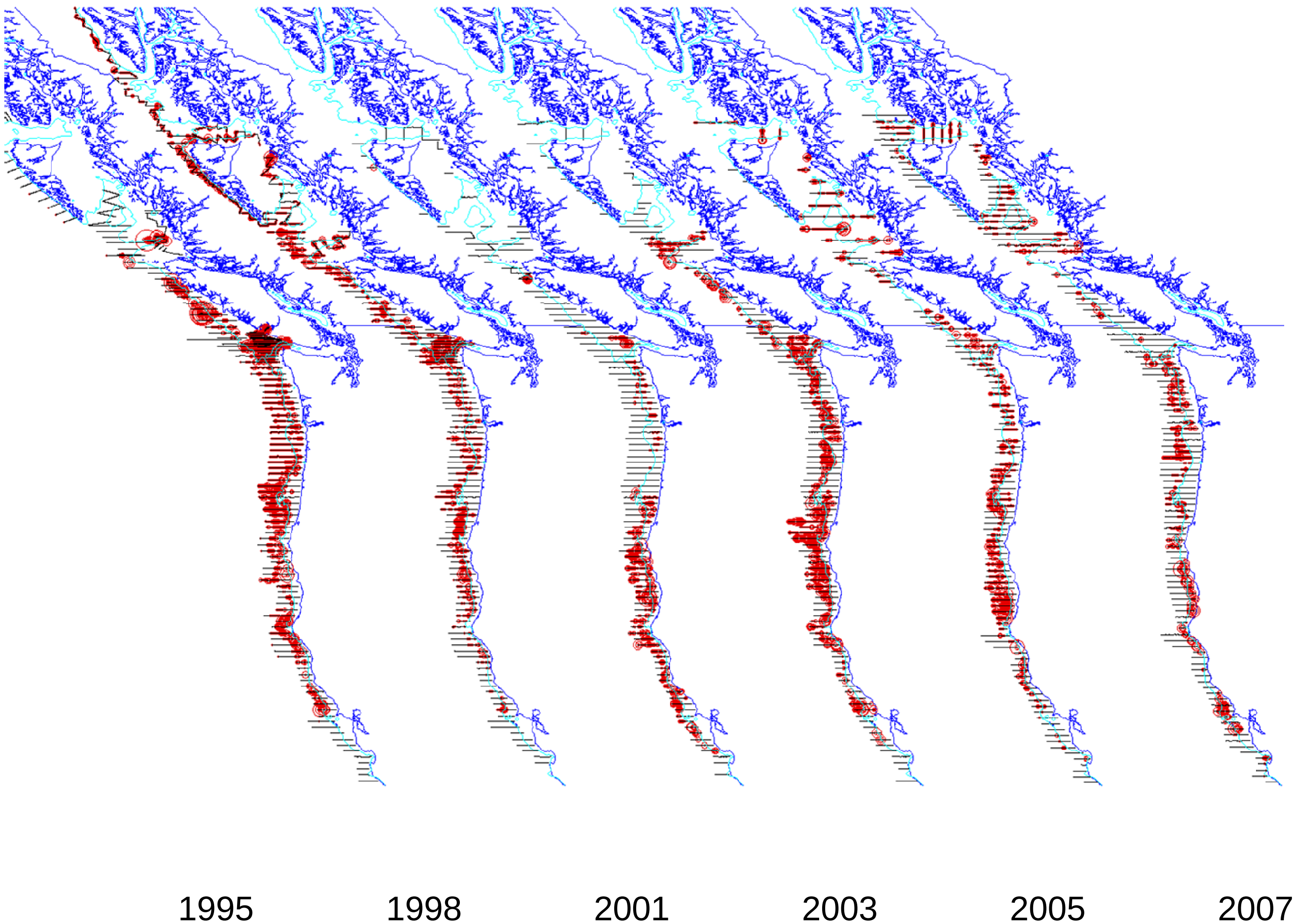


Figure 12. Occurrence of acoustic area backscattering attributable to Pacific hake in the last six (1995-2007) joint US-Canada acoustic surveys. Diameter of circles is proportional to measured backscatter levels.

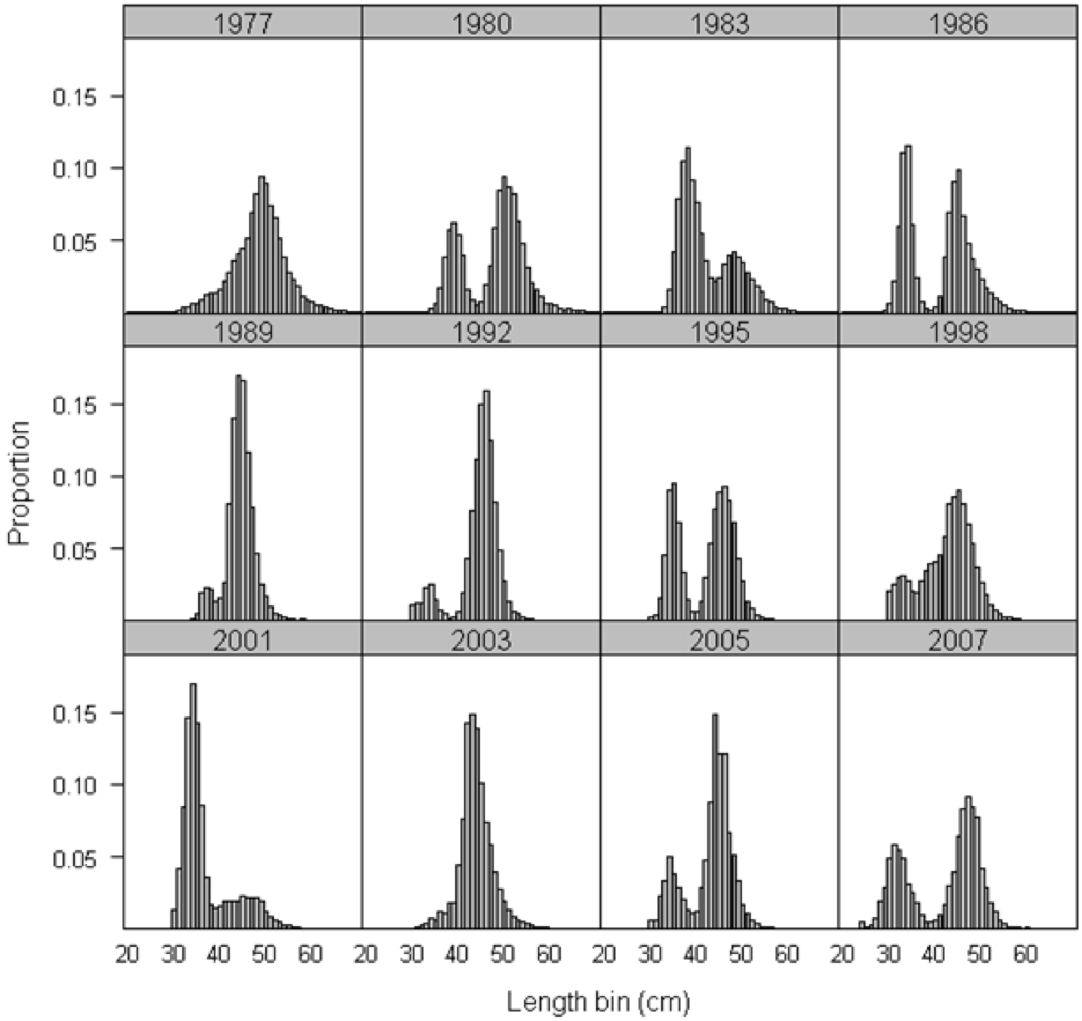


Figure 13. Plot of acoustic survey size compositions of coastal Pacific hake off the west coast of the U.S. and Canada, 1975-2007.

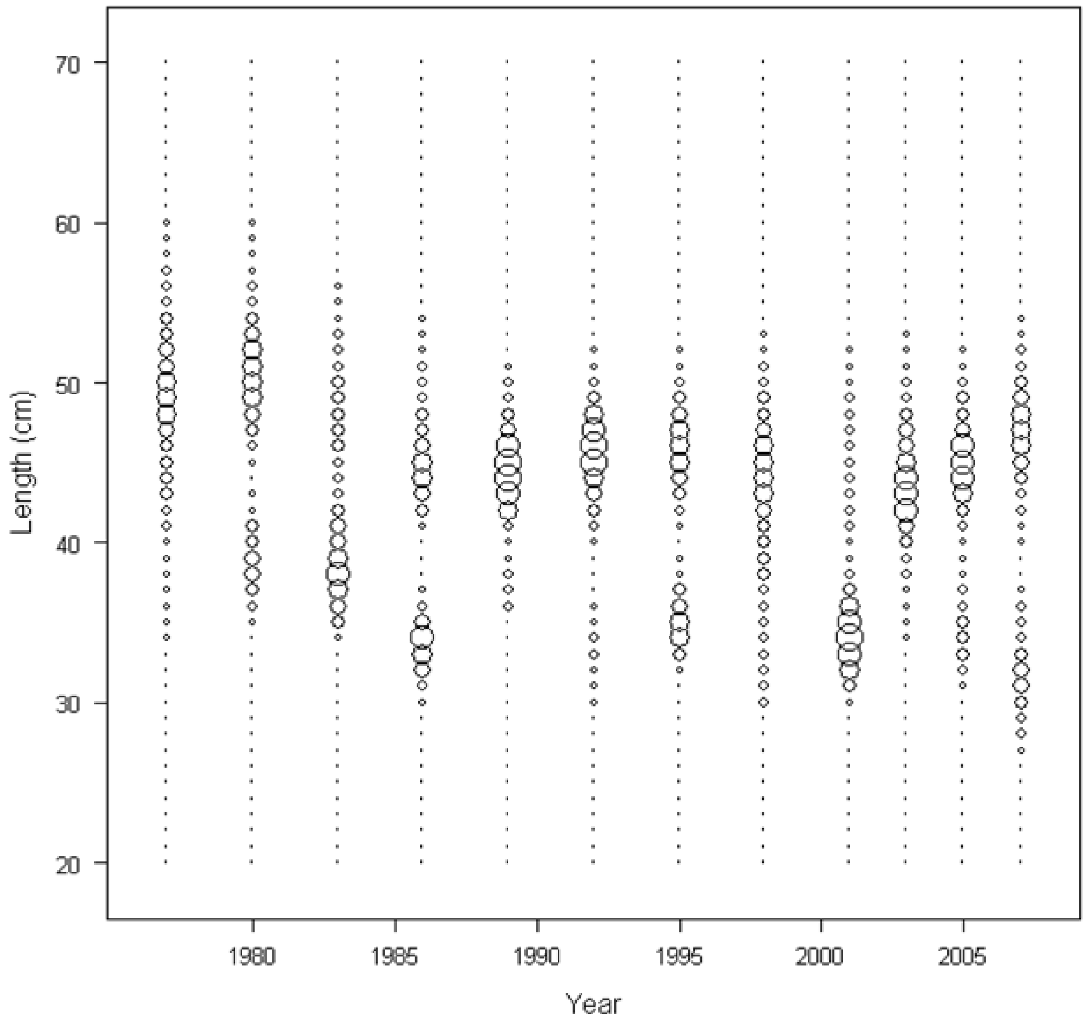


Figure 14. Length compositions of Pacific hake from the joint U.S.-Canada acoustic surveys off the west coast of the U.S. and Canada, 1977-2007. Diameter of circles are proportional by year.

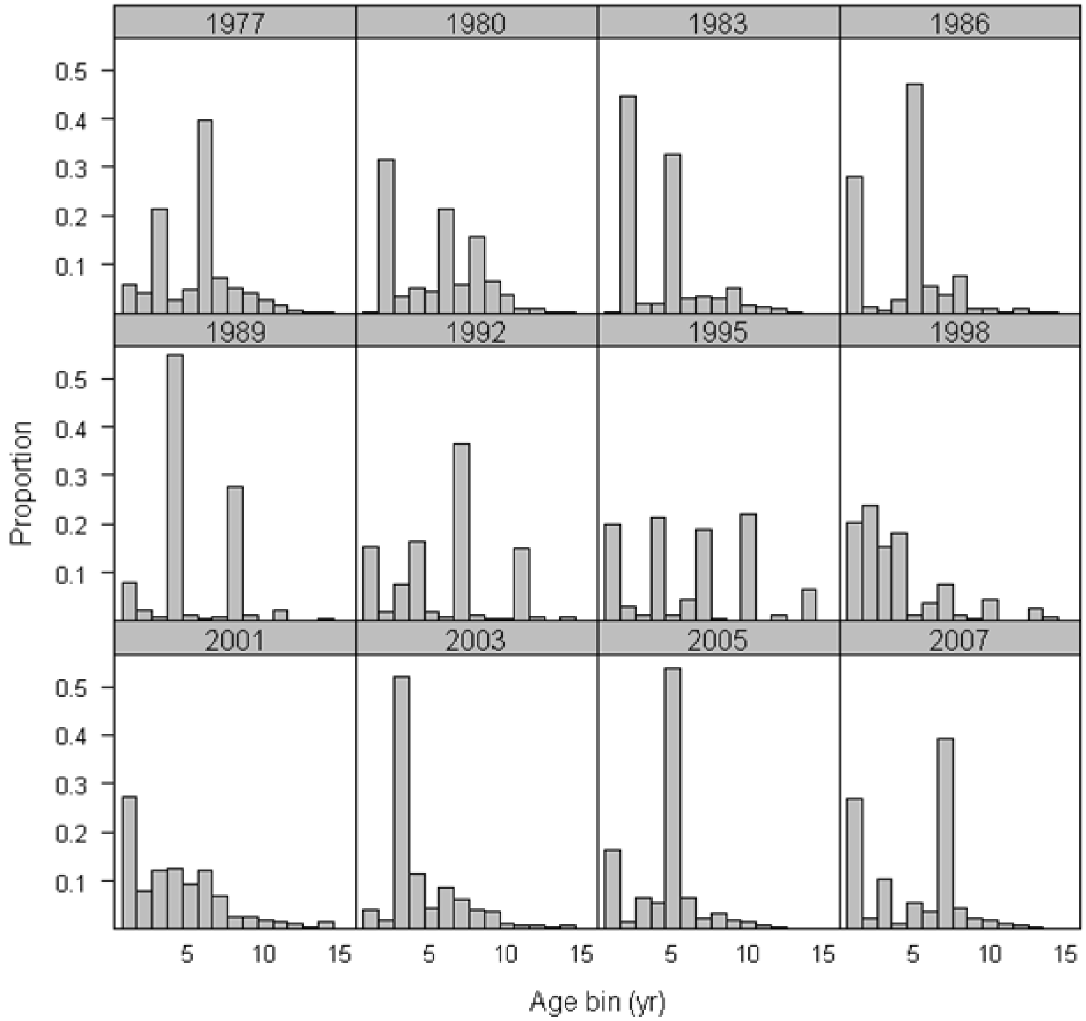


Figure 15. Plot of acoustic survey age compositions of Pacific hake off the west coast of the U.S and Canada., 1977-2007.

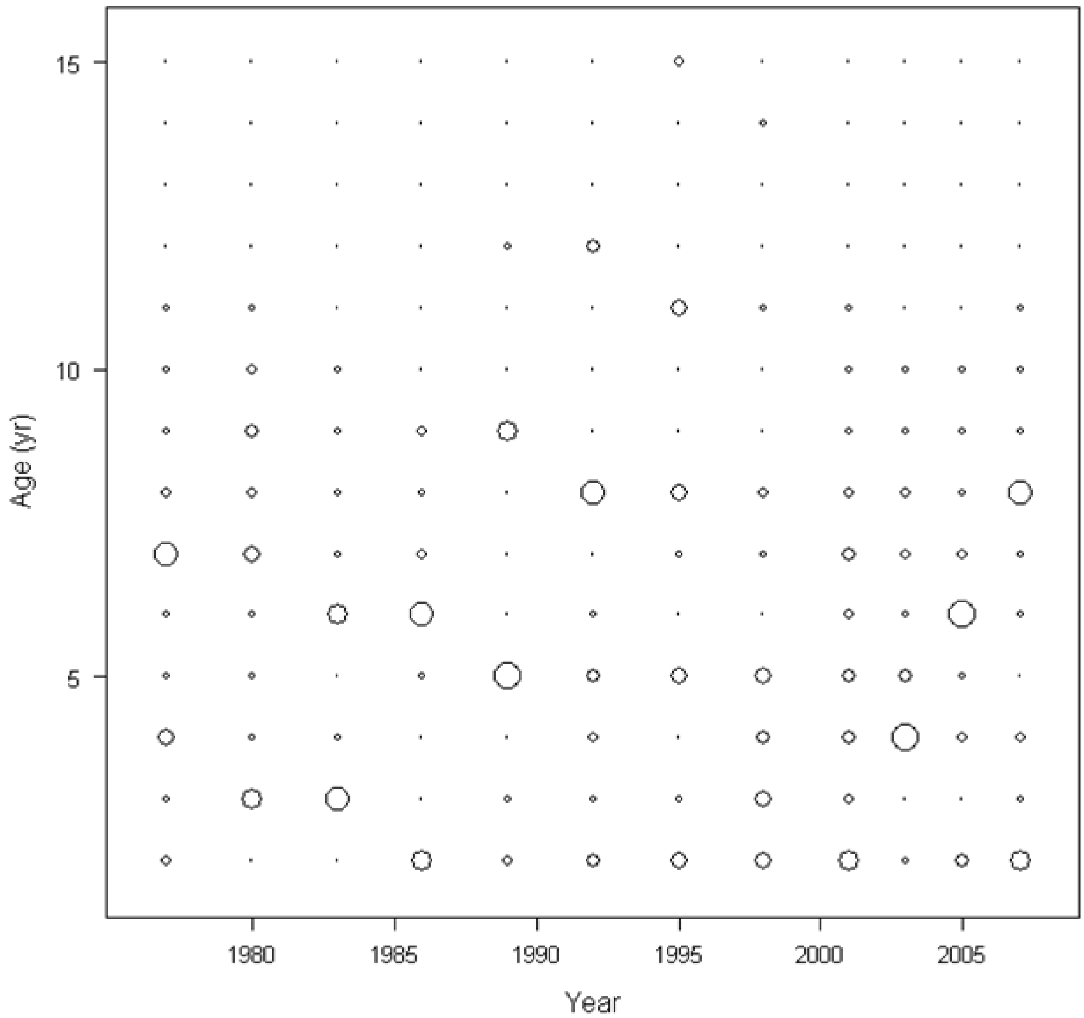


Figure 16. Age compositions of Pacific hake from the joint U.S.-Canada acoustic surveys off the west coast of the U.S. and Canada, 1977-2007. Diameter of circles are proportional by year.

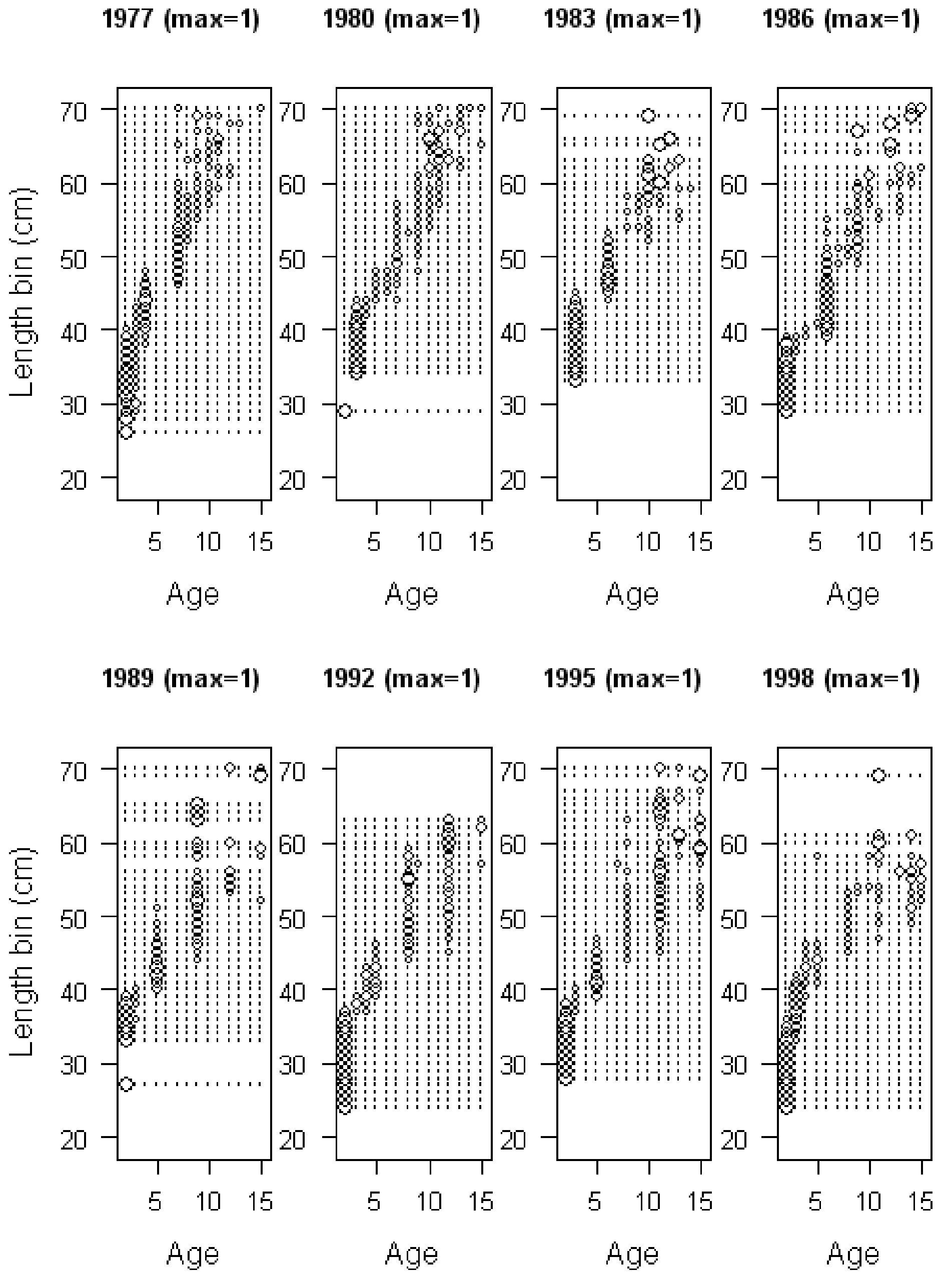


Figure 17. Conditional age at length compositions from the acoustic survey, 1977-2007. Diameter of circles are proportional by year.

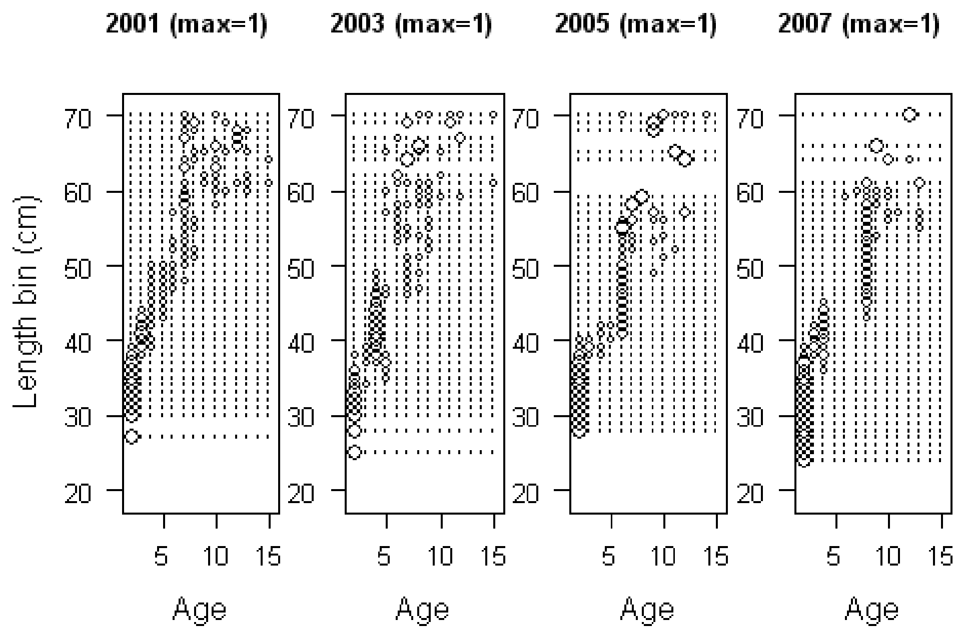


Figure 17 continued. Conditional age at length compositions from the acoustic survey, 1977-2007. Diameter of circles are proportional by year.

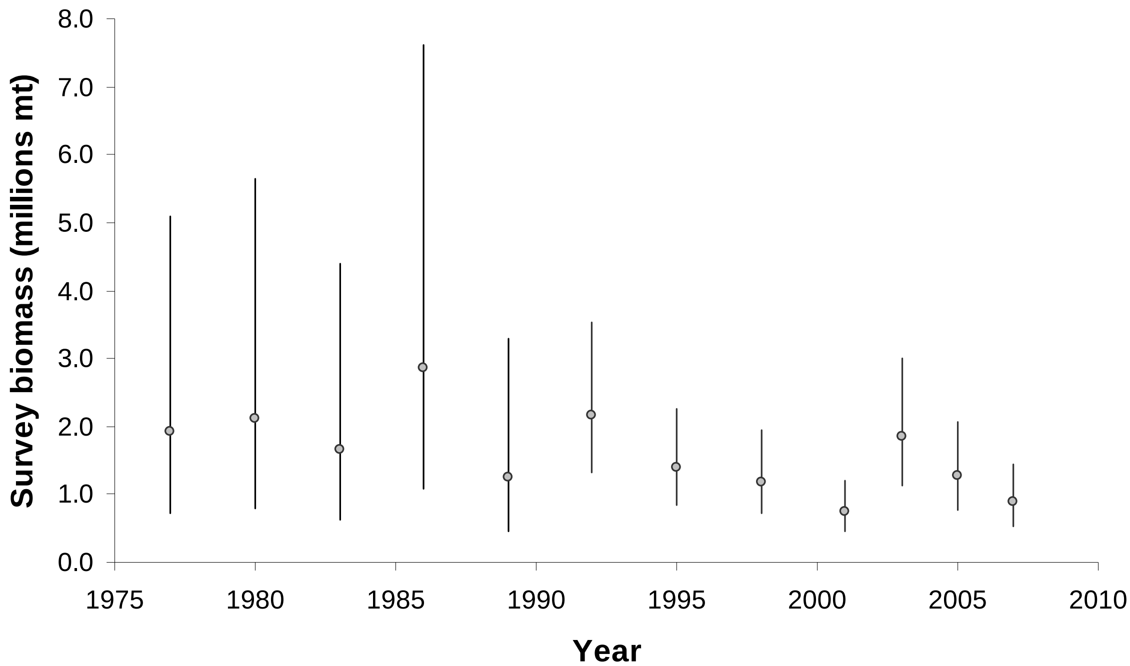


Figure 18. Time series of acoustic survey age 2+ biomass estimates, 1977-2007. Confidence intervals are based on assumed CV=0.5 1977-1989 and CV=.25 1992-2007.

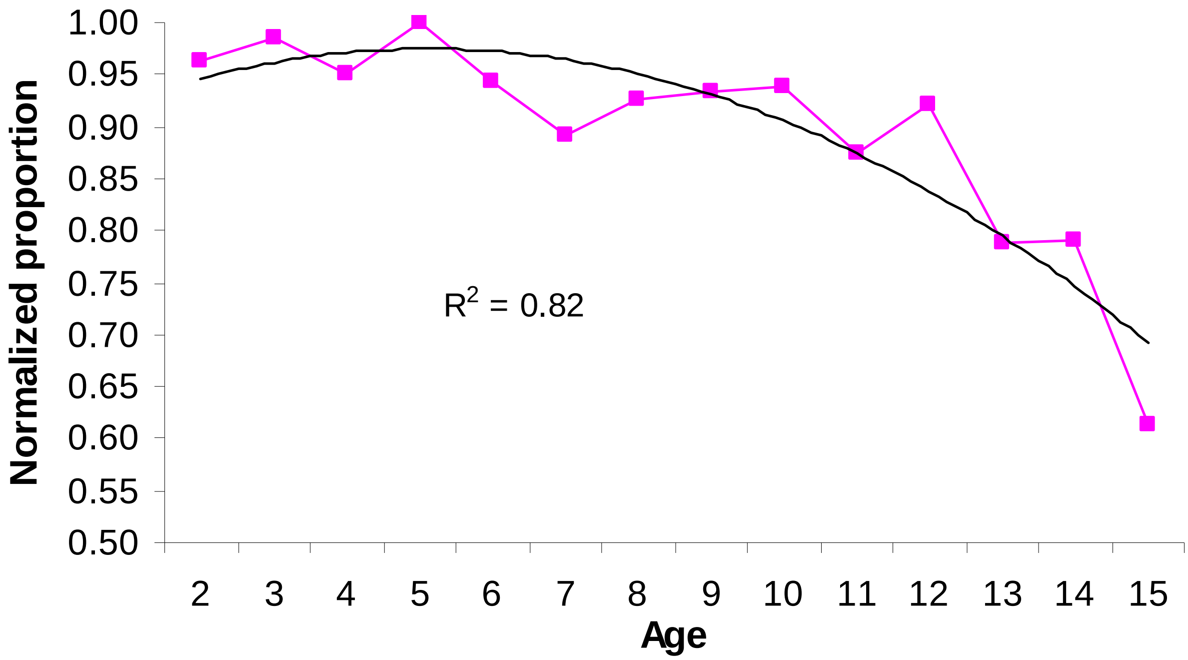


Figure 19. Plot of normalized (divided by maximum value) average (1977-2001) ratio of expanded acoustic survey numbers at age to the sum of acoustic survey and triennial bottom trawl survey expanded numbers at age. This analysis was conducted to explore empirical evidence for dome-shaped selectivity in the acoustic survey.

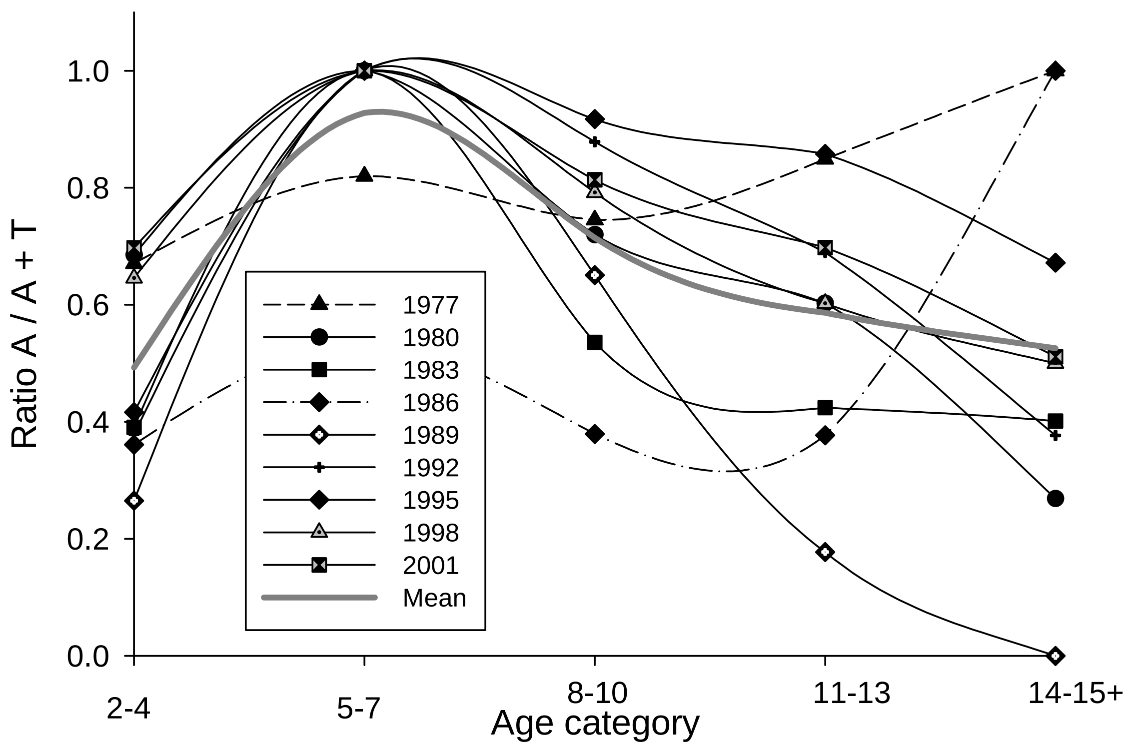


Figure 20. Plot of normalized (divided by maximum value) ratio of acoustic survey numbers at age to the sum of acoustic survey and triennial bottom trawl survey numbers at age. Numbers at age are based on aged samples taken from all hauls during that survey year and not based on expanded numbers at age. This analysis was conducted to explore empirical evidence for dome-shaped selectivity in the acoustic survey.

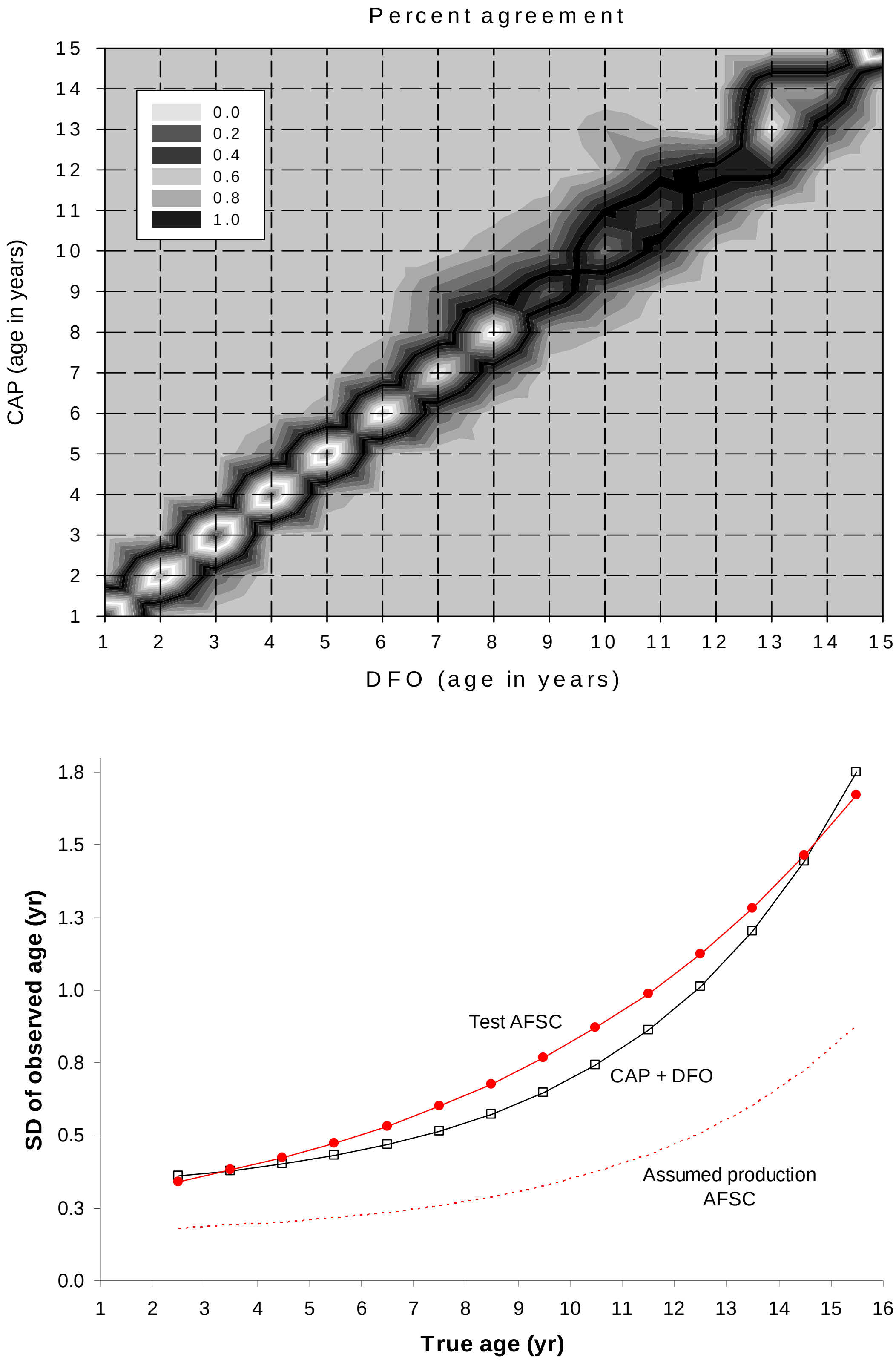
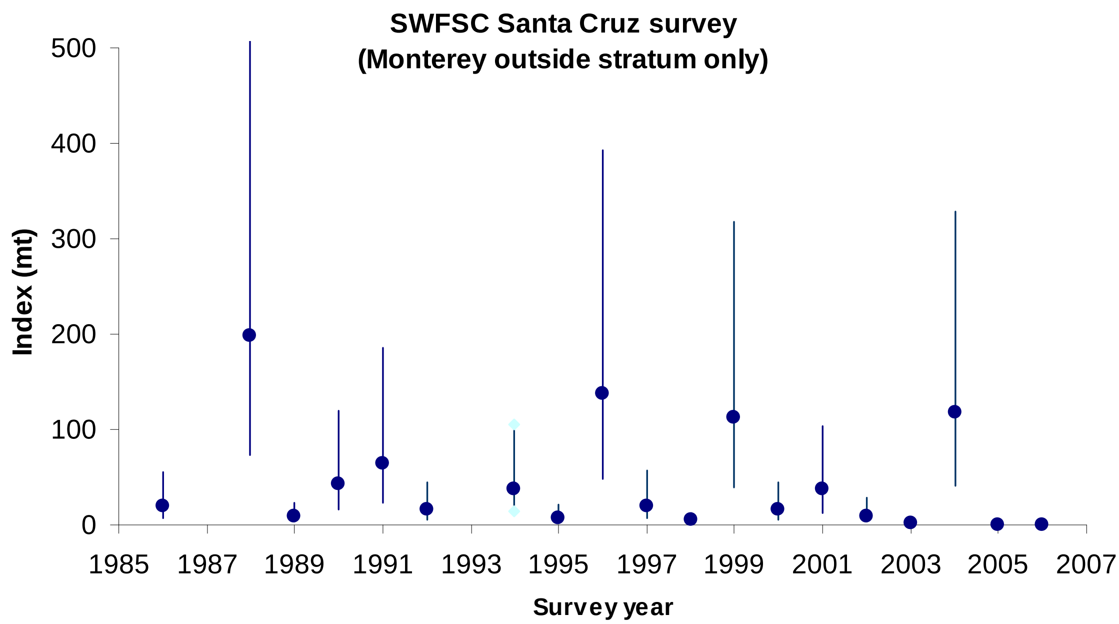


Figure 21. Comparison of 990 ototliths collected between 2001-2007 and cross-read between the Cooperative Aging Program (US) and the Canadian Department of Fisheries and Oceans. The bottom figure shows the estimated standard deviation of observed age as a function of true age.



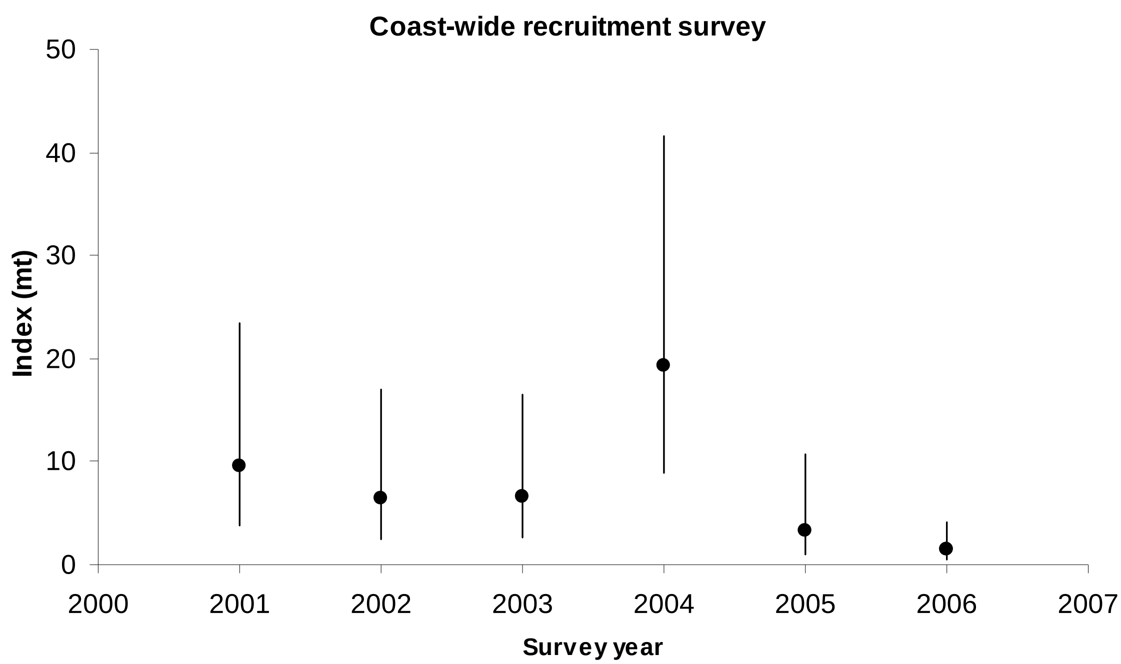
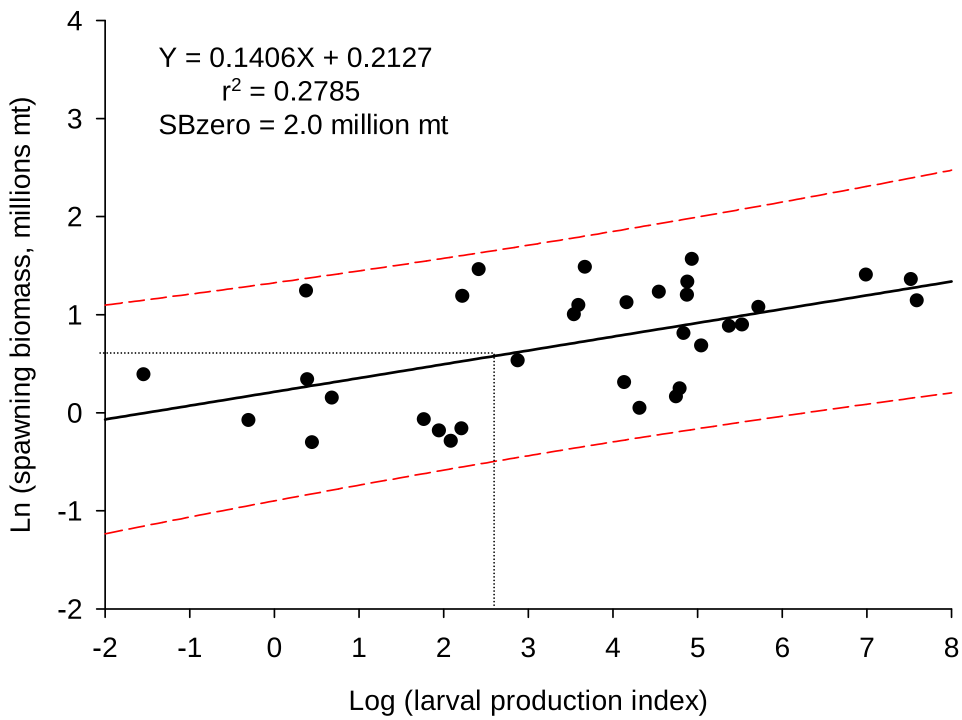


Figure 22. A) Plot of time series of the South West Fisheries Science Center Santa Cruz pre-recruit survey (Monterey outside stratum only) for young-of-year Pacific hake. Estimates and error bars are taken from back-transformed (bias corrected) year effects from GLM. B) Coast-wide Pacific hake pre-recruit survey indices based on data collected from SWFSC Santa Cruz and the joint PWCC-NMFS surveys. Estimates and error bars are obtained from a Monte Carlo simulation of a Delta-GLM analysis.



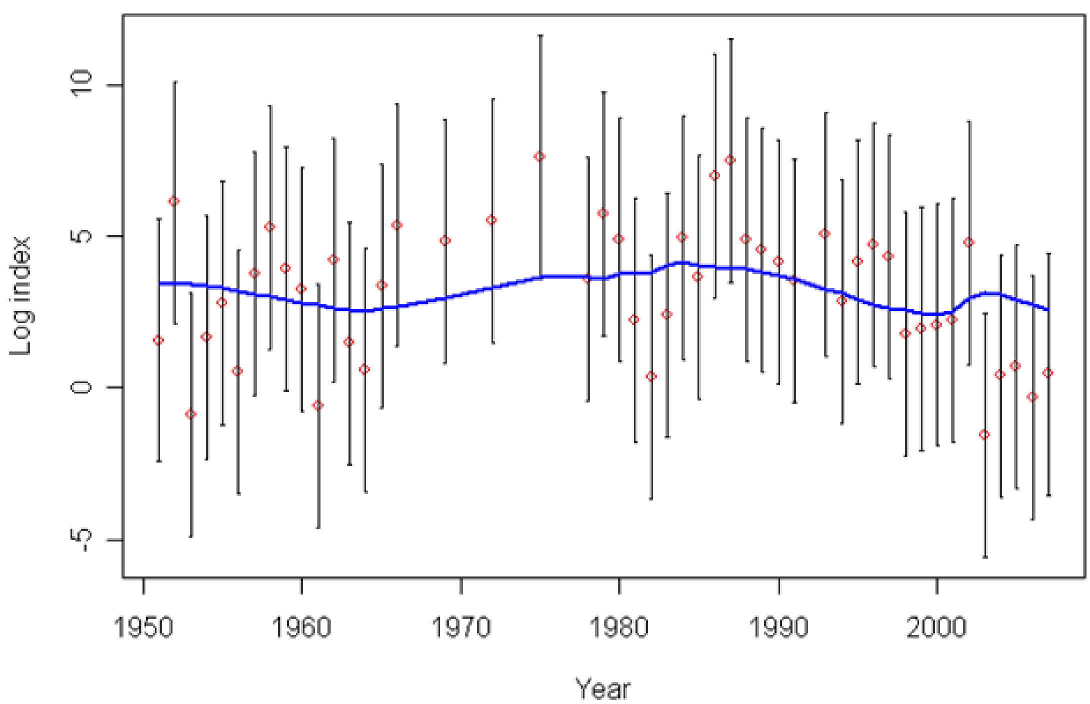


Figure 23. Top) Relationship of natural log of the daily hake larval production index (as a measure of hake spawning biomass, Lo et al. 2007) and the natural log of female spawning stock biomass as estimated from the 2007 hake assessment (Helser et al. 2007). Solid line is the expectation of a non-functional regression line and dotted lines represent prediction intervals about the regression. Bottom) Fits of SS2 model expected larval production index to observed larval production index. An estimate of unfished spawning biomass (SBzero) was obtained by taking the bias corrected back transformed predicted spawning biomass based on the average larval production index between 1951-1965.

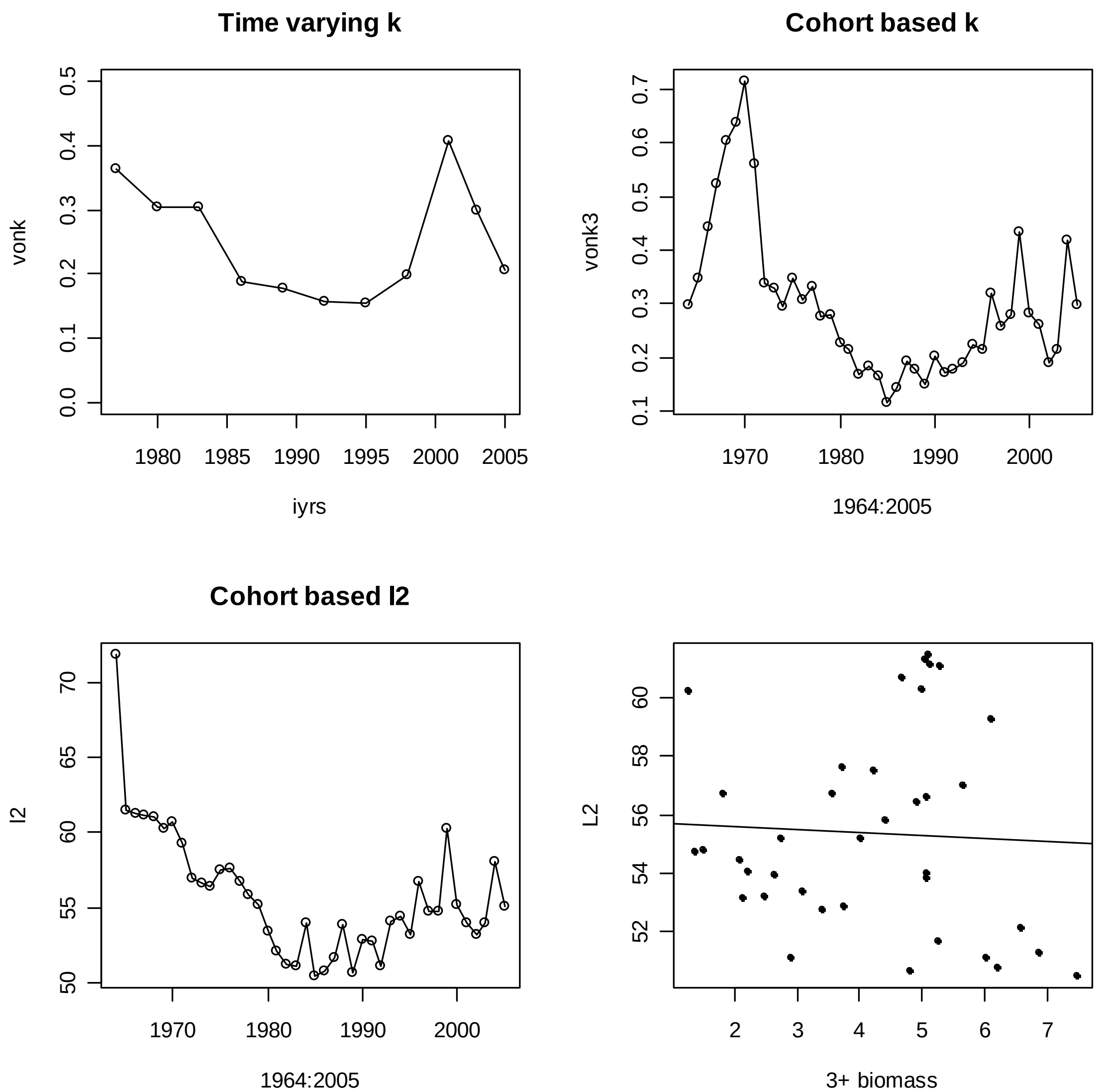


Figure 24. Time varying and cohort based fits of the von Bertalanffy growth model to Pacific hake age data from the acoustic survey, 1977-2005.

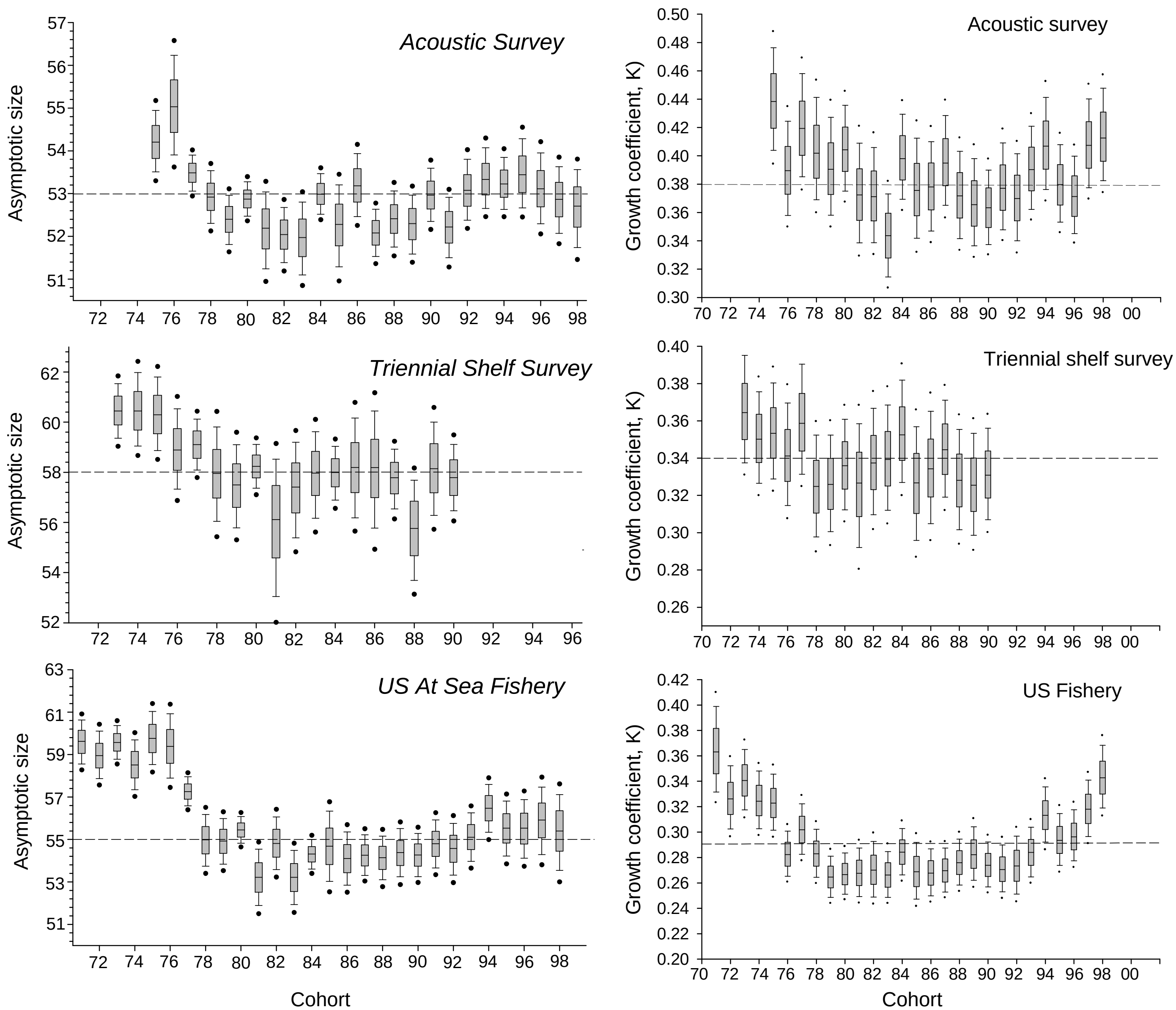


Figure 25. Results of a hierarchical von Bertalanffy growth model fit to three difference sources of Pacific hake growth data. A von Bertalanffy growth model was fit to each of the three data sources with age at length data combined and cohort treated as a random variable. The results show an early consistent decline in asymptotic size and instantaneous growth coefficient, k, in the early 1980s. Box whisker plots show the marginal posterior density of growth parameters, Lmax and K, for each cohort and the dotted line gives the overall mean parameter estimate.

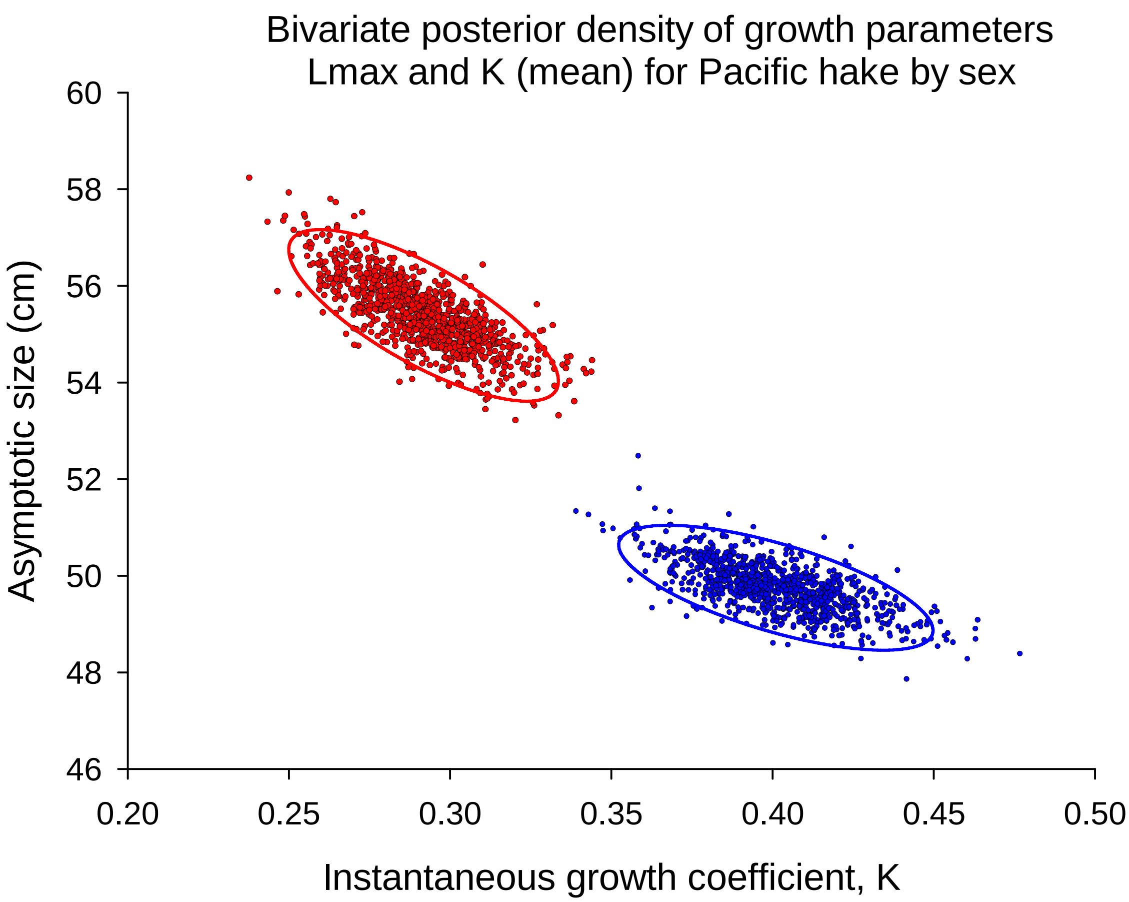


Figure 26. Results of a hierarchical von Bertalanffy growth model fit to Pacific hake growth data from the acoustic survey (all years, 1977-2007). A von Bertalanffy growth model was fit separately to each sex and cohort treated as a random variable. The results show that female pacific hake achieve a significantly larger size the males, but also growth at a slower rate. The dots show the bivariate distribution of Lmax and K from a sample of 1,000 draws from the joint posterior density and the solid ellipses give the 95% posterior interval.

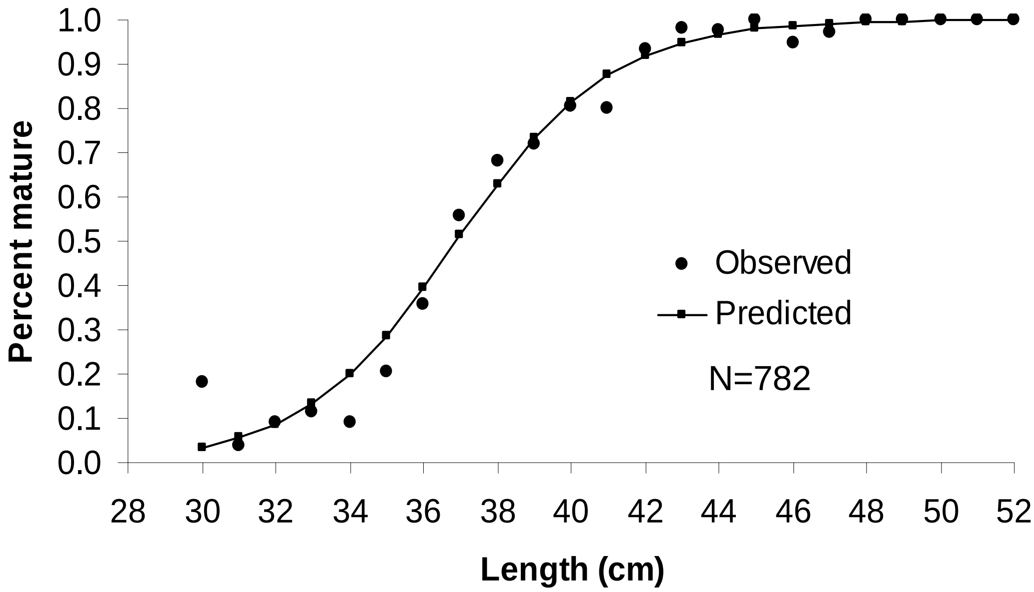


Figure 27. Observed and predicted fraction of Pacific hake mature at length.

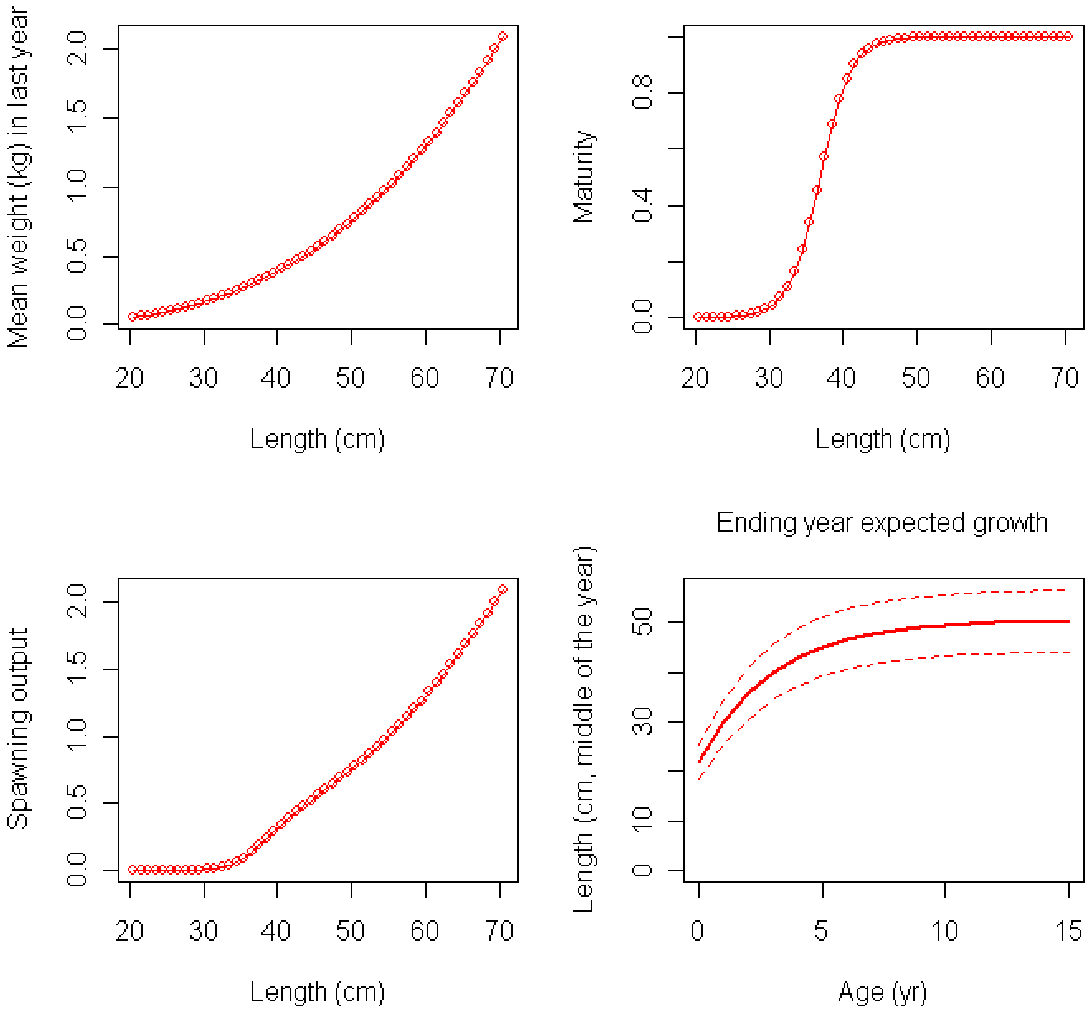
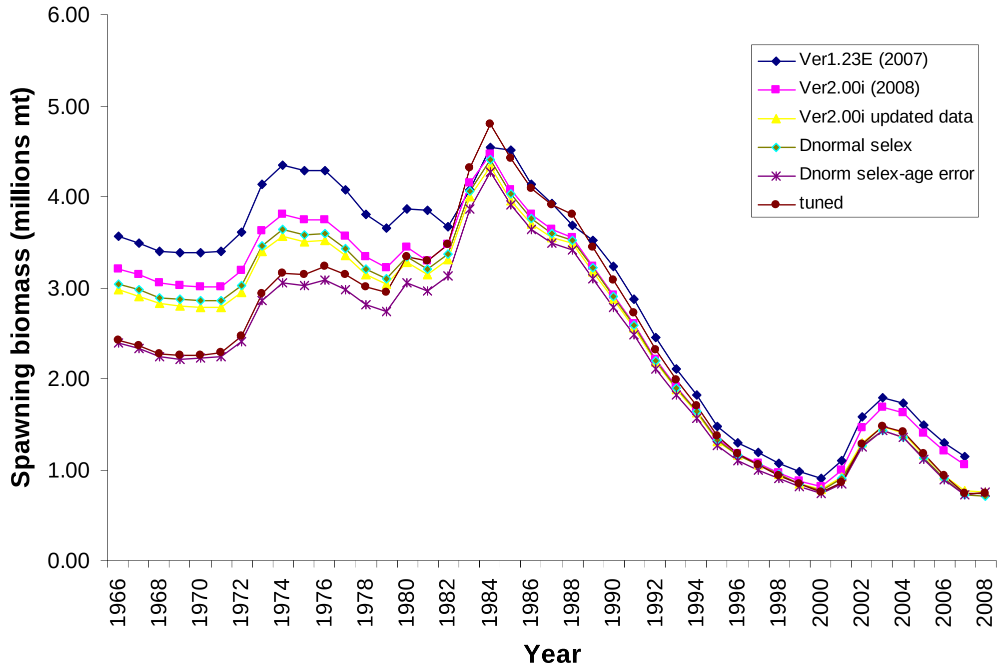


Figure 28. Biological parameters (functional forms) assumed in the hake model.



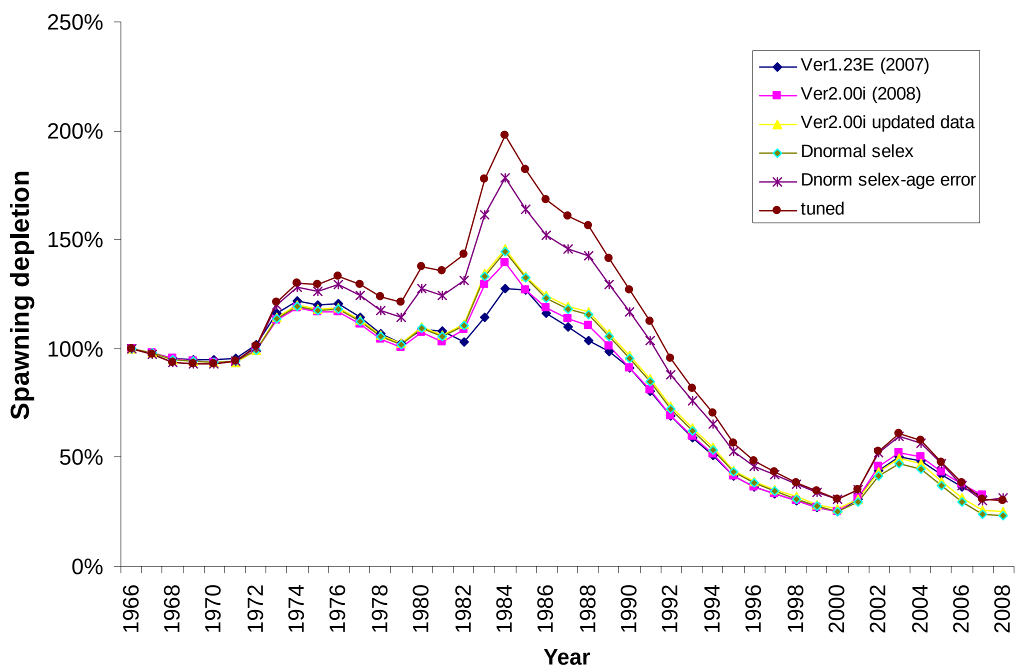


Figure 29. Time series of spawning biomass and depletion (% unfished biomass) from comparative assessment model results between the 2007 (Helser et. al. 2006) and the present assessment. The trends represent the sequence of changes made to the previous assessment including: 1) transition to the newest version of SS2 (Version 2.00n) with the same model structure and data through 2006, 2) SS2 (version 2.00n) with inclusion of updated fishery and acoustic survey data through 2007, 3) same as (2) but with implementation of the double normal selectivity function for the acoustic survey, 4) same as (3) but with implementation of aging error matrix, and 5) same as (4) with the model tuned.

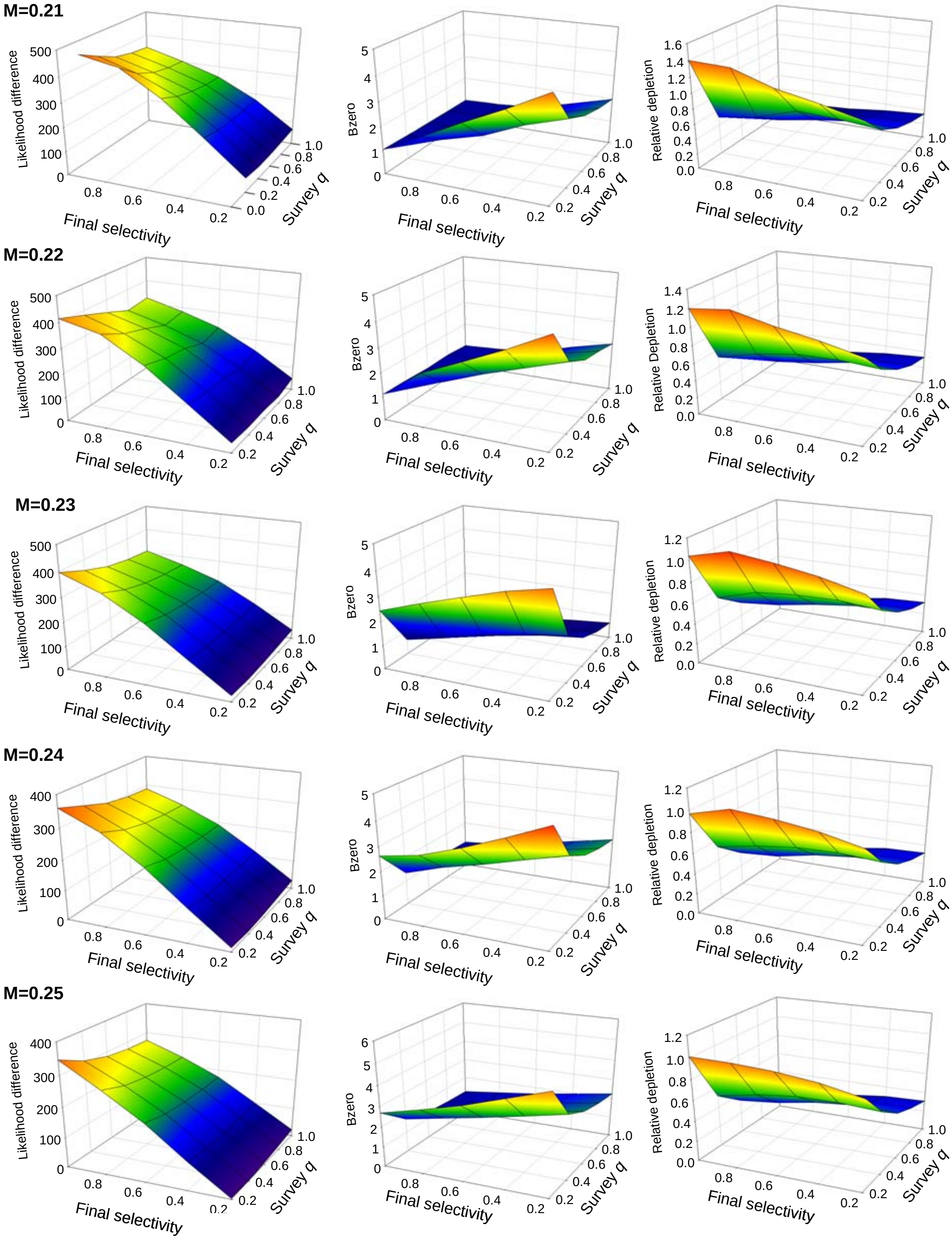


Figure 30. Results of profiling over 5 values of the acoustic survey selectivity at age 15 (0.2 to 1.0) within 5 values of the acoustic survey catchability, q (0.2 to 1.0), and within 5 values of natural mortality (0.21 to 0.25 by 0.01). The rows in the figure from top to bottom give the results for M=0.21, 0.22, 0.23, 0.24, and 0.25.

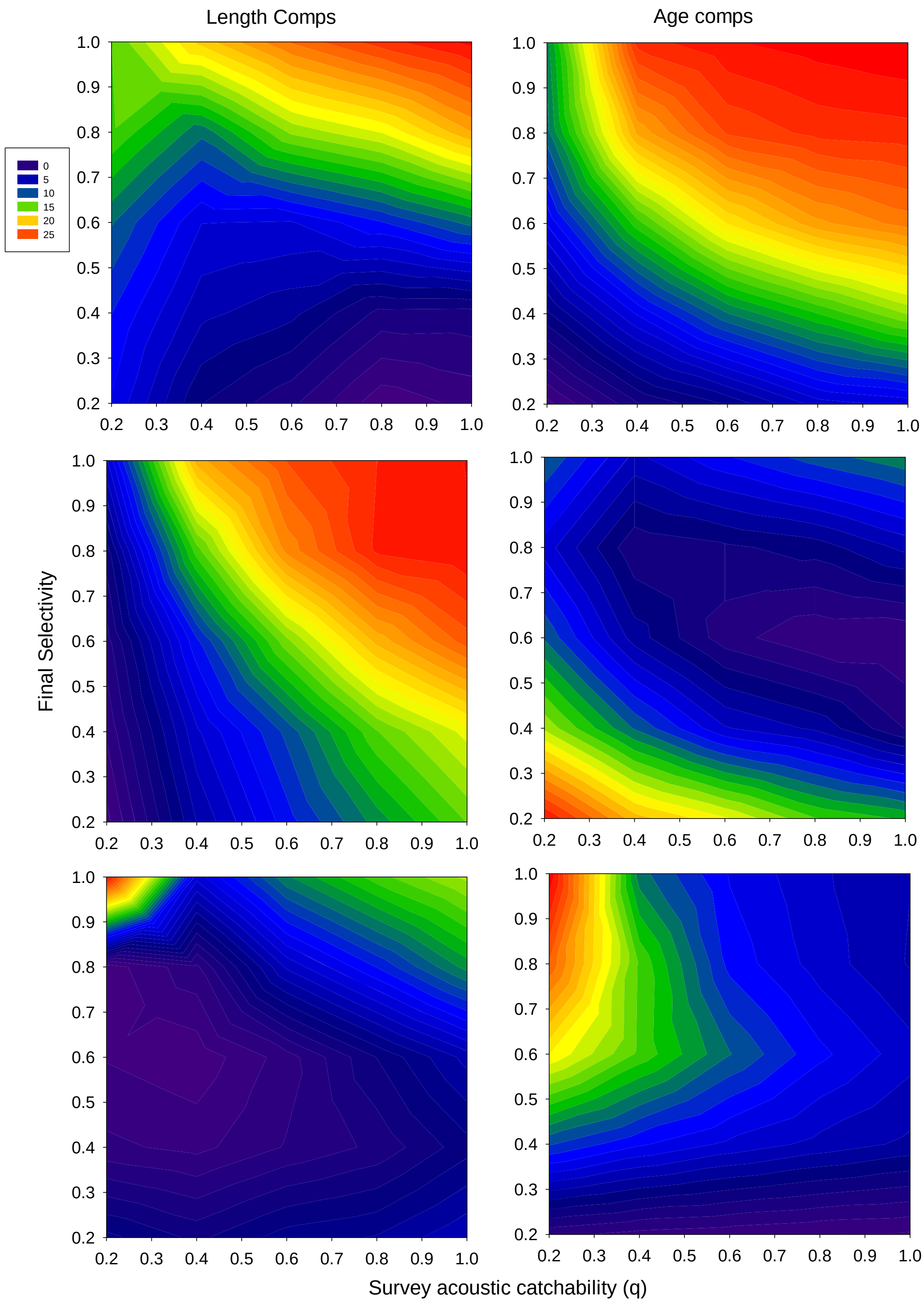


Figure 31. Contour plots showing changes in individual likelihood components for the US fishery (top row), Canadian fishery (middle row) and Acoustic survey (bottom row) length and age compositions as a function of final acoustic survey electivity at age 15 (0.2 to 1.0) and acoustic survey catchability, q (0.2 to 1.0). These results are shown for the M=0.23 run.

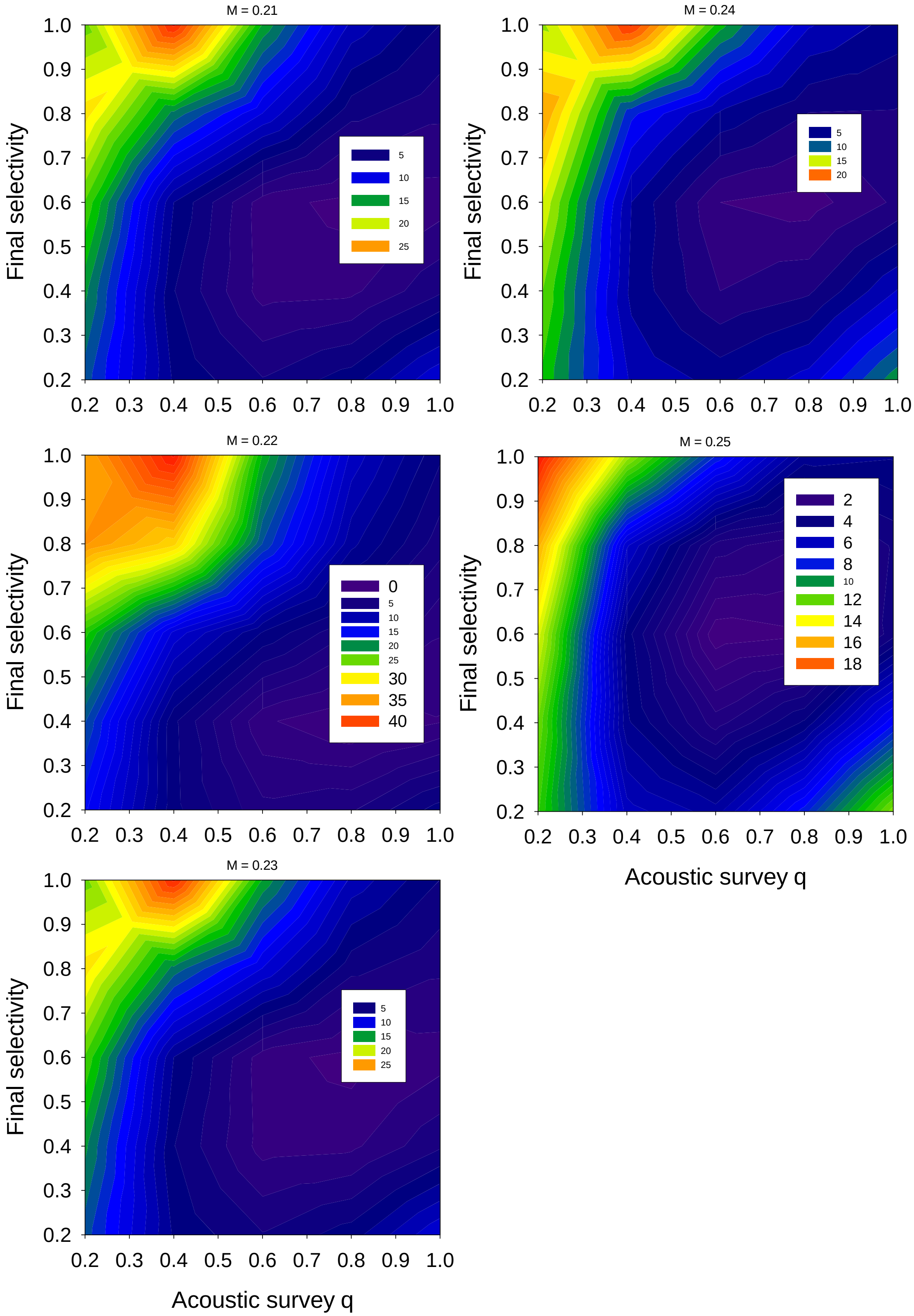


Figure 32. Contour plots showing changes in individual likelihood components for the Acoustic survey biomass index as a function of final acoustic survey electivity at age 15 (0.2 to 1.0) and acoustic survey catchability, q (0.2 to 1.0) and five different values of natural mortality.

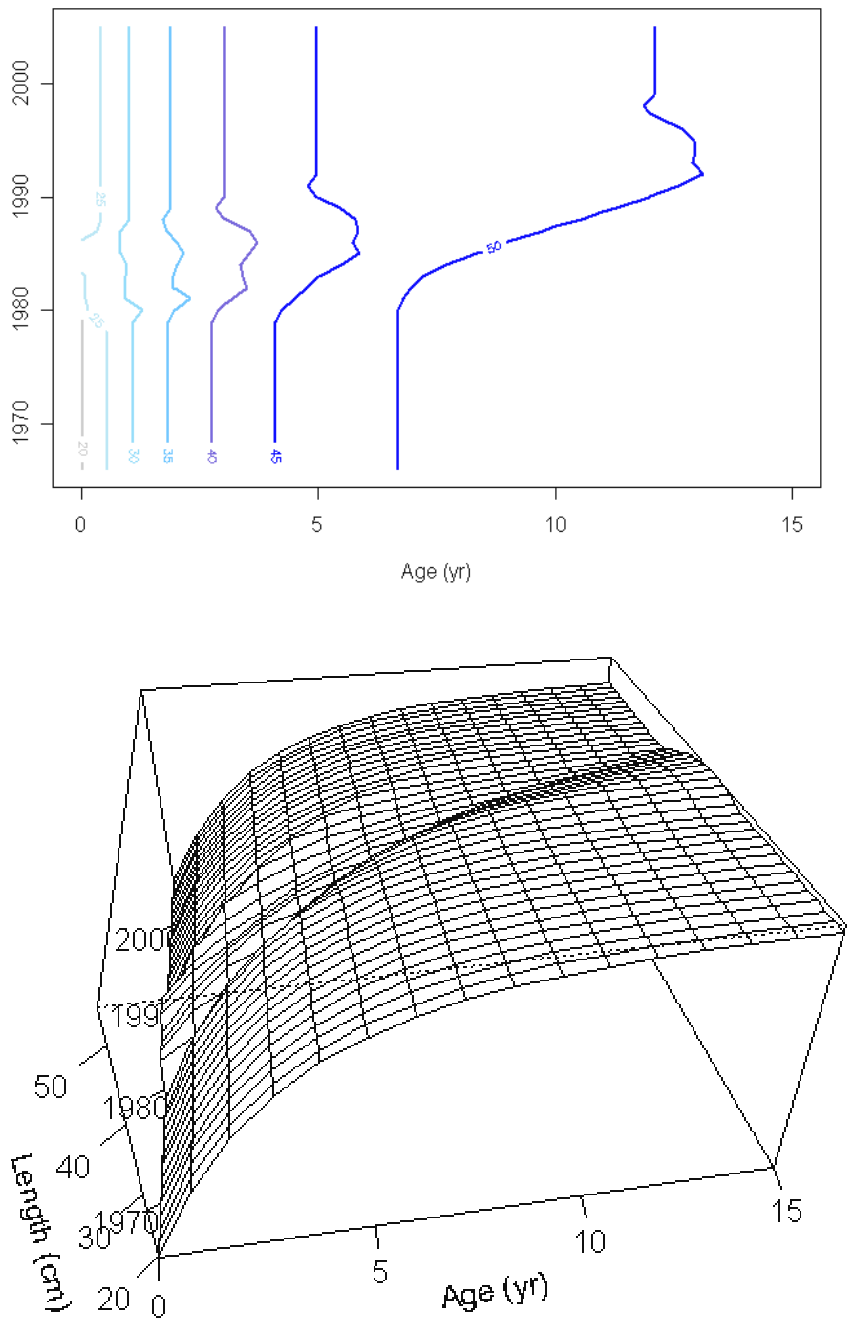


Figure 33. Time varying trajectory of growth in size at age estimated for Pacific hake.

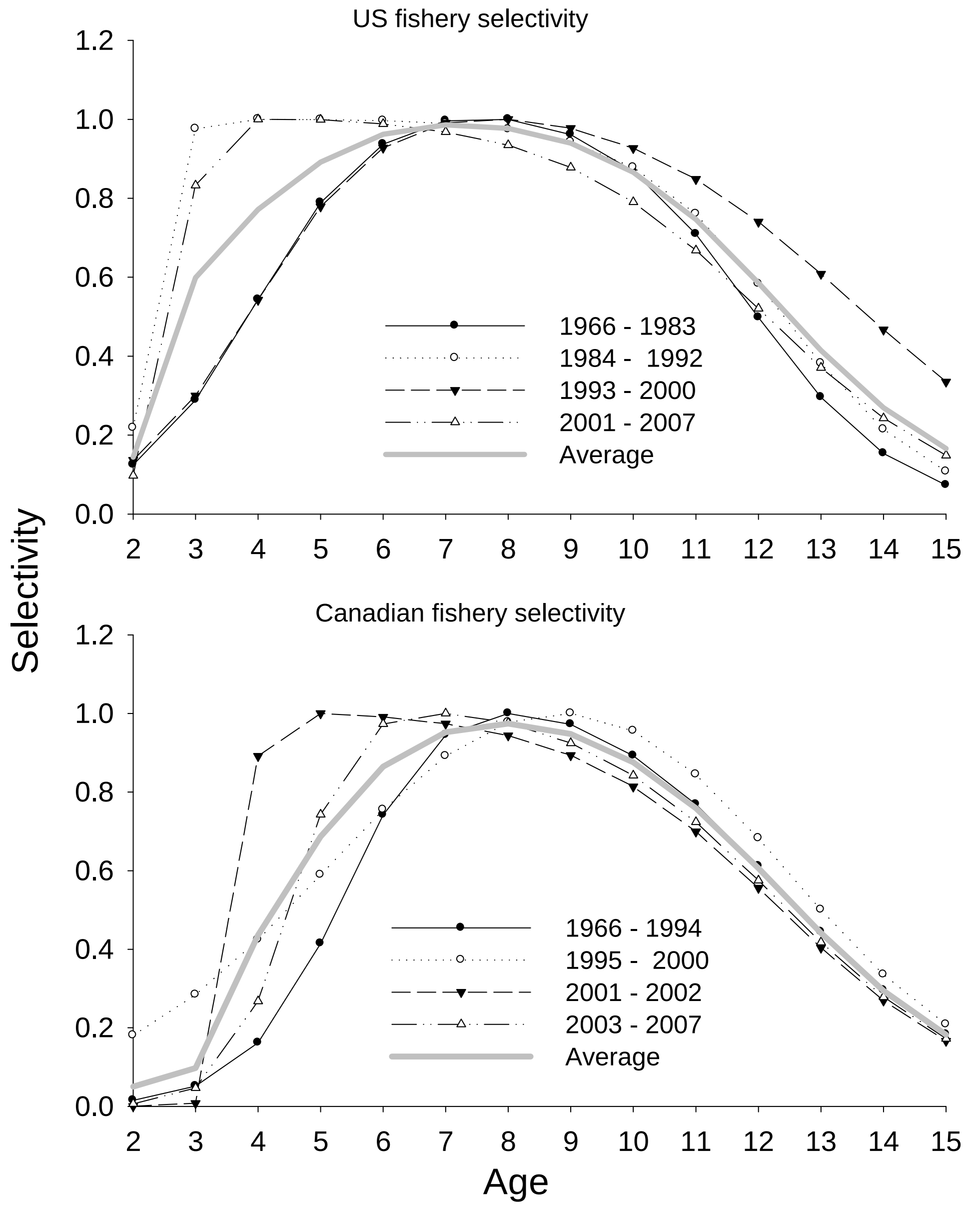


Figure 34. Estimated selectivity curves for different time blocks in the U.S. fishery, Canadian fishery and acoustic survey. Selectivity in the acoustic survey was assumed to be time-invariant with the final selectivity at age 15 fixed at 0.5. The ascending limb was freely estimated.

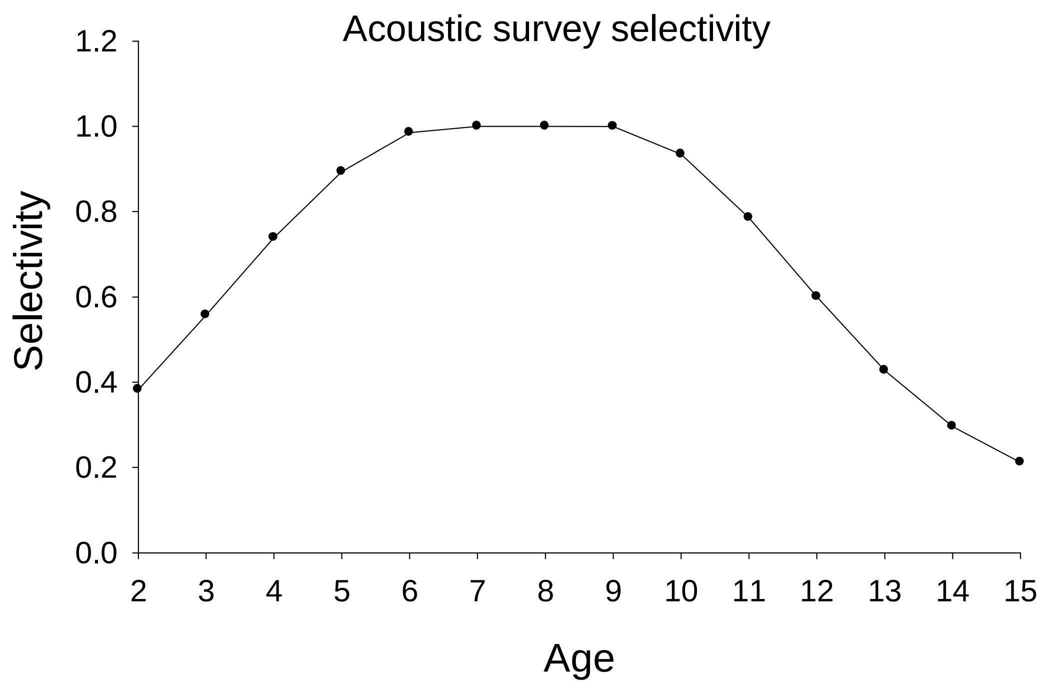


Figure 34. Continued. Estimated selectivity curve for the acoustic survey selectivity (assumed to be time invariant).

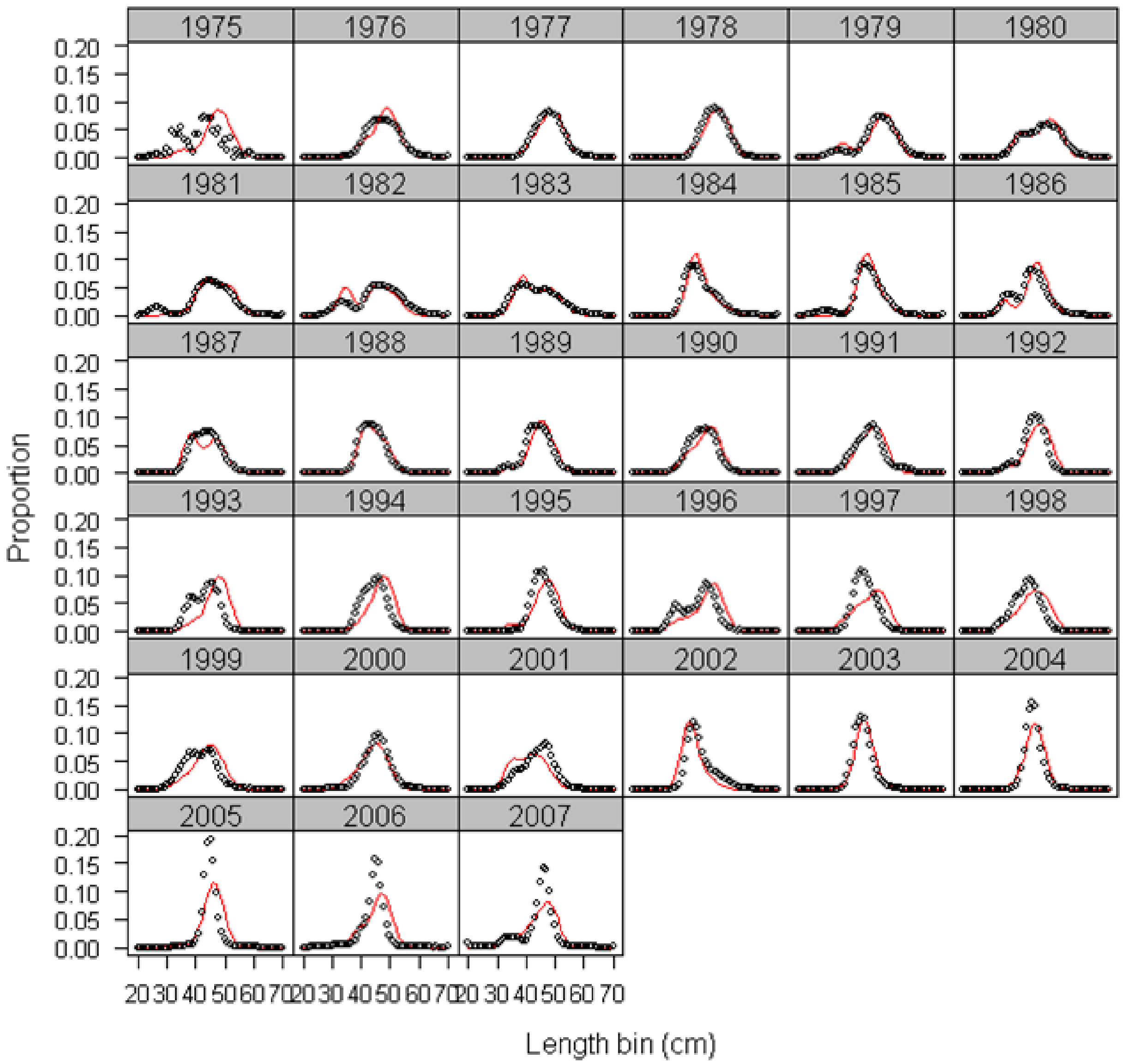


Figure 35. Predicted fits to the observed U.S. fishery length composition data.

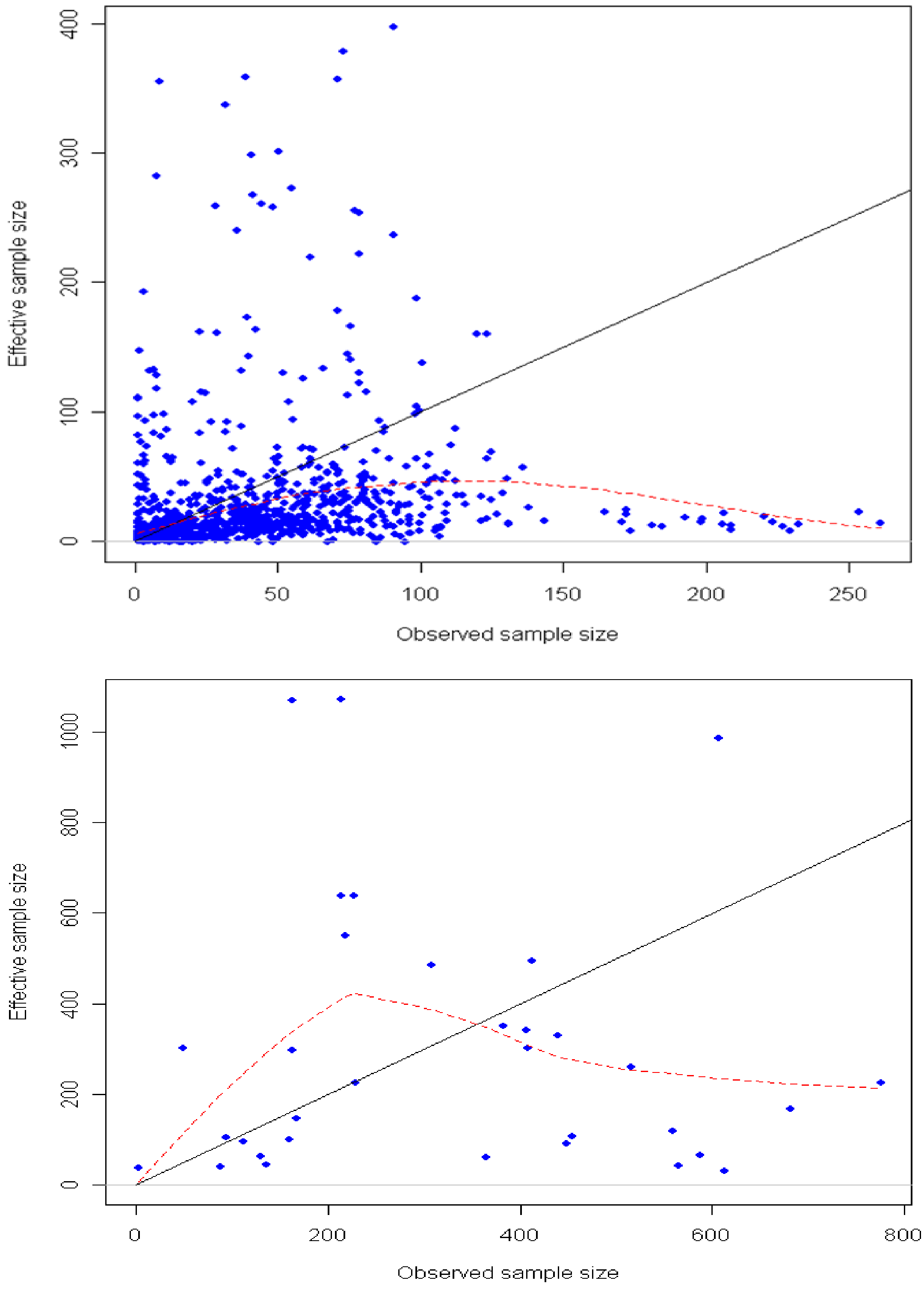


Figure 36. Plot of effective vs. observed input sample sizes for the U.S. fishery conditional age at length compositions (top) and length compositions (bottom).

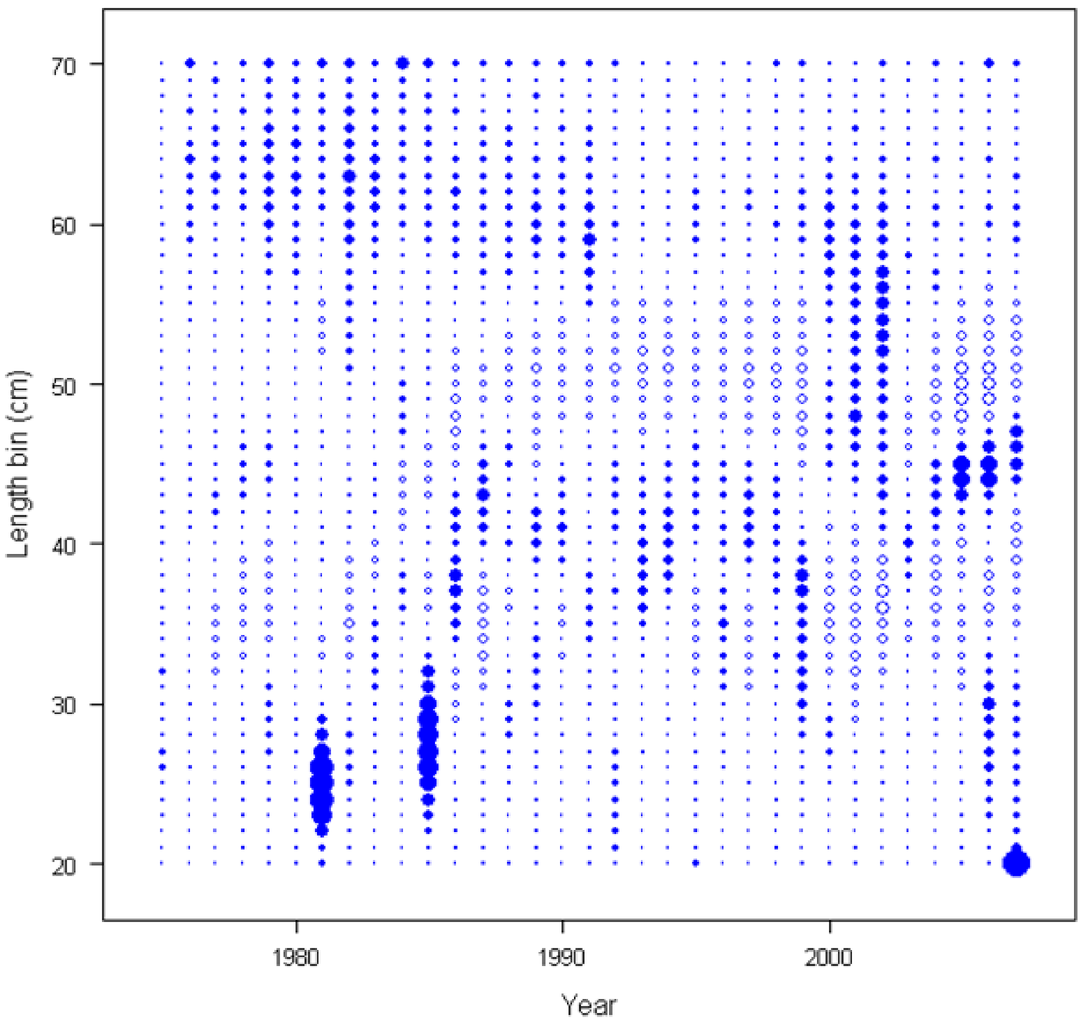


Figure 37. Pearson residuals of model fits to the U.S. fishery length composition data

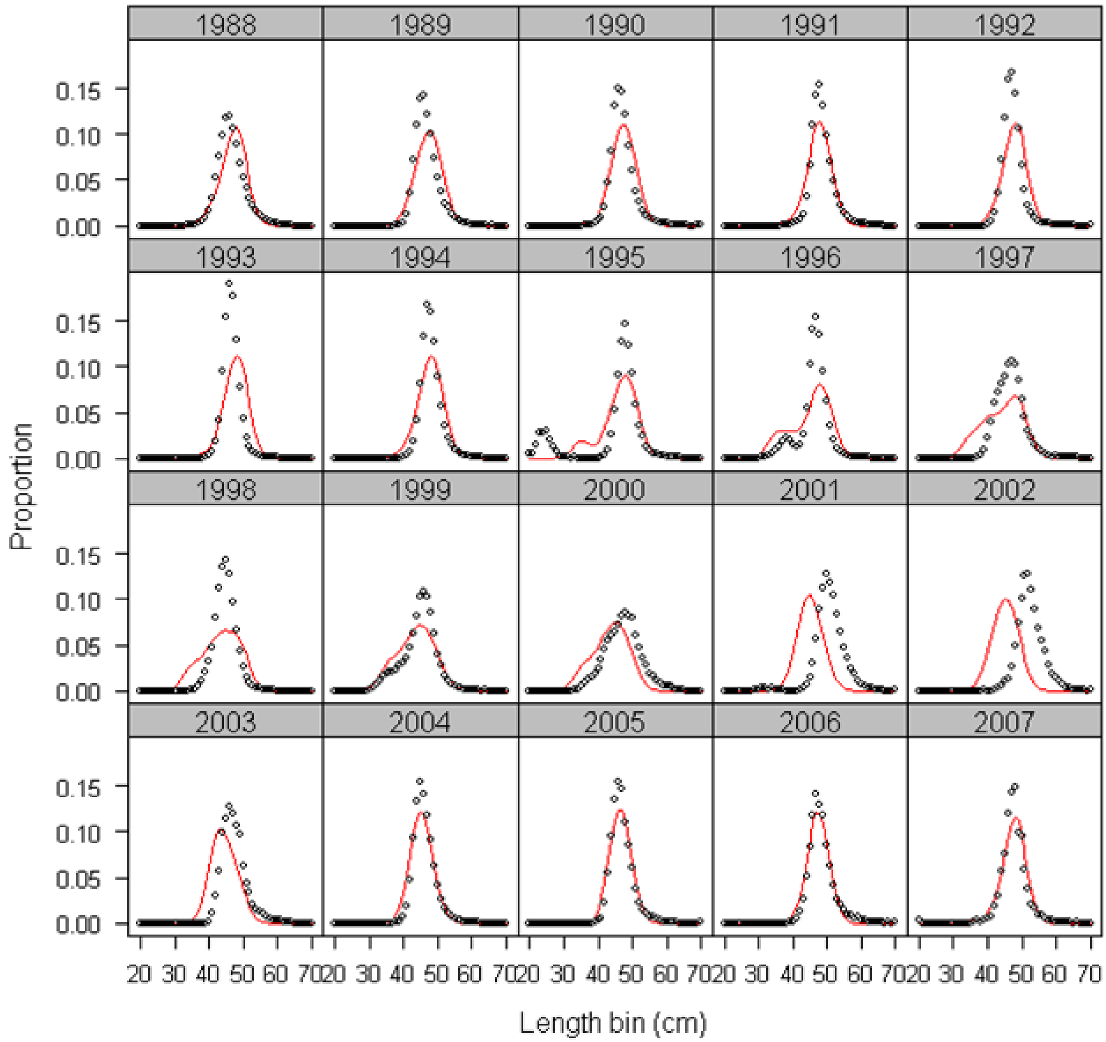


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Figure 38. Predicted fits to the observed Canadian fishery length composition data.

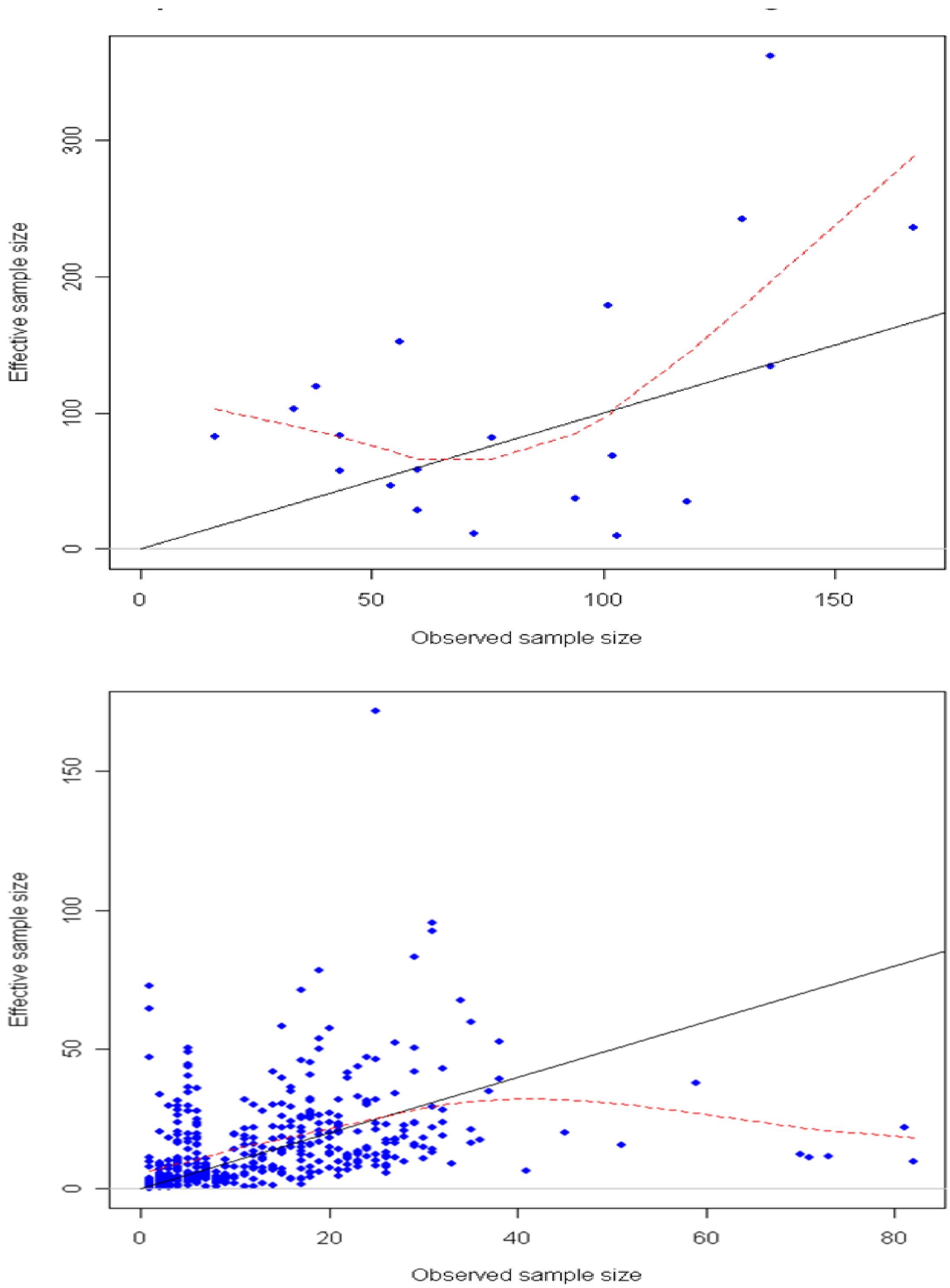

Figure 39. Plot of effective vs. observed input sample sizes for the Canadian fishery conditional age at length compositions (top) and length compositions (bottom).

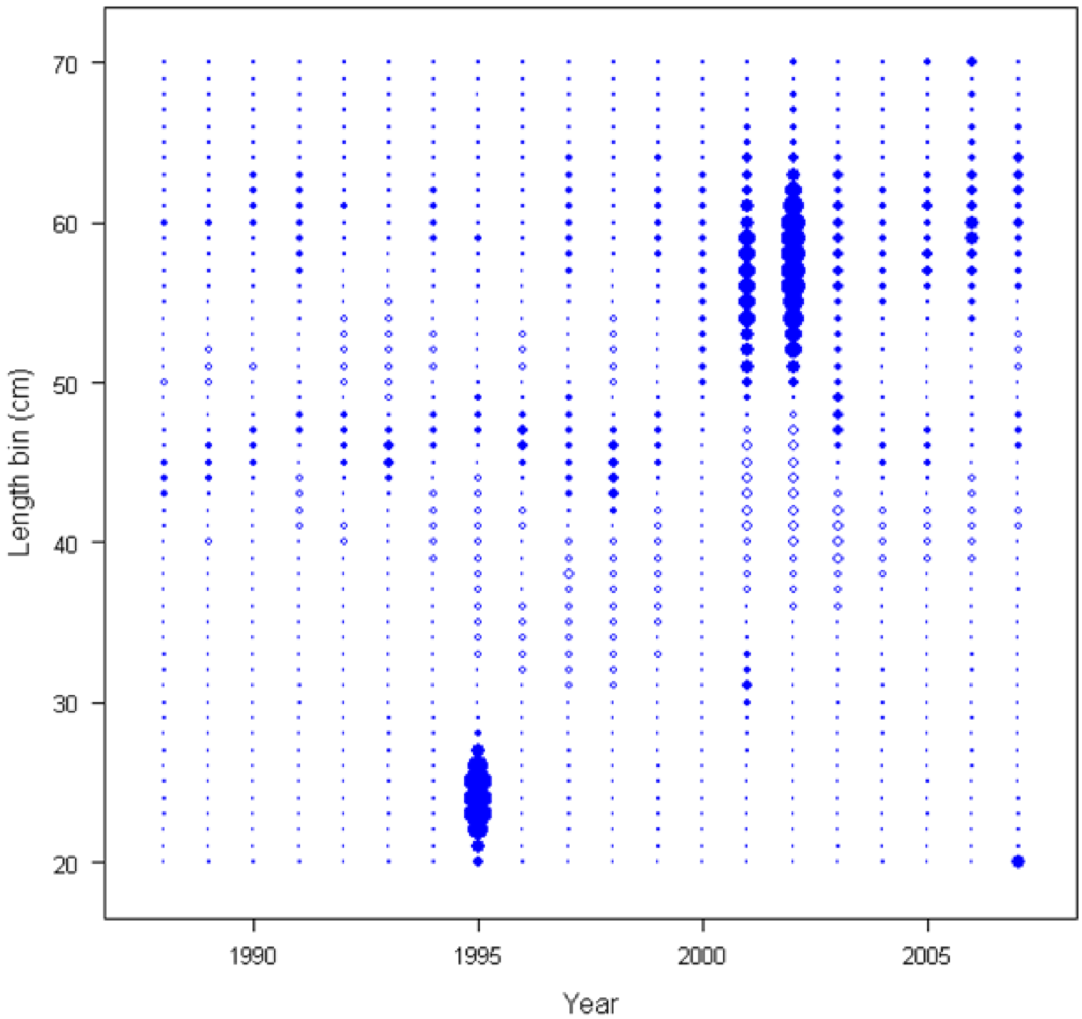

Figure 40. Pearson residuals of model fits to the Canadian length composition data.

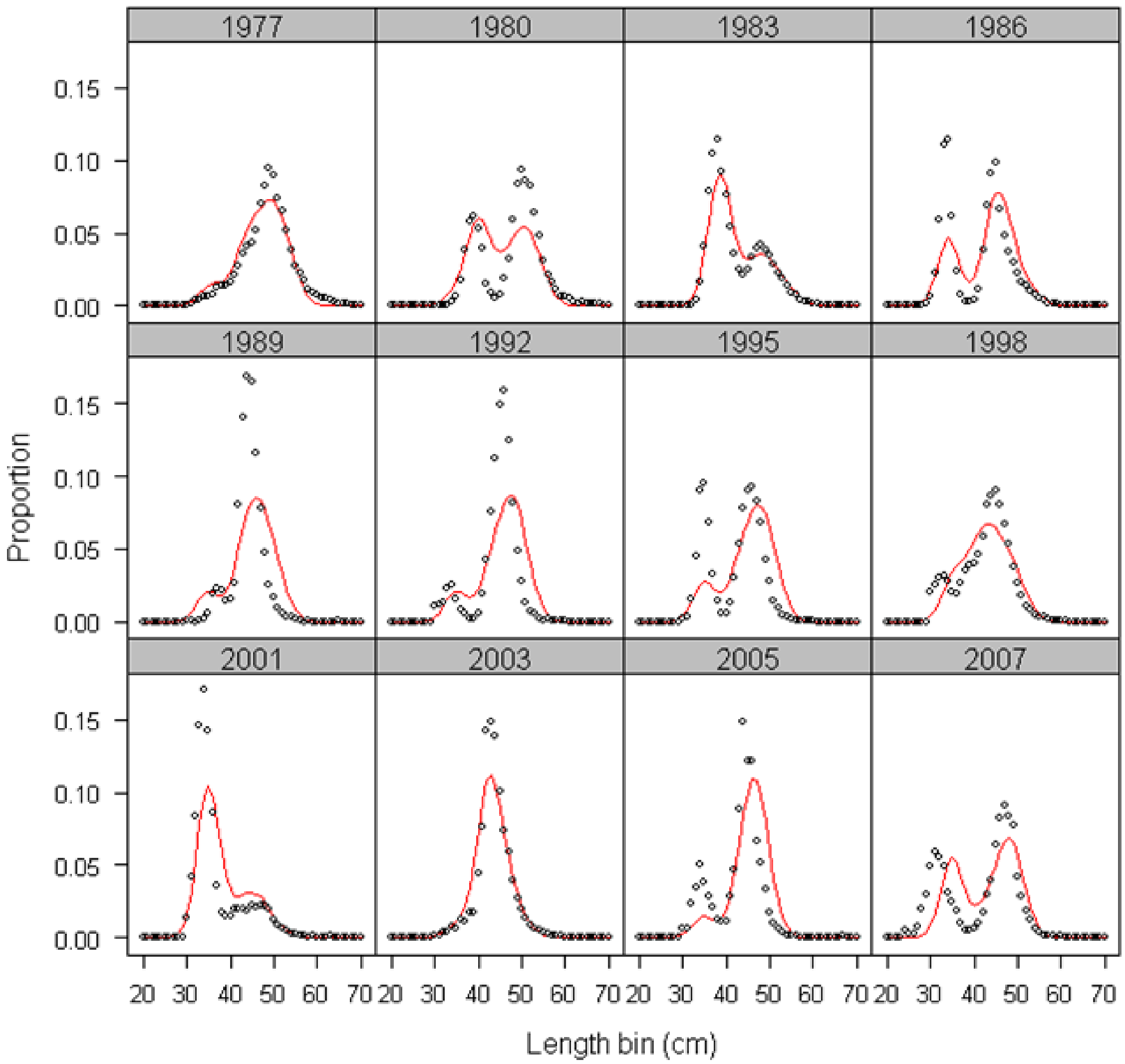

Figure 41. Predicted fits to the observed acoustic survey length composition data.

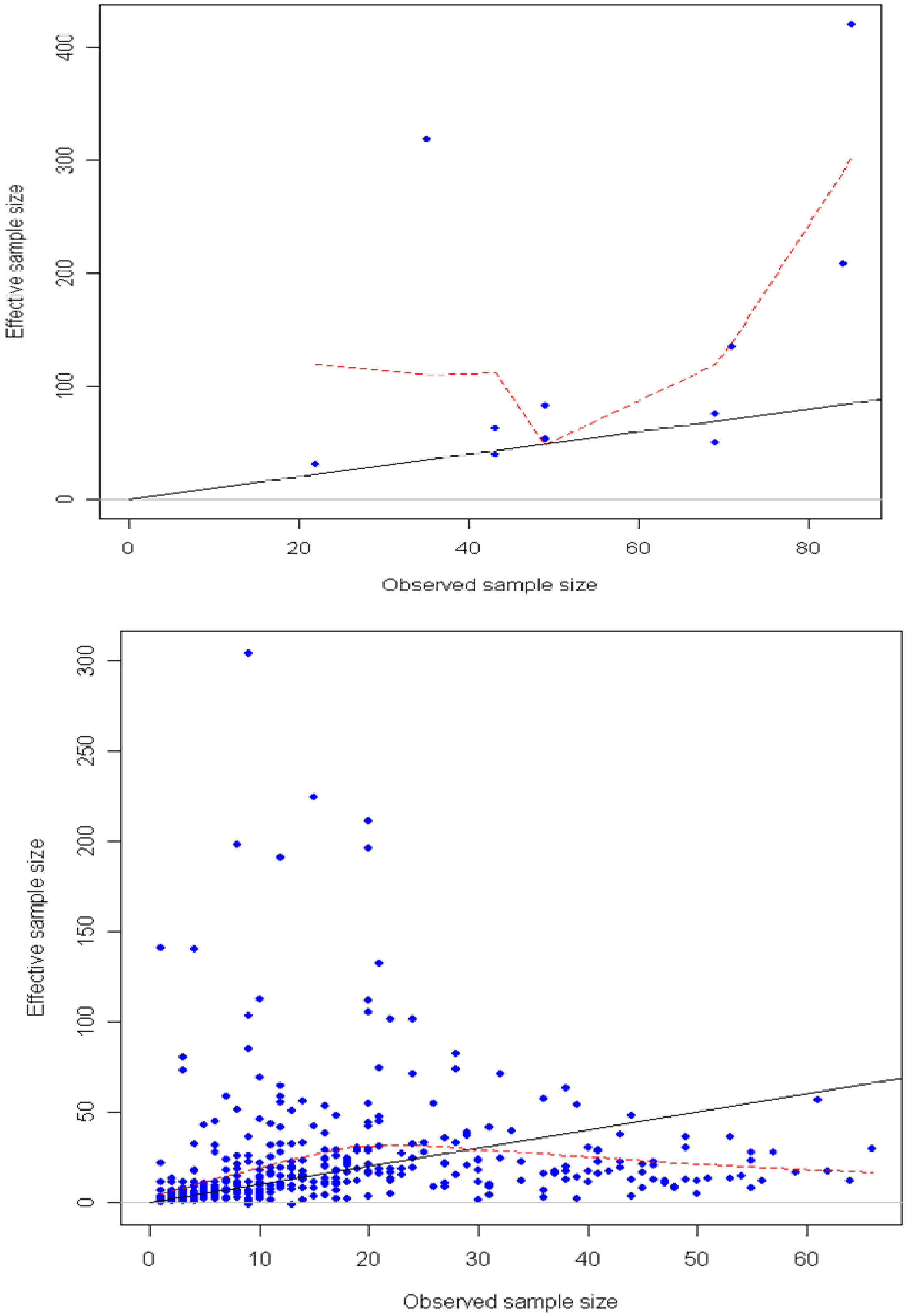

Figure 42. Plot of effective vs. observed input sample sizes for the acoustic survey conditional age at length compositions (top) and length compositions (bottom).

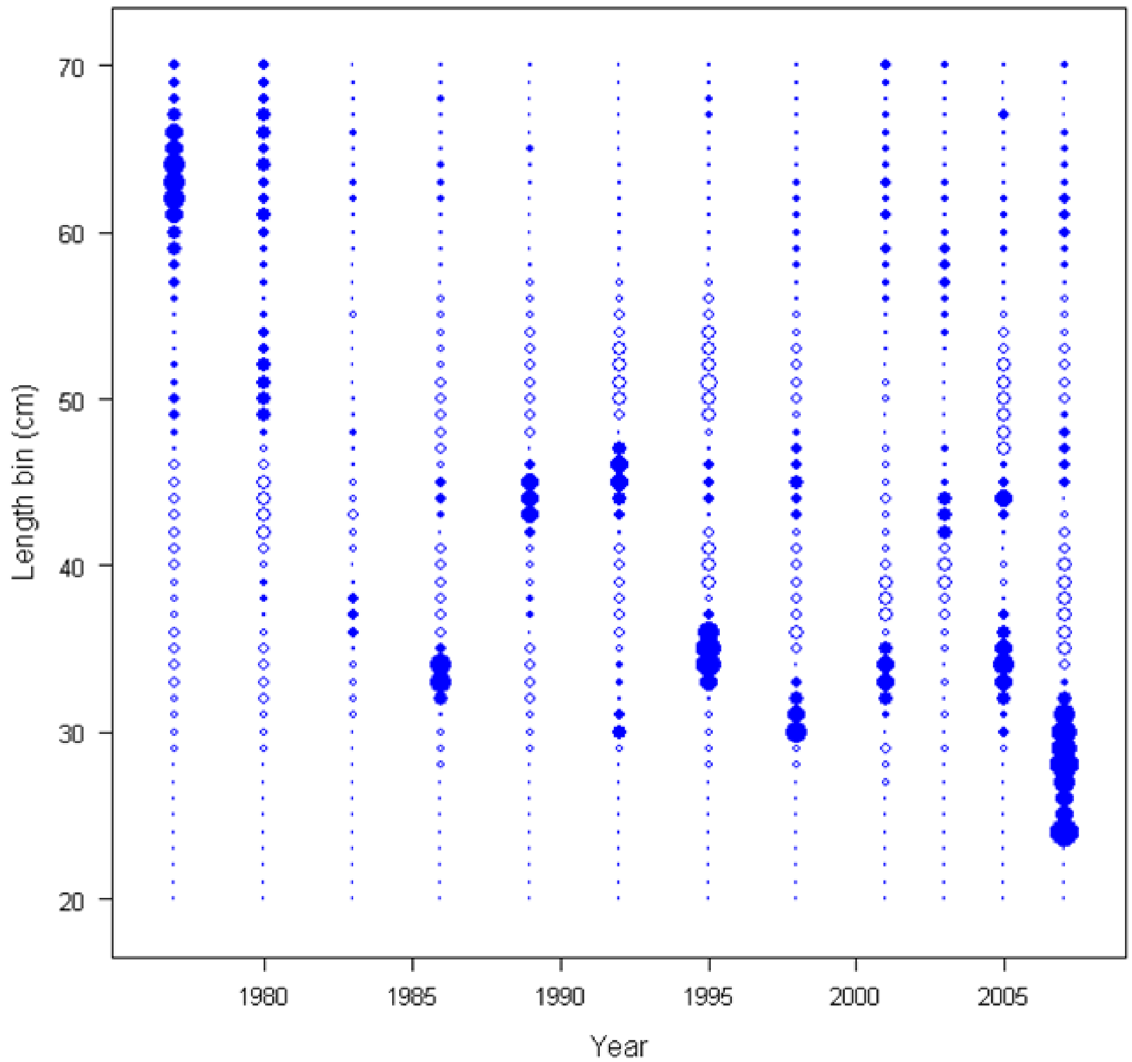

Figure 43. Pearson residuals of model fits to the acoustic survey length composition data.

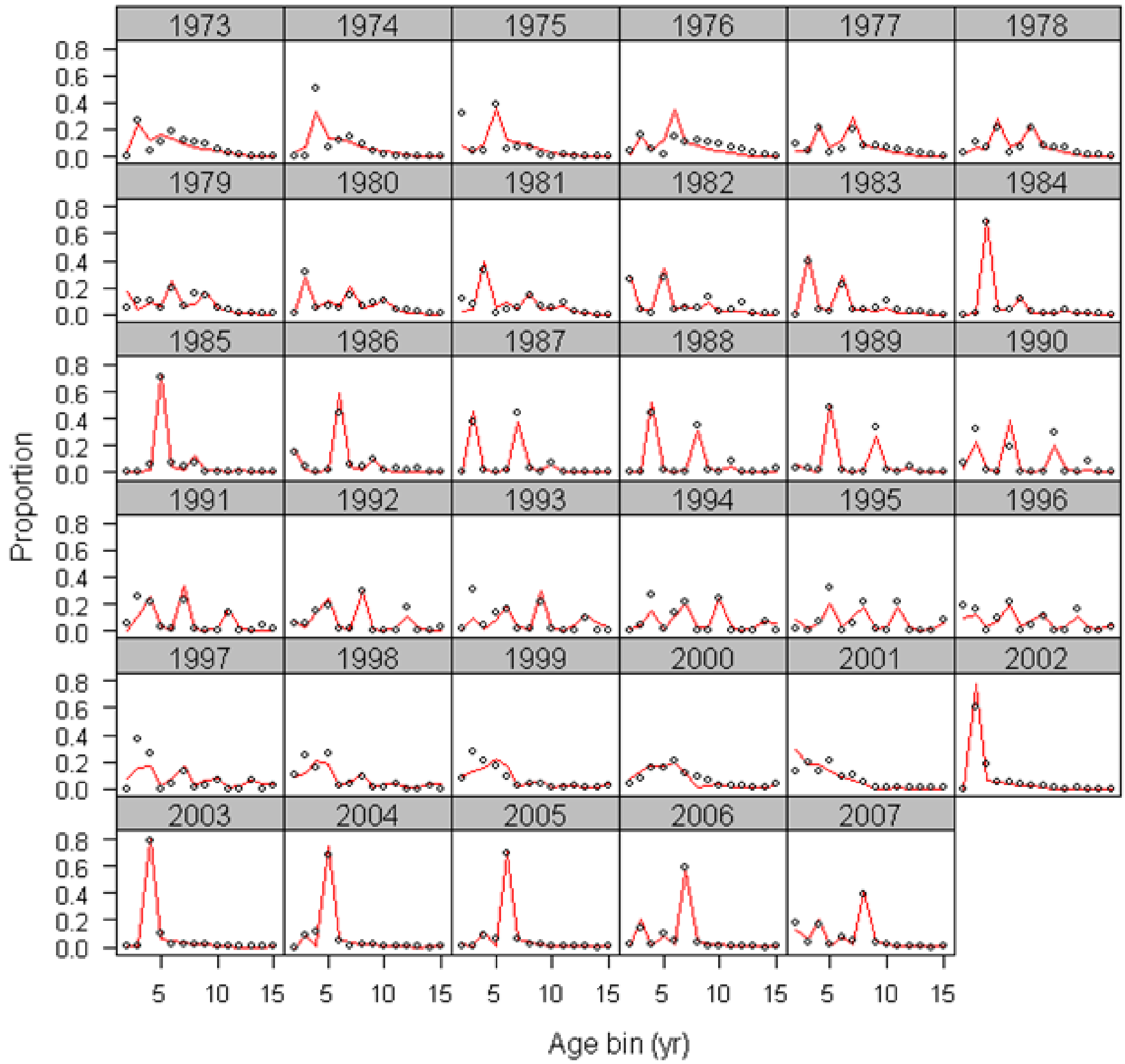

Figure 44. Predicted (implied) fits to the observed U.S. fishery age composition data.

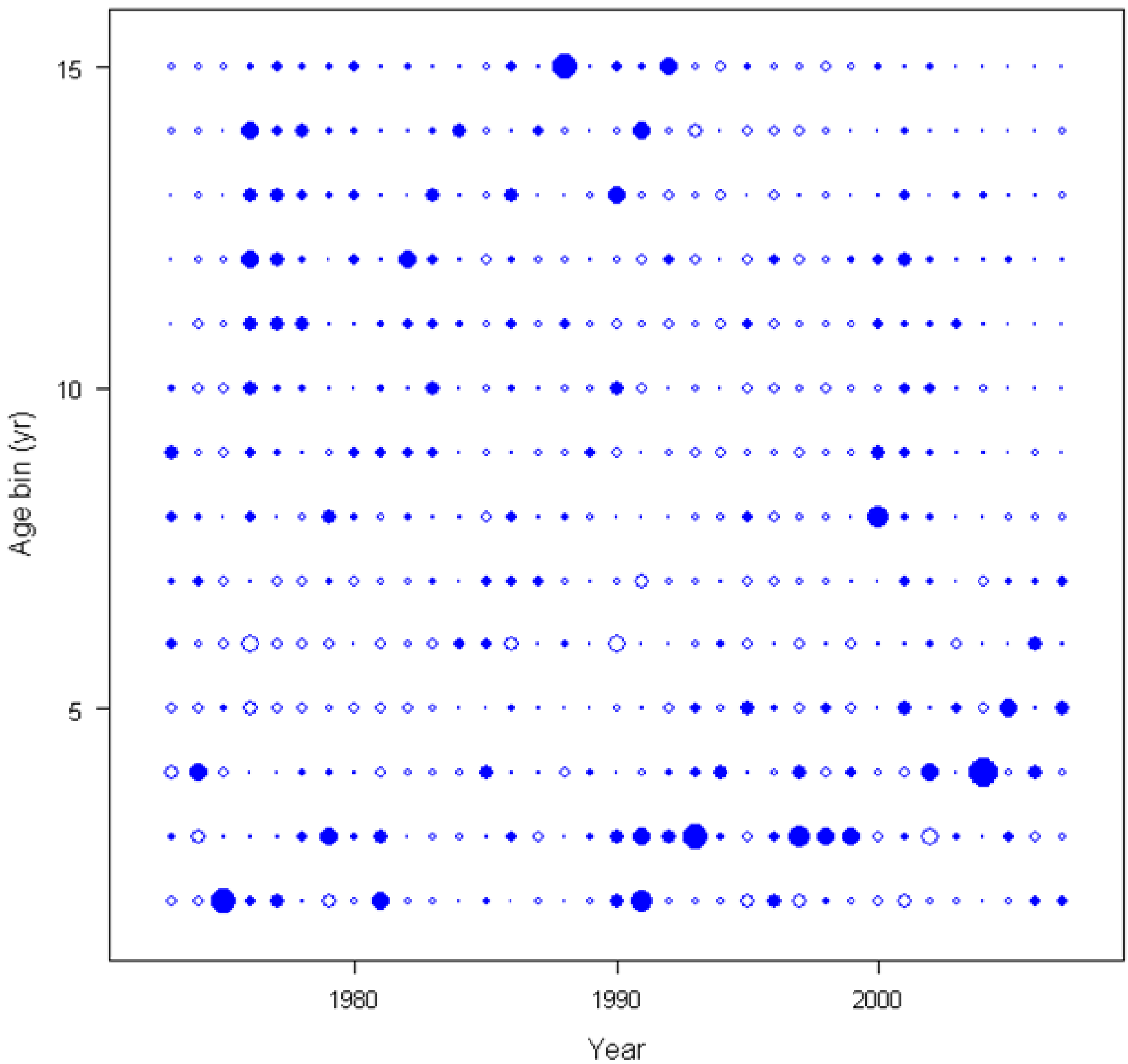

Figure 45. Pearson residuals of model fits to the acoustic survey age composition data.

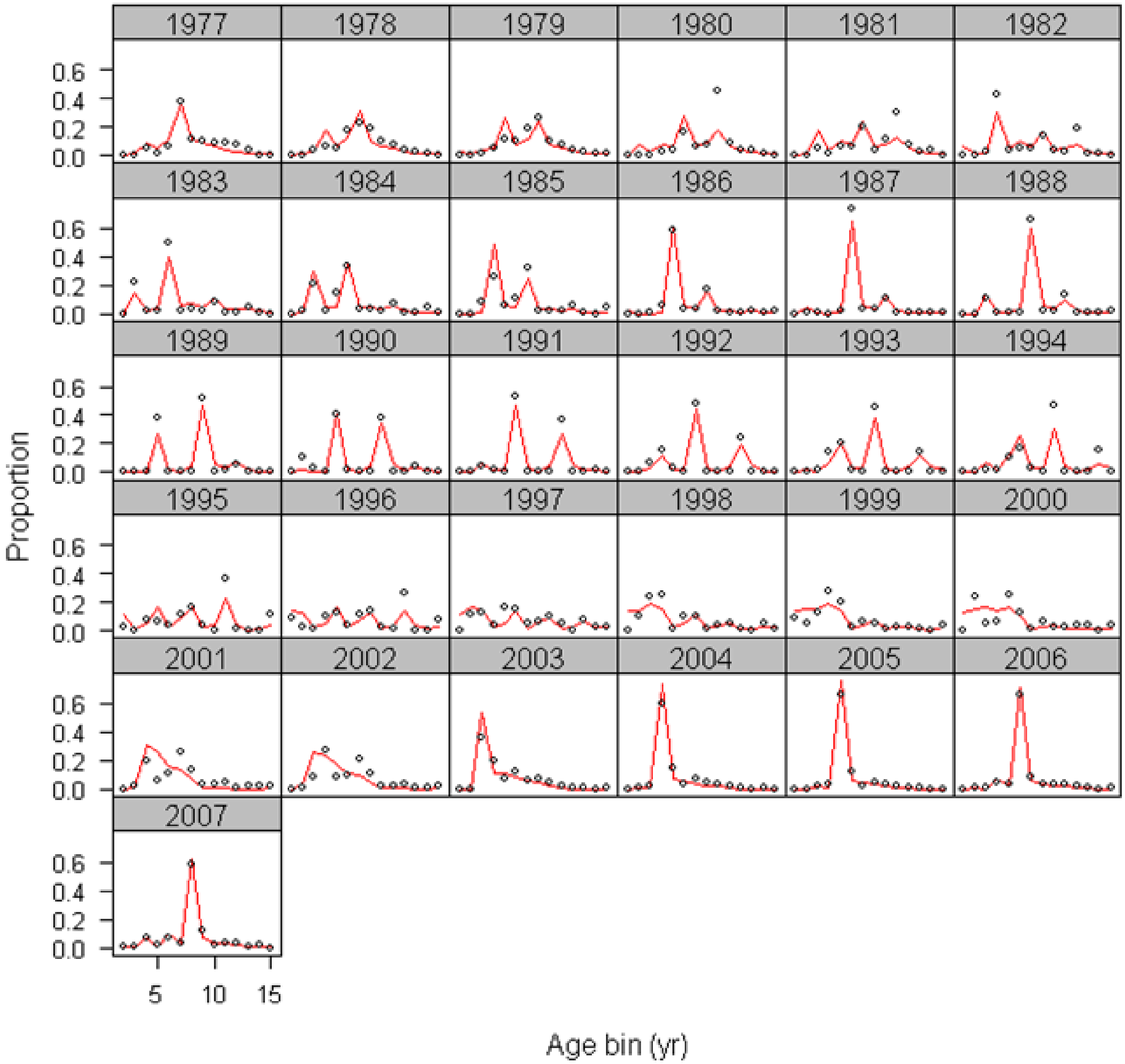

Figure 46. Predicted fits (implied) to the observed Canadian fishery age composition data.

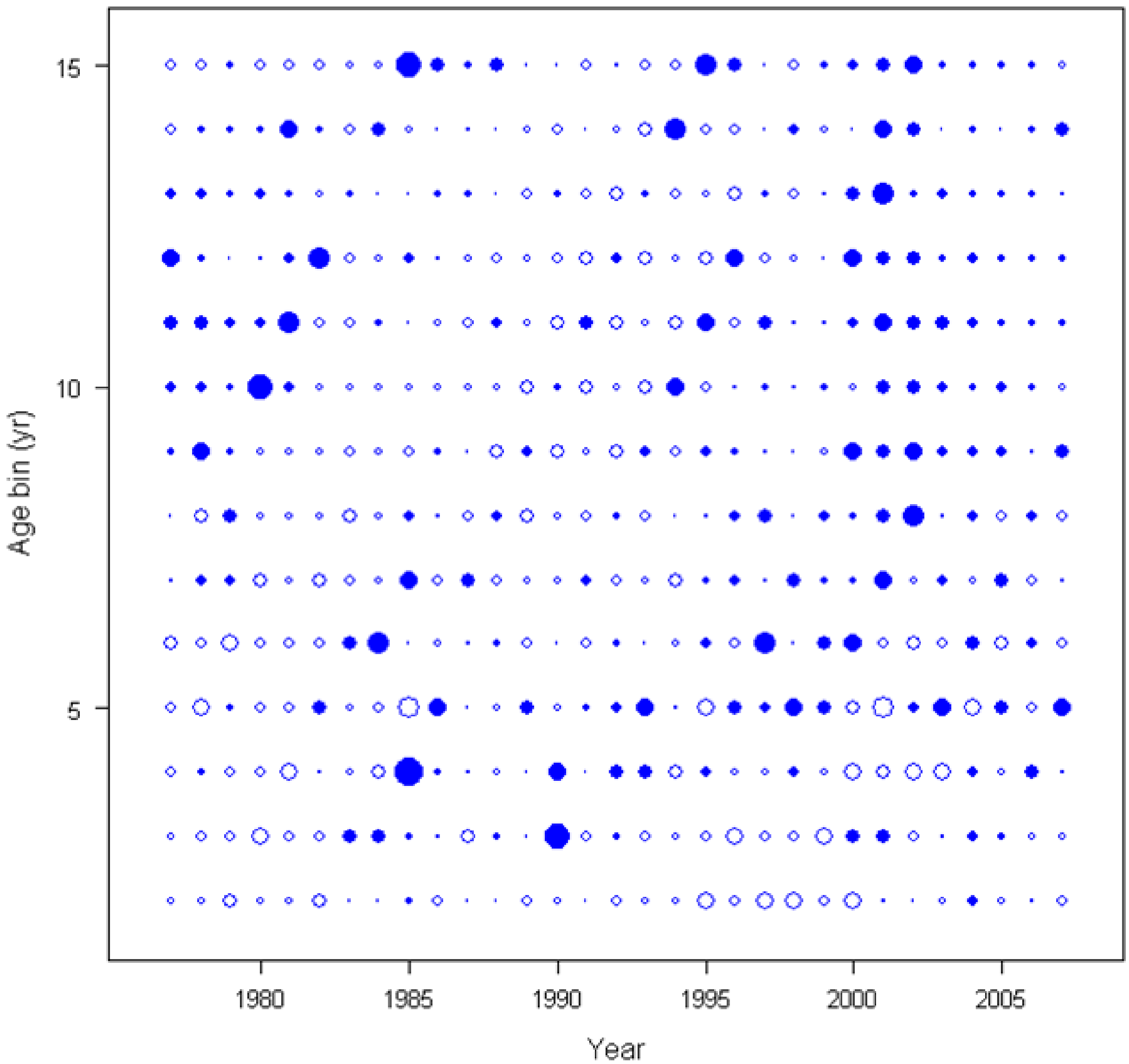

Figure 47. Pearson residuals of model fits to the Canadian fishery age composition data.

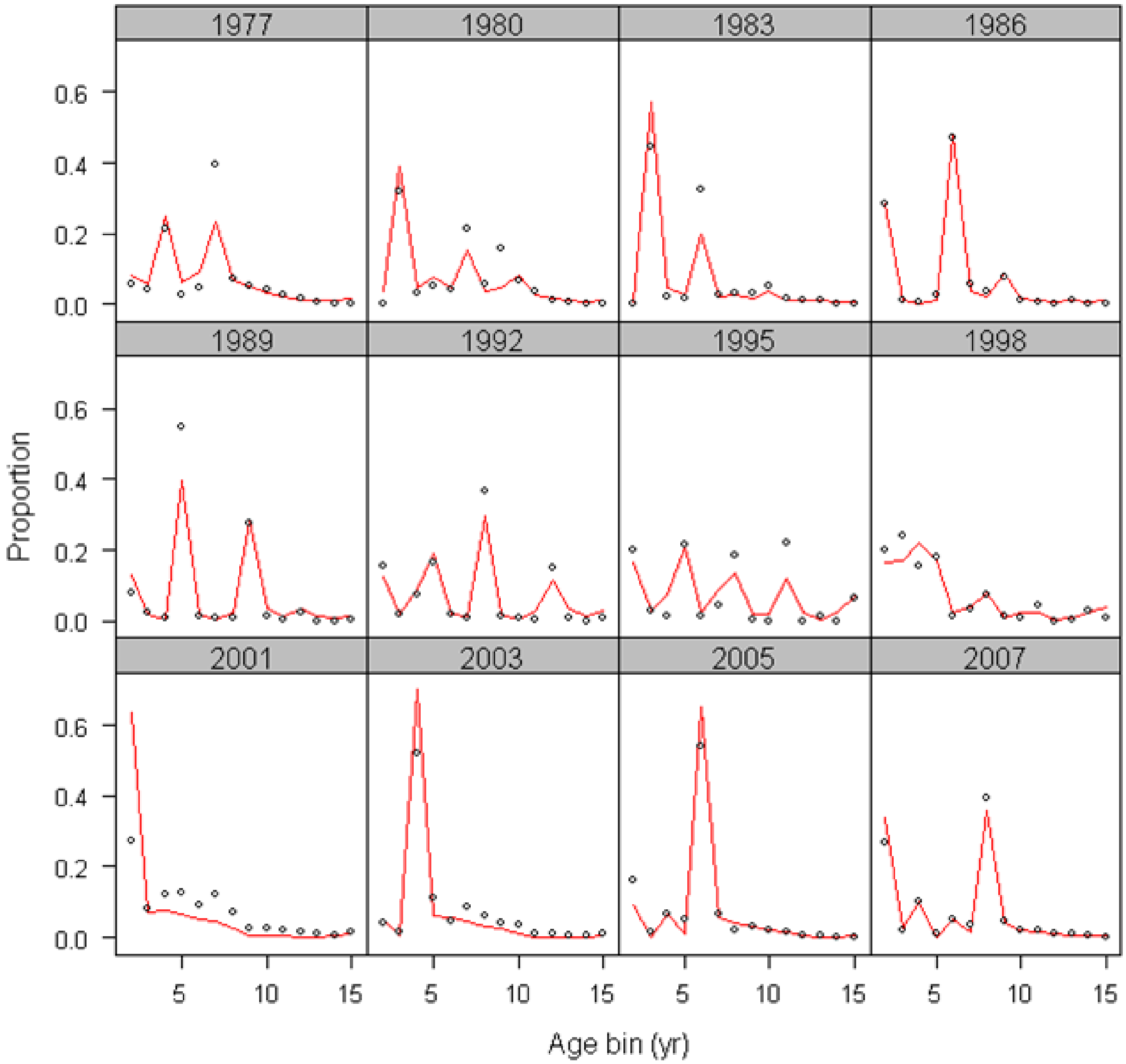

Figure 48. Predicted (implied) fits to the observed acoustic survey age composition data.

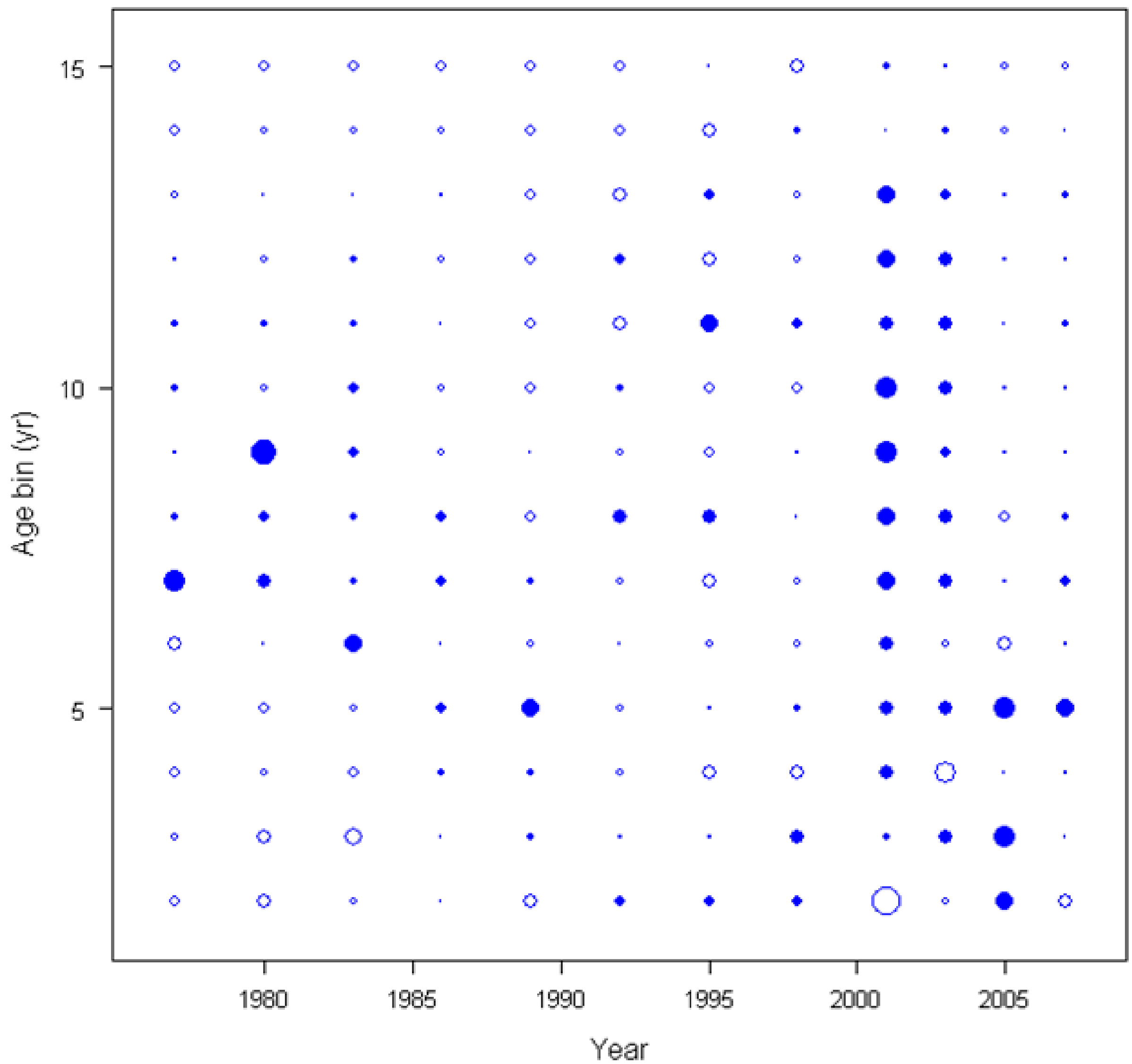

Figure 49. Pearson residuals of model fits to the acoustic survey age composition data.

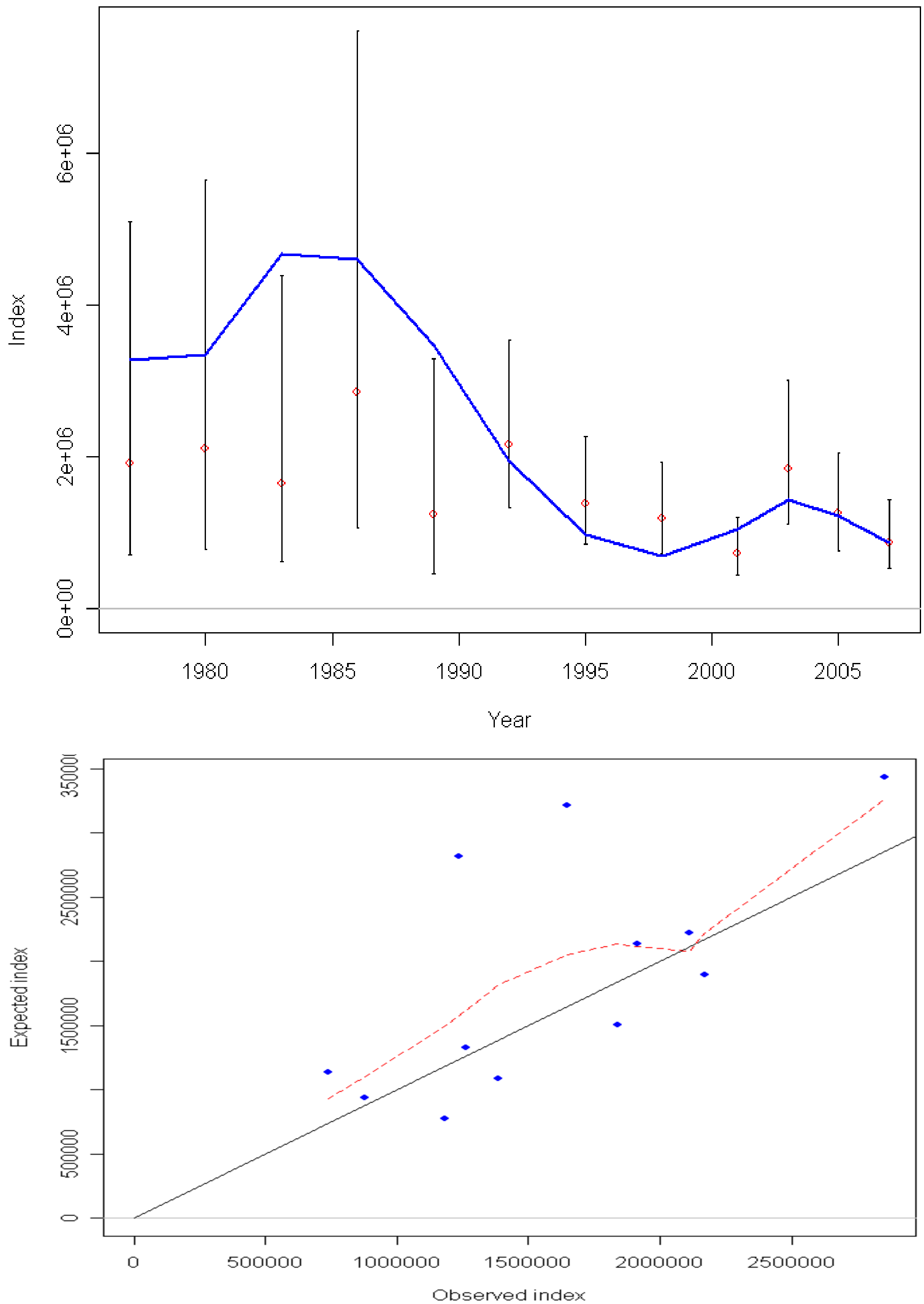

Figure 50. Predicted fit of acoustic survey biomass to the observed time series.

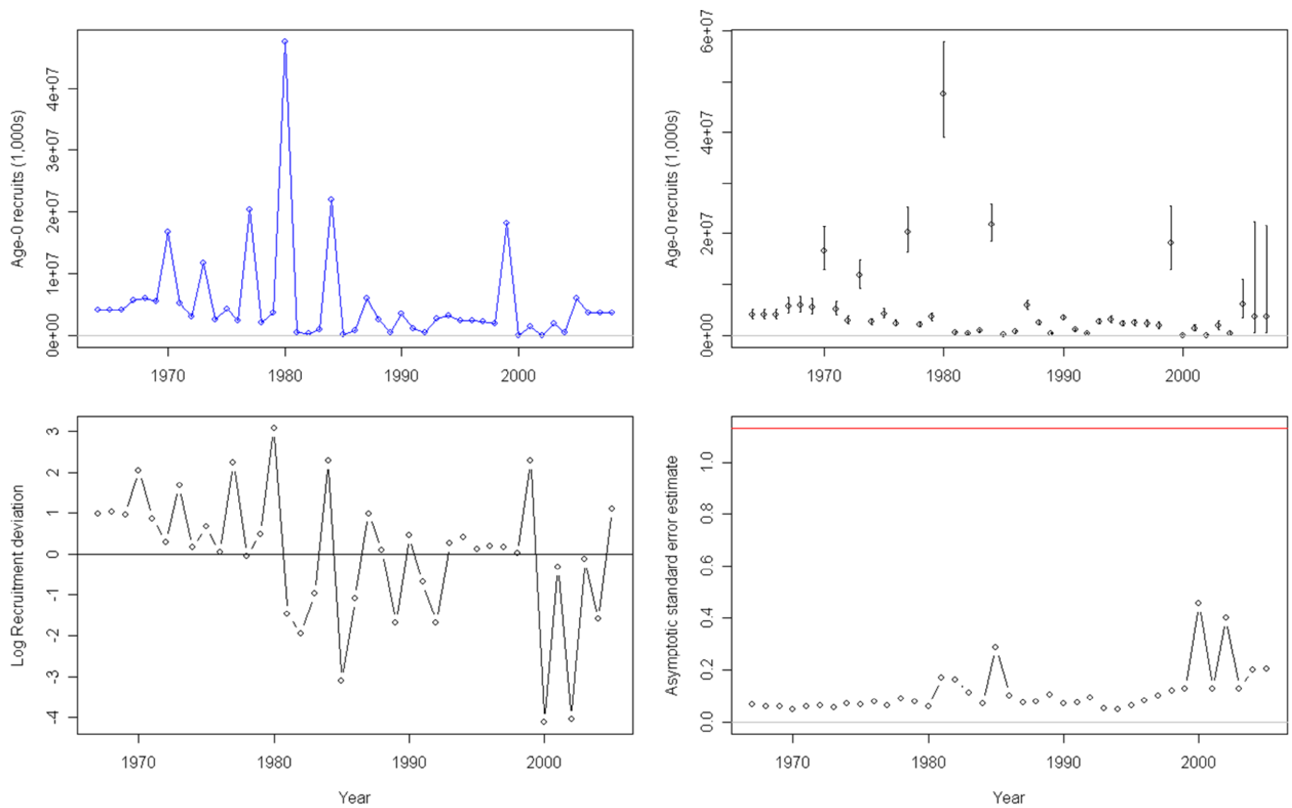

Figure 51. Estimates of Pacific hake recruitment (A), recruitment variability (B), recruitment deviations (C), and asymptotic standard errors (D). Recruitments were estimated from 1967-2005, but 2006-2007 were taken from the S-R curve.

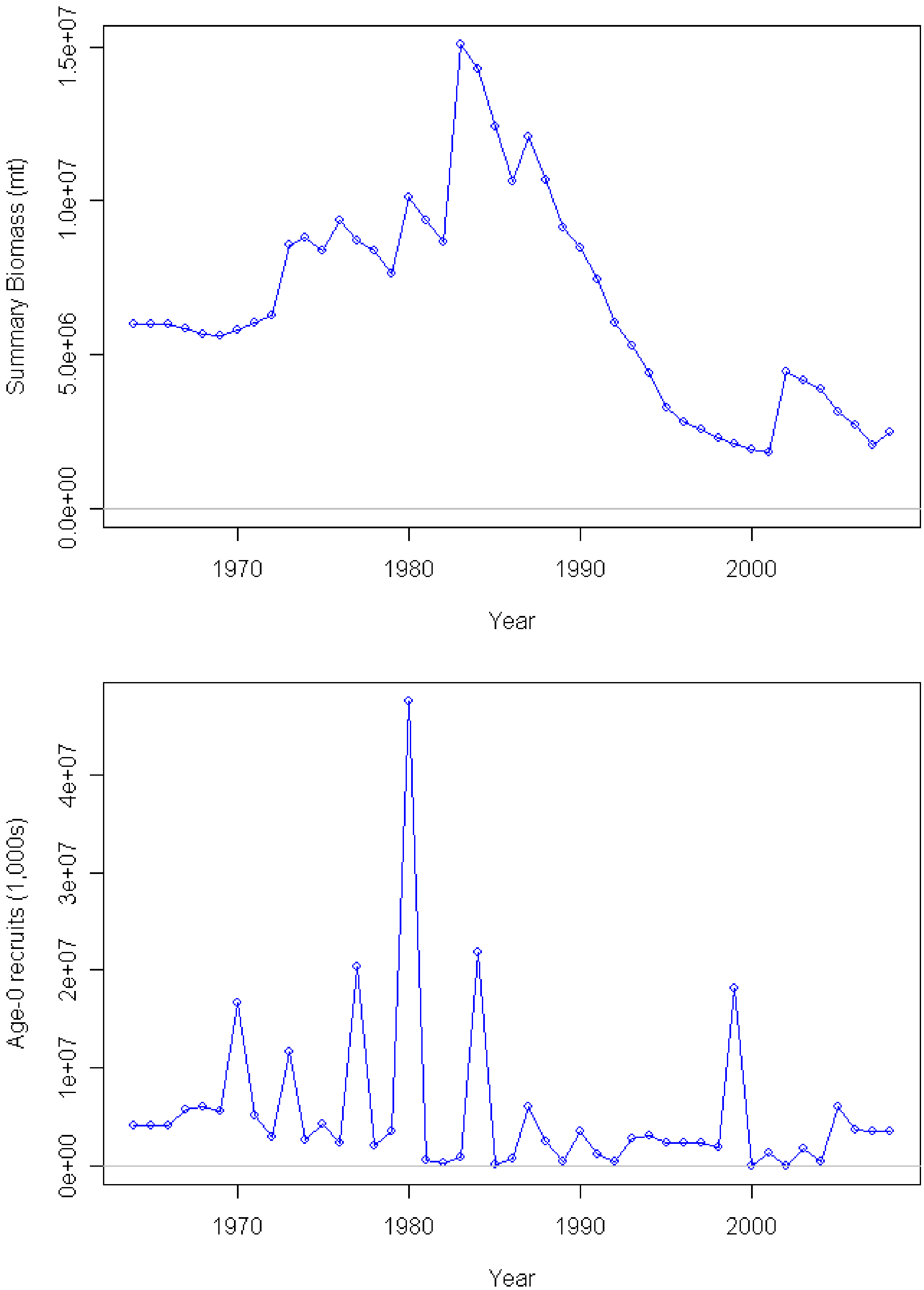

Figure 52. Estimated time series of Pacific hake summary biomass (age 3+) and recruitment from the base SS2 model.

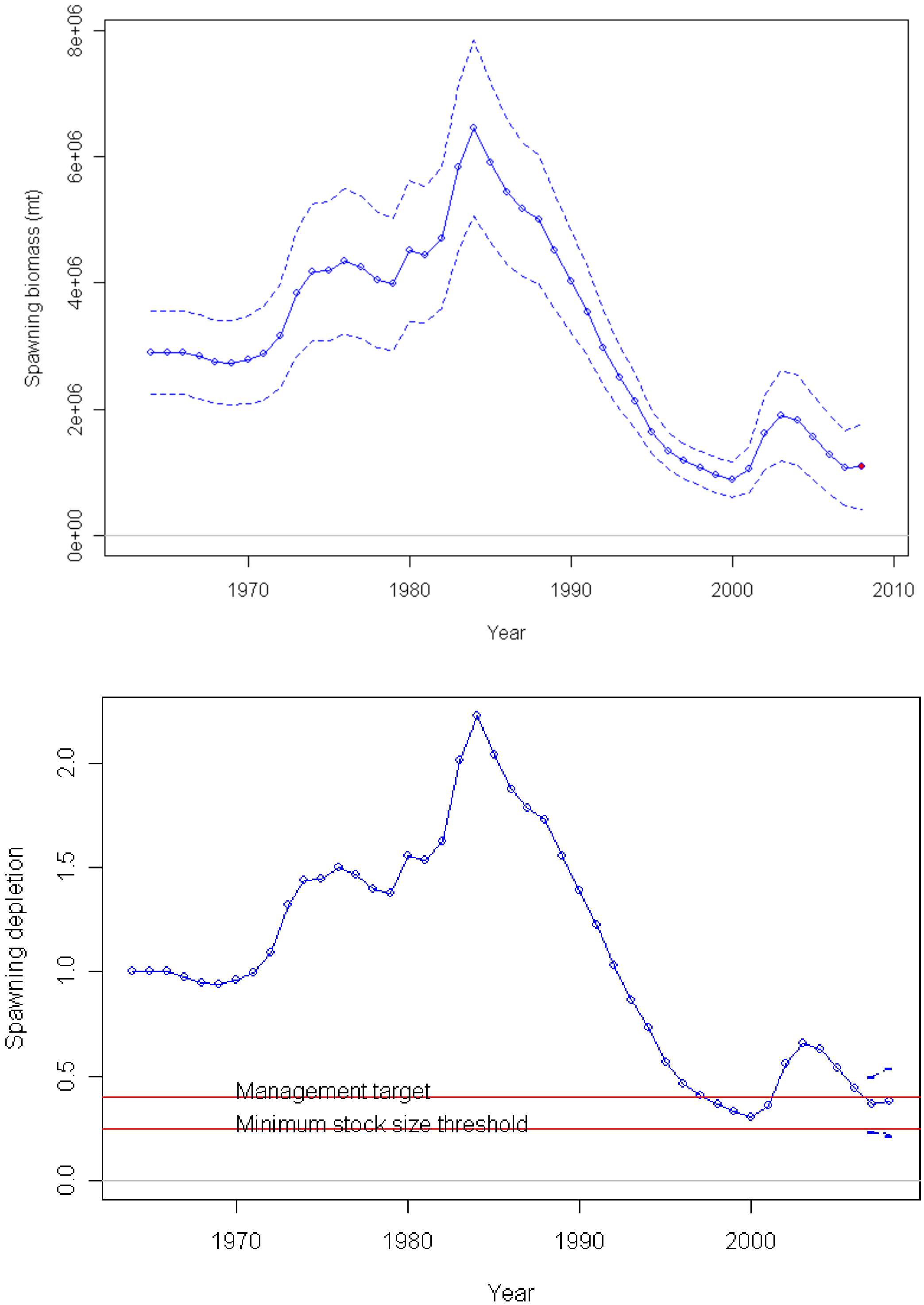

Figure 53. Estimated time series of Pacific hake spawning biomass (along with asymptotic 95% confidence intervals and spawning depletion (fraction of unfished spawning biomass).

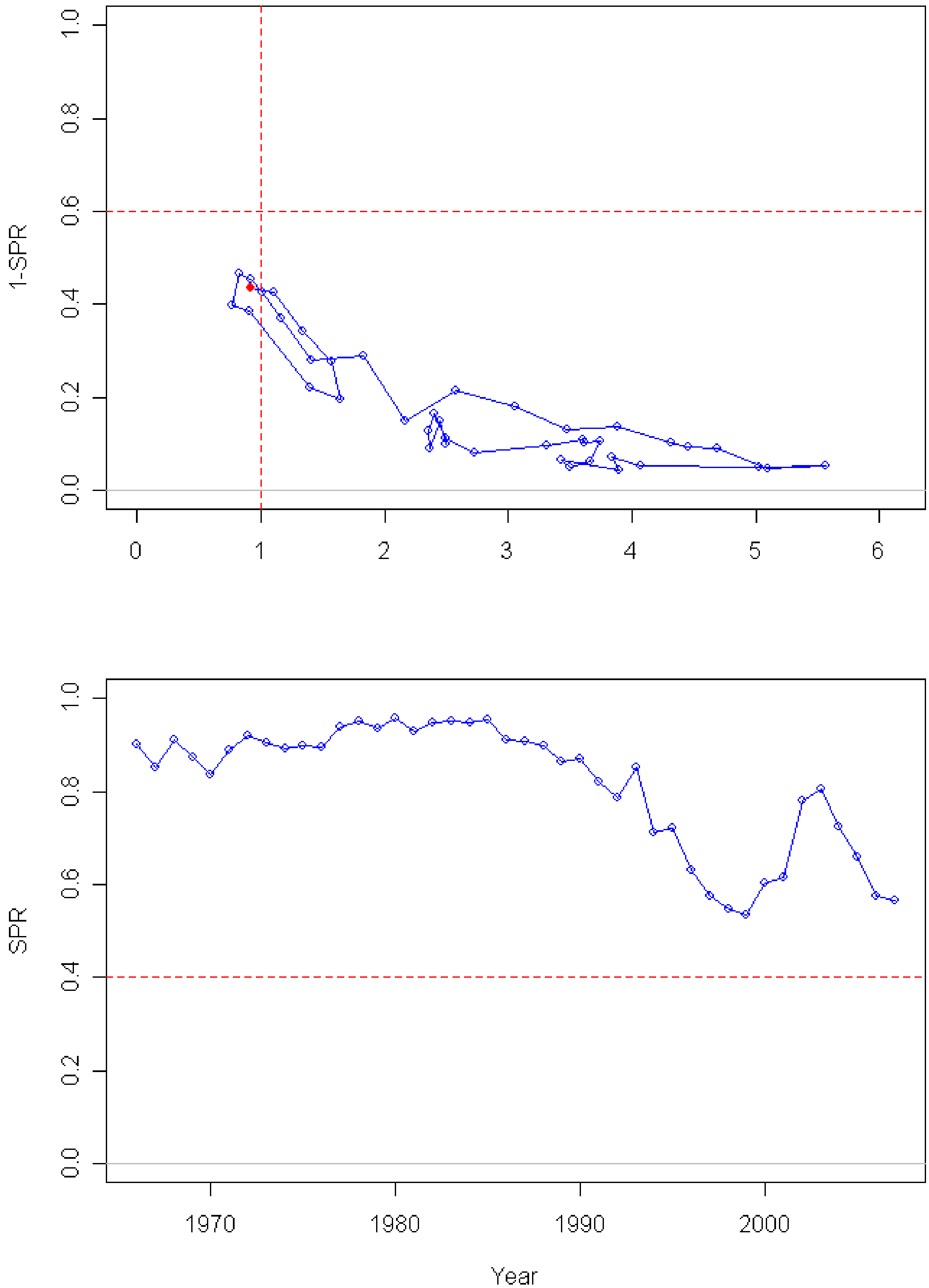

Figure 54. Estimated time series of Pacific hake spawning potential ratio (SPR) and fishery performance relative to reference point targets from the base SS2 model. Current (2007) performance relative to targets is shown as solid dot.

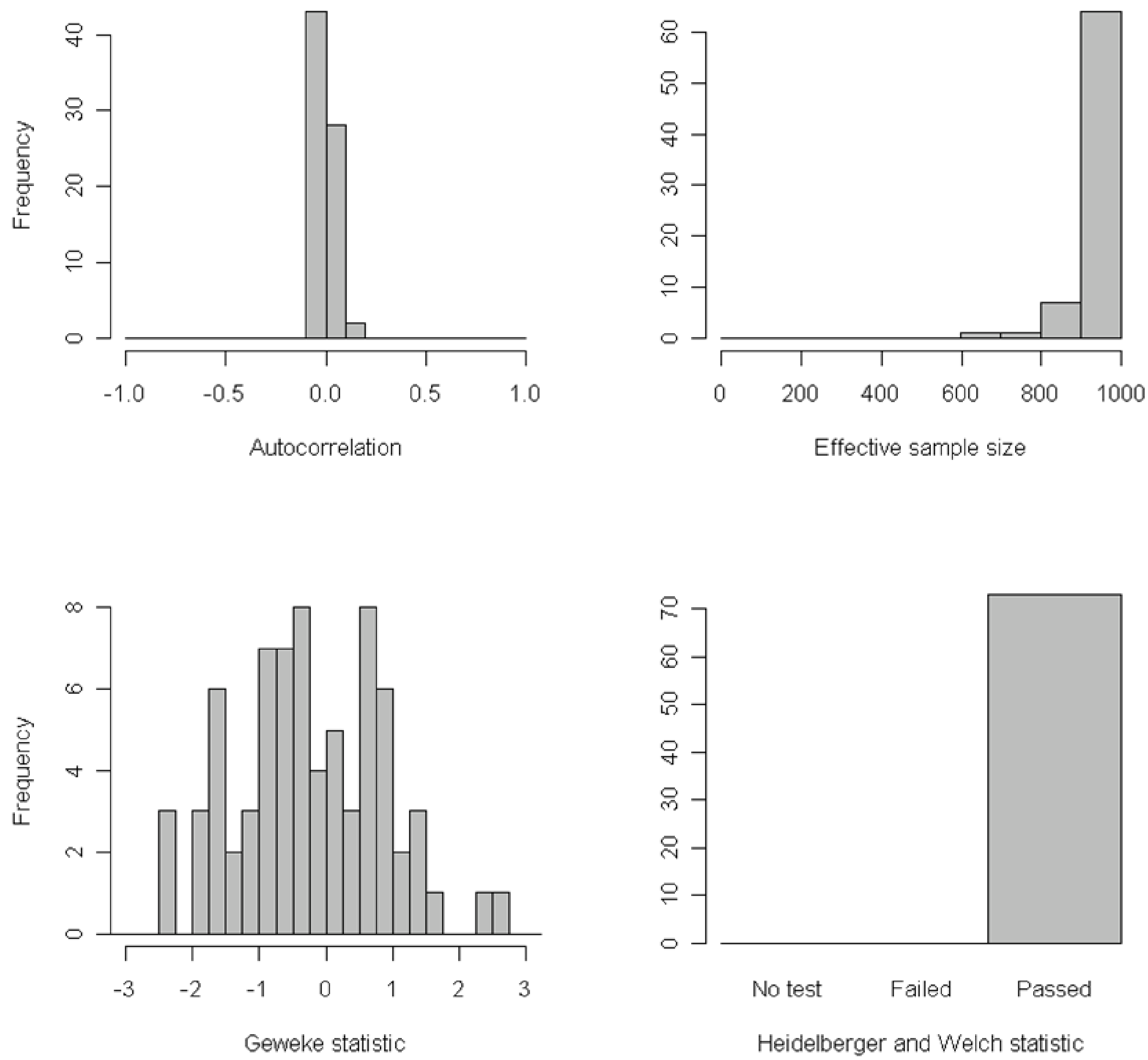

Figure 55. Summary of convergence criteria for all estimated model parameters from the base model.

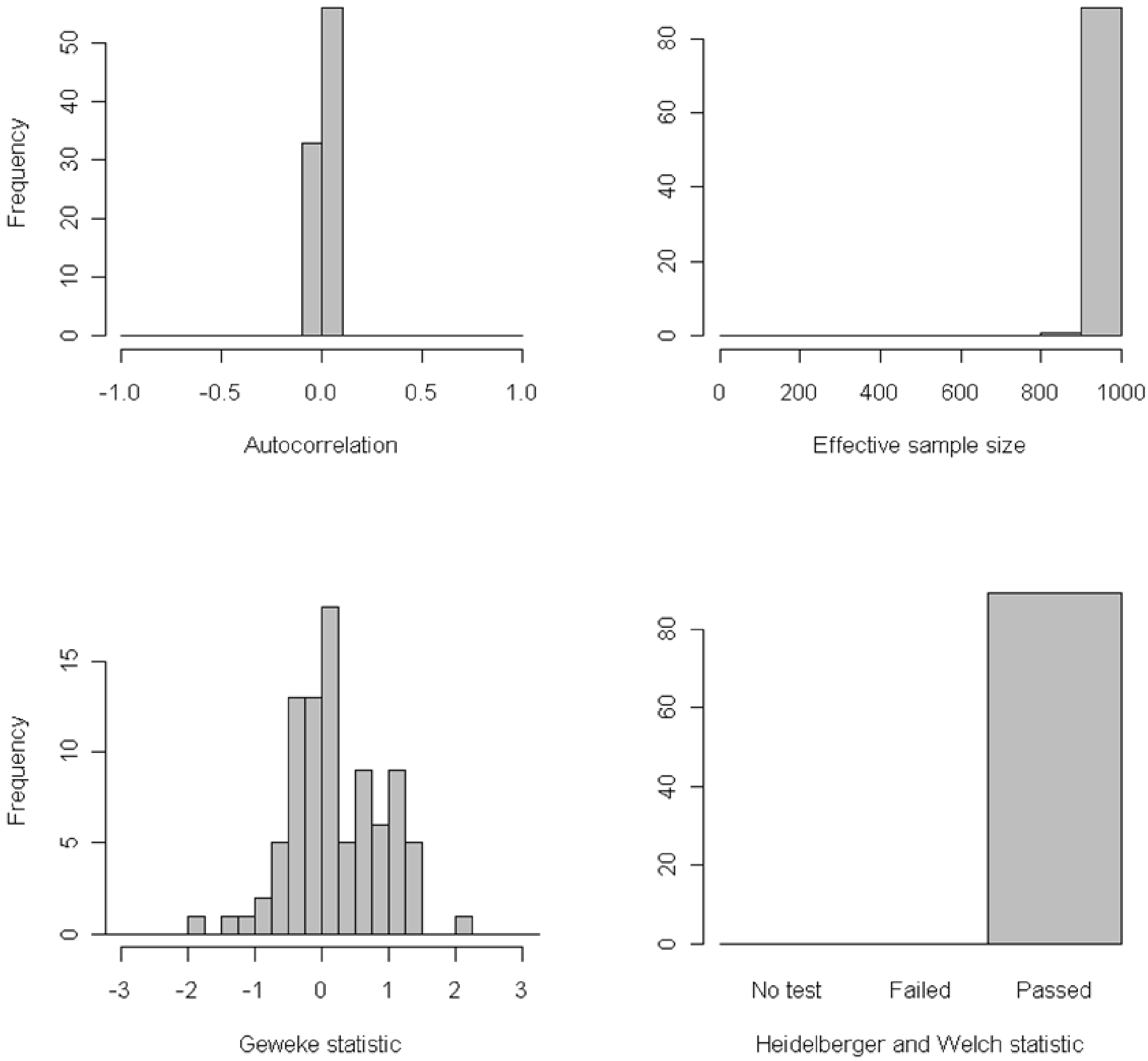

Figure 56. Summary of convergence criteria for the derived variables such as spawning biomass and recruitment time-series'.

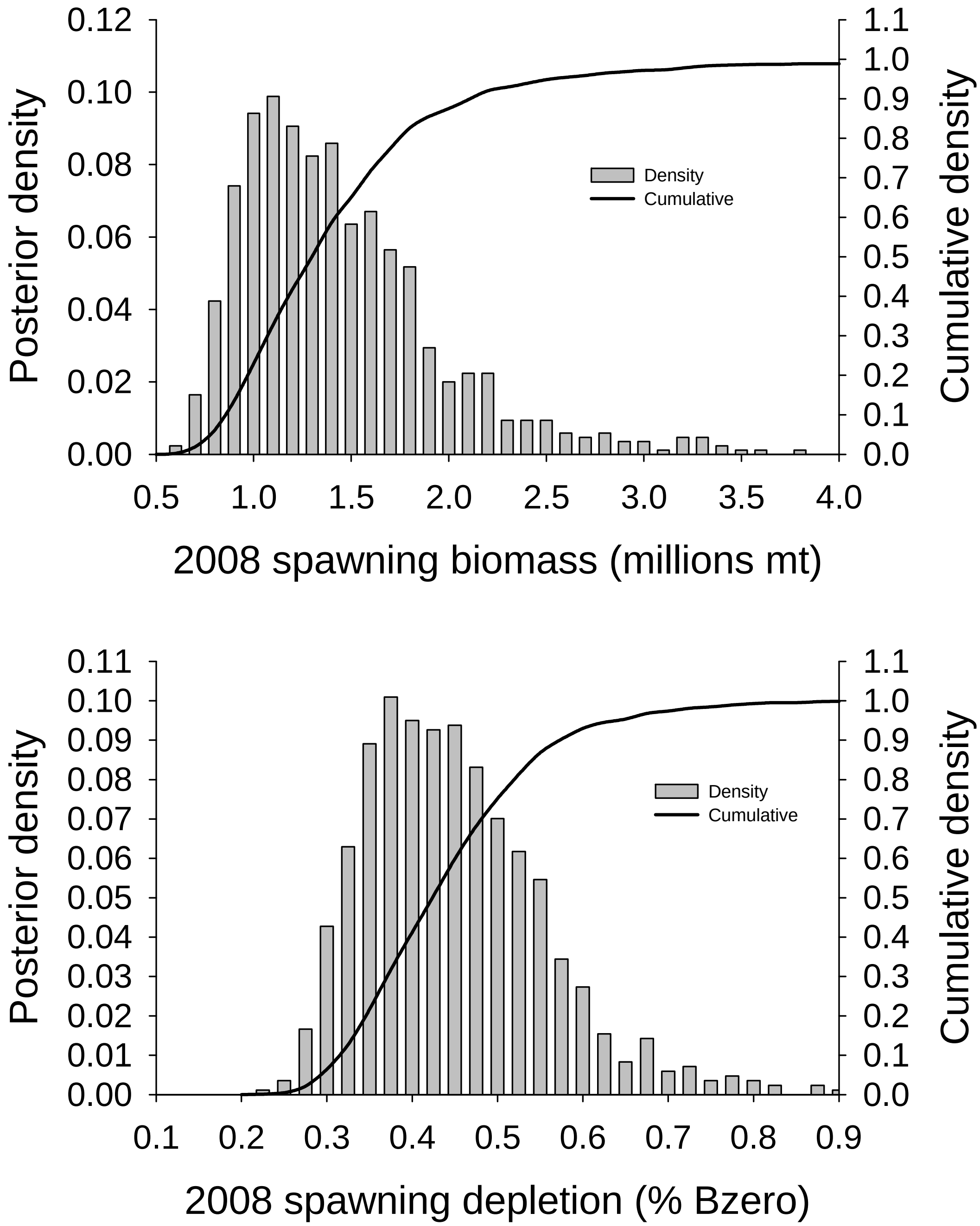

Figure 57. Uncertainty in 2008 female spawning biomass and relative depletion generated from 1,000,000 Markov Chain Monte Carlo simulations of the joint posterior distribution. Note that the MPD is slightly larger then the MLE.

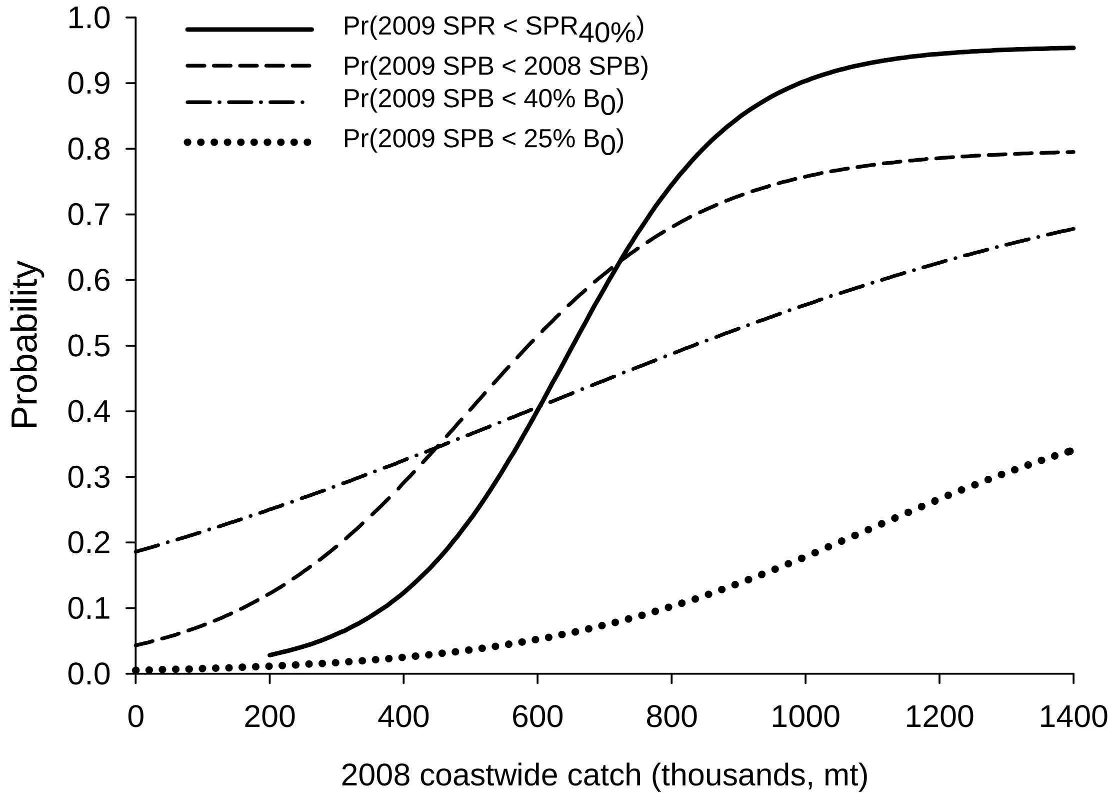

Figure 58. Risk profiles showing probability of the 2009 SPR rate being less than target SPR40% and 2009 spawning biomass being less than 25% Bzero for a suite of different coastwide catches in 2008.

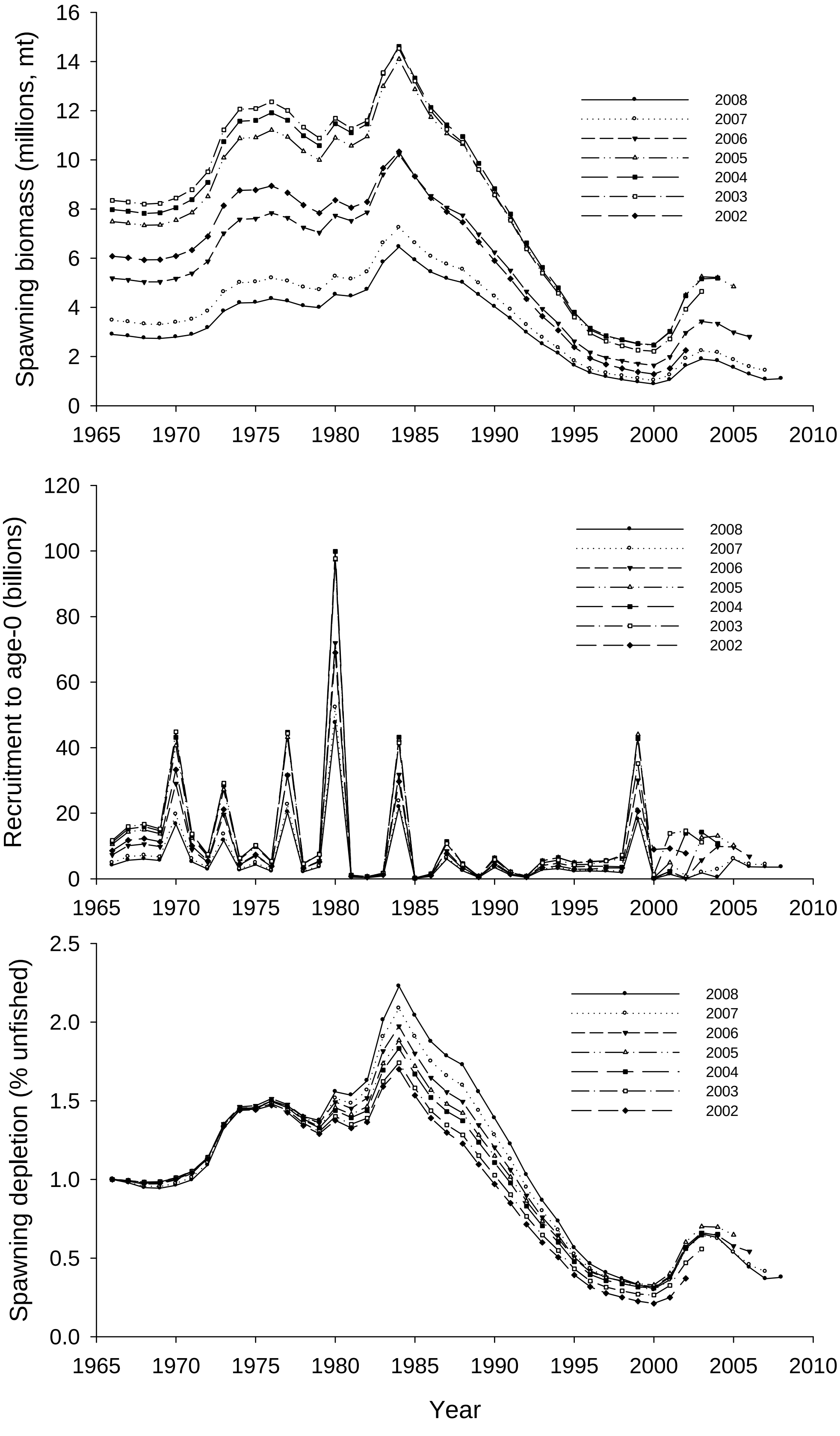

Figure 59. Retrospective analysis of the hake model showing spawning biomass, recruitment to age-0 and spawning depletion.

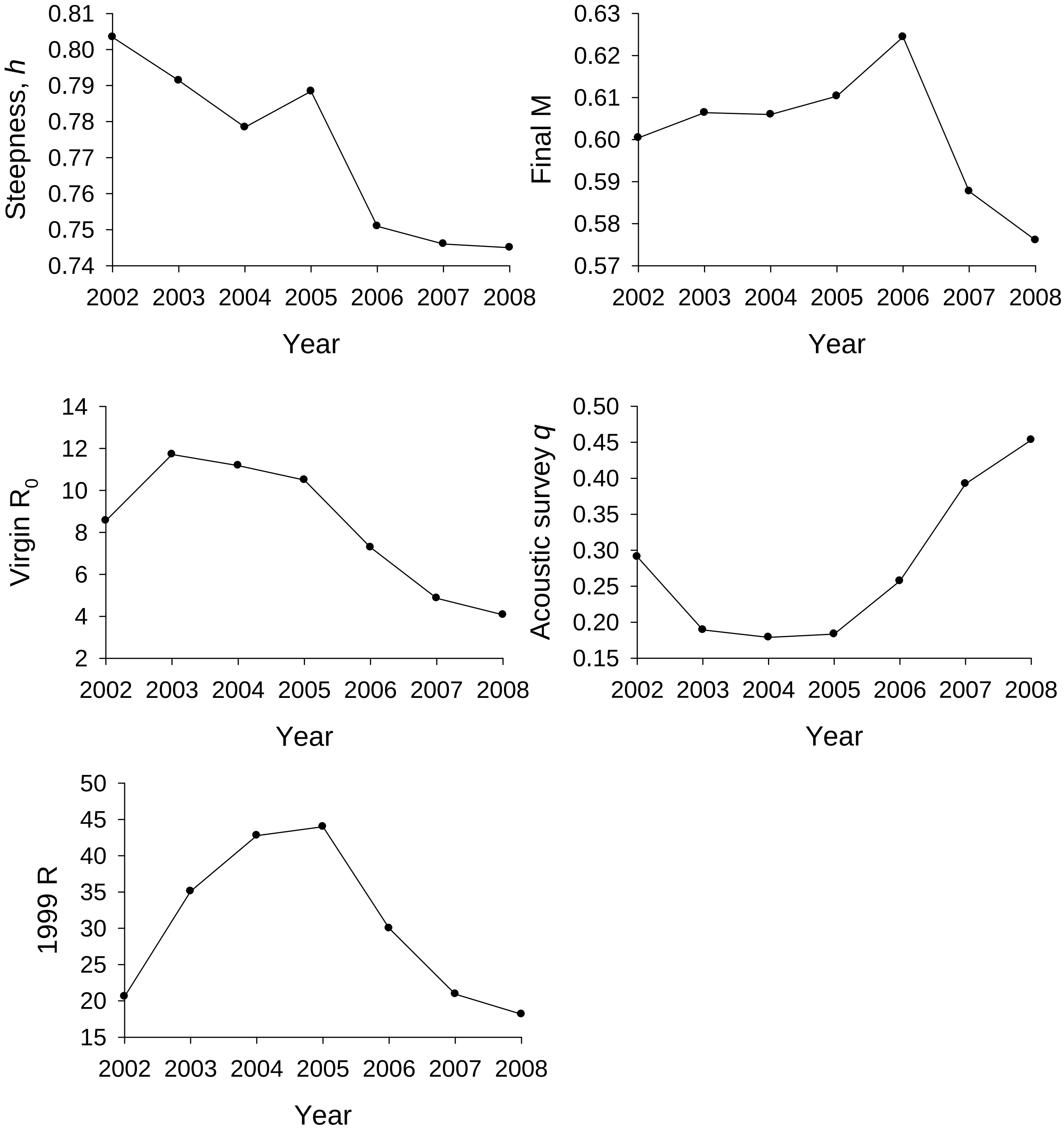

Figure 60. Retrospective analysis of the hake model showing changes in selected estimated parameters when years are sequentially removed from analysis.