Stock Assessment of Pacific Hake (Whiting) in U.S. and Canadian Waters in 2004

Thomas E. Helser[1]
Guy W. Fleischer[1]
Steve Martell[2]
Nathan Taylor[2]

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

[2] *University of British Columbia*
Fisheries Centre
2259 Lower Mall
Vancouver, B.C. Canada
V6T 1Z4

February 16, 2005
Version 2
Revised as per STAR Panel Review

Summary of Stock Status

The coastal population of Pacific hake (*Merluccius productus*, also called Pacific whiting) is distributed off the west coast of North America from 25˚ N. to 51˚ N. latitude and was assessed using an age-structured assessment model. The U.S. and Canadian fisheries were treated as distinct fisheries. The primary indicator of stock abundance is the acoustic survey, and a midwater trawl juvenile survey provides an indicator of recruitment. New data in this assessment included only updated catch at age through 2004 and recruitment indices from the Santa Cruz juvenile survey in 2004. The US/Canadian acoustic survey, which is the primary index of hake abundance, was last conducted in summer of 2003, but another is planned for the summer of 2005. As in last year's assessment, uncertainty in model results is represented by a range of biomass. The lower biomass end of the range is based upon the conventional assumption that the acoustic survey catchability coefficient, q=1.0, while the higher end of the range represents the q=0.6 assumption.

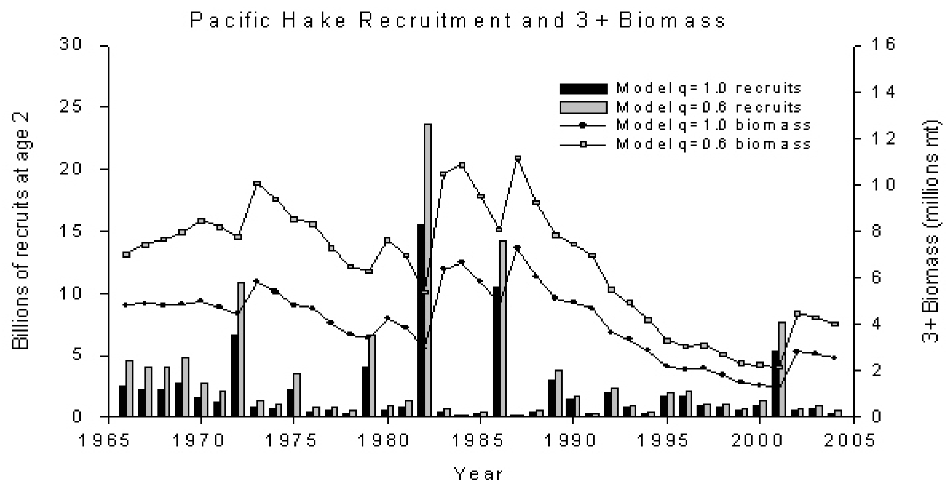
Status of Stock: The hake stock in 2004 was estimated to range from 2.5 to 4.0 million mt (age 3+ biomass) for the q=1.0 and q=0.6 model scenarios, respectively. Stock biomass increased to a historical high in 1987 due to exceptionally large 1980 and 1984 year classes, then declined as these year classes passed through the population and were replaced by more moderate year classes. Stock size stabilized briefly between 1995-1997, but then declined continuously to its lowest point in 2001. Since 2001, stock biomass has increased substantially as the strong 1999 year class has entered the population. The mature female biomass in 2004 was estimated to range from 50% to 55% (q=1.0 and q=0.6) of an unfished stock. Thus the stock can be considered to be rebuilt to the target level of abundance

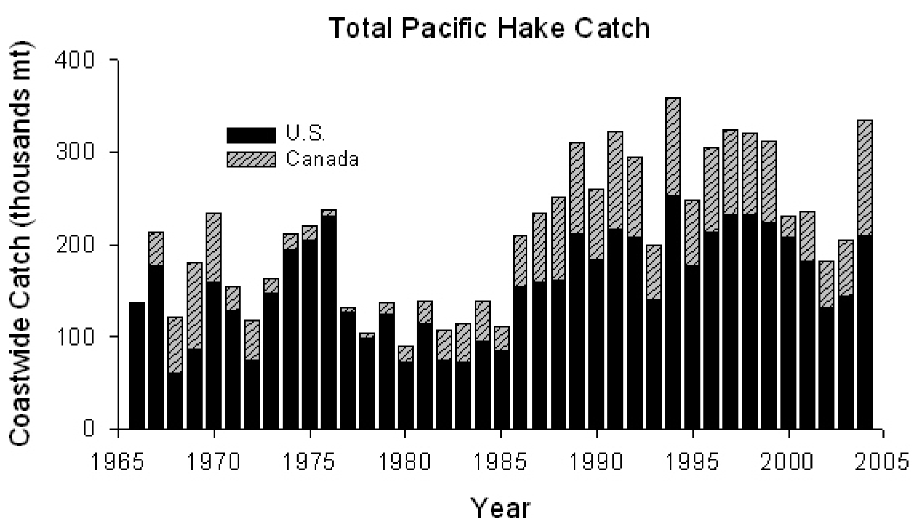
Pacific hake (whiting) catch and stock status table (catches in thousands of metric tons, biomass in millions of metric tons and Age 2 recruits in billions of fish):

Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
U.S. landings	253	178	213	233	233	225	208	182	132	144	211
Canadian landings	106	70	93	92	89	87	22	54	51	62	124
Total	359	248	306	325	321	312	230	236	183	206	335
ABC	325	223	265	290	290	290	290	238	208	235	514
Model (q=1.0)											
Age 3+ stock biomass	2.8	2.2	2.1	2.1	1.8	1.5	1.4	1.3	2.9	2.7	2.5
Female mature biomass	1.5	1.2	1.1	1.0	0.9	0.8	0.7	0.7	1.2	1.3	1.2
Age 2 recruits	0.33	1.71	1.72	0.90	0.85	0.55	0.93	5.34	0.53	0.72	0.34
Total F	0.24	0.22	0.27	0.26	0.30	0.36	0.29	0.34	0.19	0.20	0.32
Depletion level (%B0)	58%	47%	42%	41%	36%	30%	28%	29%	46%	51%	50%
Exploitation rate	12.6%	11.4%	14.9%	15.4%	17.5%	20.9%	16.8%	18.5%	6.5%	7.6%	13.2%
Model (q=0.6)											
Age 3+ stock biomass	4.2	3.3	3.1	3.1	2.7	2.3	2.2	2.1	4.5	4.3	4.0
Female mature biomass	2.2	1.8	1.6	1.6	1.4	1.2	1.2	1.2	1.9	2.1	2.0
Age 2 recruits	0.39	2.03	2.05	1.13	1.10	0.74	1.37	7.60	0.72	0.89	0.51
Total F	0.18	0.16	0.19	0.19	0.22	0.25	0.18	0.20	0.11	0.11	0.17
Depletion level (%B0)	60%	50%	44%	43%	38%	33%	32%	34%	52%	57%	55%
Exploitation rate	9.4%	8.2%	10.8%	11.2%	12.6%	14.3%	11.0%	11.8%	4.4%	5.1%	8.7%

The coastwide ABC and OY for 2005 are estimated to be 364,000 mt and 598,000 mt (q=1.0 and q=0.6) based upon a F40% harvest rate and 302,000 mt and 483,300 mt mt (q=1.0 and q=0.6) based upon the F45% harvest rate. With biomass above 40% unfished biomass level, the 40:10 OY adjustment would not be applied. Projections beyond 2005 are for a decline in stock biomass and ABC-OY as the 1999 year class passes through its age of peak abundance. At this time there is no evidence of sufficiently large recruitments after 1999 to maintain the stock at a high abundance level. Preliminary results from pre-recruit surveys suggest a larger than average 2003 year-class, but this remains unconfirmed until the 2005 acoustic survey. As such, spawning stock biomass is projected to again decline within the precautionary zone (25% - 40% unfished) by 2006-2007.

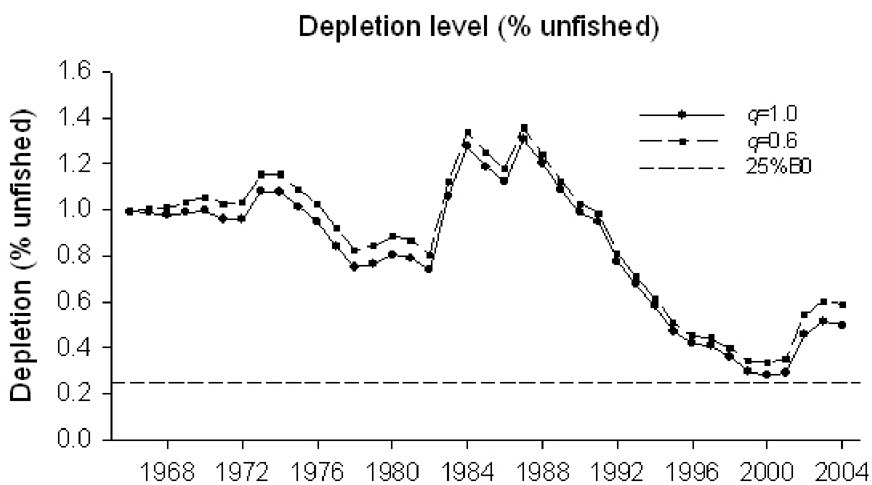
Data and Assessment: An age-structured assessment model was developed by Dorn et al. (1998) using AD model builder, a modeling environment for developing and fitting multi-parameter non-linear models. Data used in this assessment included: 1) U.S. and Canadian commercial landings data (discards included in the at sea component, 2) age composition and weight at age from both fisheries, 3) Santa Cruz larval rockfish survey as an index of age 2 recruitment, and 4) U.S.-Canada triennial acoustic survey data as an index of total stock biomass. The most recent assessment presented here represents an update based on the same model configuration used in the 2003 assessment. This included a revised 1977-1992 acoustic survey biomass estimates based on new deep-water and northern expansion factors. New data for this assessment includes 2004 fishery removals and age compositions and the 2004 Santa Cruz pre-recruit hake index.

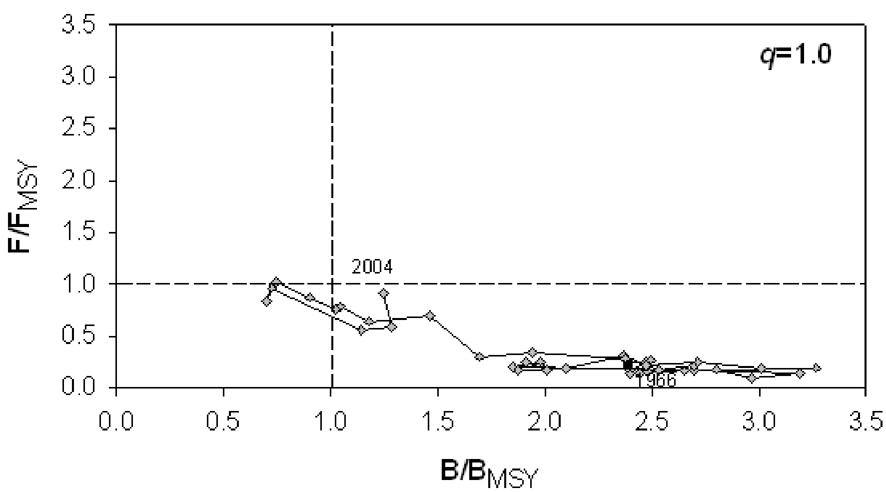


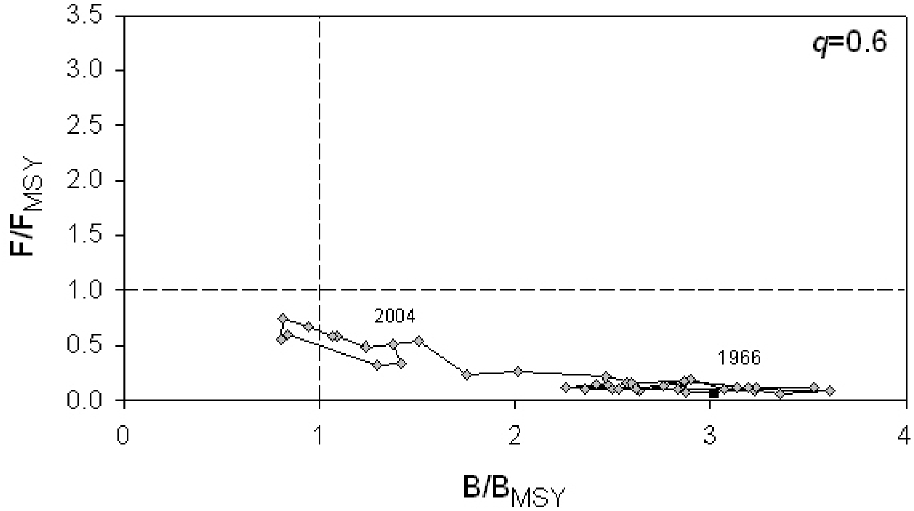


Reference points and Management Performance: Management targets for Pacific hake are based on proxy measures of F_{MSY} and B_{MSY} corresponding to 40% (i.e. $F_{40\%}$ and $B_{40\%}$) of spawning stock biomass-per-recruit in the absence of fishing (B0=SSB/R*ave.R), with the 40-10 policy implemented when biomass falls below 40% unfished**.** Overfishing is defined to occur when spawning stock biomass falls below 25% B0 (uncertainty in the table below is expressed as 10th and 90th percentiles of the MCMC posterior distribution).

Pacific hake/Whiting	Model (q=1.0)	Model (q=0.6)
Unfished Spawning Stock Biomass (SB_0)	2.5 million mt	3.65 million mt
Age 3+ Unfished Population Biomass (B_0)	4.8 million mt	7.0 million mt
Unfished Recruitment (R_0)	1.9 billion	2.8 billion
Spawning Stock Biomass at MSY (SB_{msy})	1.0 million mt	1.46 million mt
Basis for SB_{msy}	SB40% proxy	SB40% proxy
F_{msy}	0.35	0.34
Basis for F_{msy}	F40% proxy	F40% proxy
MSY	374,000 mt	537,000 mt
2004 Spawning Stock Biomass w/ uncertainty	1.17 (1.03-1.34) mt	1.94 (1.48-2.42) mt







Major Uncertainties: The hake assessment is highly dependent on acoustic survey estimates of abundance. Since 1993, the assessment has relied primarily on an absolute biomass estimate from the joint US-Canadian acoustic survey. The acoustic target strength of Pacific hake, used to scale acoustic data to biomass, is based on a small number of *in situ* observations. While the fit to the acoustic survey time series has improved with revision of past survey biomass estimates (1977-1992) these are still uncertain with poor fits in some years.

Uncertainty in the assessment result is characterized in terms of variability in model parameters and in terms of the assumption regarding the acoustic survey catchability coefficient, q. All past assessment results and recommendations have been based upon fixing the acoustic survey q=1.0; thus asserting that the acoustic survey estimate of biomass is an absolute measure of biomass and not just a relative measure. The past several assessments have explored relaxation of this assumption, but final results have been based upon the q=1.0 scenario. The ability to relax the q=1.0 assumption in this year's assessment is based upon: 1) continued lengthening of the acoustic survey time series, thus allowing the survey to be treated as an index of relative abundance in the model; 2) relatively better model fits to the data when q is less than 1.0; and 3) high quality of expertise in the STAR Panel to allow critical examination of the q=1.0 assertion. Uncertainty in the final model result is therefore represented by a range of biomass. The lower biomass end of the range is based upon the conventional assumption that the acoustic survey catchability coefficient, q=1.0, while the higher end of the range represents the q=0.6 assumption. Even lower q values are indicated by some model runs, but these are considered by the STAT team and STAR panel to be implausibly low. The relative probability of the range of plausible q levels was discussed extensively. The two endpoints are considered as less likely than intermediate points and an equal blending of results from the two endpoints is not unreasonable.

Target Fishing Mortality Rates: Target fishing mortality rates used in projections were based on F40% and F45% the fishing mortality rate corresponding to the corresponding F %B0 of unfished spawning stock biomass-per-recruit, with the 40-10 policy implemented when biomass falls below 40% unfished. Bayesian credibility intervals generated from 2,500,000 Markov Chain Monte Carlo samples were used to evaluate uncertainty in biomass, spawning biomass, depletion rates and coastwide yield. An estimate of stock productivity (e.g. ABC) that equally blends the two model endpoints is reasonable as a risk-neutral best estimate. An OY that is closer to the q=1.0 result would be risk-averse, would not constrain the expected short-term fishery demands and would reduce the magnitude of the projected short-term stock decline.

Coastwide and U.S. yield in 2005 (in metric tons):

	2005 Coastwide OY	2005 U.S. OY
Model q =1.0		
F40% (40-10)	364,197	269,069
F45% (40-10)	302,305	223,343
Model q =0.6		
F40% (40-10)	597,625	441,525
F45% (40-10)	482,899	356,766

Projection table of coastwide yield (thousands of tons), spawning biomass (millions of tons), and depletion rates under different harvest rate policies and model alternatives. Percentiles shown (10%, 50% and 90%) are based on 2,500,000 Markov chain Monte Carlo simulations:

Model q =1.0

		3+ Bioimass (millions mt)			SpawningBioimass (million mt)			Age-2 Recruits (billion)			Depletion Rate			Coastwide yield (t)		
	Year	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
F40% (40-10) Harvest Policy	2005	1.638	1.952	2.338	0.842	0.997	1.184	0.092	0.259	0.736	0.324	0.383	0.455	294,258	364,197	438,815
	2006	1.042	1.252	1.554	0.577	0.696	0.850	0.477	1.448	4.631	0.222	0.268	0.327	192,114	258,507	345,172
	2007	1.051	1.418	2.484	0.542	0.707	1.064	0.285	1.134	4.000	0.208	0.272	0.409	159,956	248,323	425,987
	2008	0.993	1.619	3.019	0.535	0.779	1.335	0.249	1.114	4.731	0.206	0.300	0.513	150,452	278,576	529,730
	2009	1.061	1.742	3.558	0.539	0.838	1.578	0.232	0.954	3.906	0.207	0.322	0.607	154,230	321,665	641,017
	2010	1.103	1.860	3.829	0.598	0.921	1.723	0.336	1.087	4.593	0.230	0.354	0.663	180,131	353,427	682,167
	2011	1.211	1.949	3.867	0.606	0.936	1.798	0.292	0.931	3.717	0.233	0.360	0.691	190,821	371,392	713,404
	2012	1.155	1.944	3.675	0.589	0.934	1.736	0.303	1.035	3.853	0.227	0.359	0.667	190,315	369,845	705,711
	2013	1.177	1.877	3.727	0.612	0.909	1.704	0.240	0.989	4.313	0.235	0.350	0.655	200,654	363,418	689,173
	2014	1.171	1.864	3.948	0.607	0.919	1.818	0.197	1.099	4.732	0.234	0.353	0.699	194,951	365,660	725,154
F45% (40-10) Harvest Policy	2005	1.638	1.952	2.338	0.842	0.997	1.184	0.092	0.259	0.736	0.324	0.383	0.455	244,229	302,305	363,377
	2006	1.093	1.315	1.629	0.605	0.729	0.887	0.477	1.448	4.631	0.233	0.280	0.341	172,562	230,359	304,634
	2007	1.125	1.505	2.574	0.580	0.753	1.119	0.285	1.134	4.000	0.223	0.289	0.430	149,984	225,028	368,429
	2008	1.080	1.723	3.154	0.580	0.831	1.408	0.249	1.114	4.731	0.223	0.319	0.541	142,603	251,998	457,461
	2009	1.138	1.853	3.724	0.577	0.896	1.676	0.232	0.954	3.906	0.222	0.345	0.645	145,064	290,260	560,357
	2010	1.193	2.003	4.044	0.643	0.997	1.853	0.336	1.087	4.593	0.247	0.383	0.713	166,897	318,141	604,656
	2011	1.309	2.115	4.157	0.658	1.020	1.942	0.292	0.931	3.717	0.253	0.392	0.747	179,031	336,497	639,758
	2012	1.265	2.123	3.991	0.644	1.022	1.900	0.303	1.035	3.853	0.248	0.393	0.730	179,943	338,863	639,545
	2013	1.289	2.062	4.048	0.674	1.008	1.869	0.240	0.989	4.313	0.259	0.388	0.719	189,901	336,312	632,219
	2014	1.303	2.065	4.256	0.673	1.018	1.965	0.197	1.099	4.732	0.259	0.391	0.756	190,028	338,300	650,107

Model q =0.6

		3+ Bioimass (million mt)			SpawningBioimass (million mt)			Age-2 Recruits (billion)			Depletion Rate			Coastwide yield (t)		
	Year	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
F40% (40-10) Harvest Policy	2005	2.445	3.356	4.323	1.287	1.673	2.151	0.106	0.349	1.034	0.320	0.437	0.562	418,345	597,625	791,728
	2006	1.587	2.123	2.771	0.900	1.185	1.500	0.661	2.054	6.483	0.226	0.298	0.377	278,998	422,115	590,706
	2007	1.640	2.240	3.652	0.861	1.140	1.662	0.342	1.428	6.156	0.216	0.286	0.418	242,757	382,138	640,772
	2008	1.588	2.399	4.580	0.840	1.192	2.063	0.340	1.537	6.902	0.211	0.300	0.519	218,160	408,865	794,166
	2009	1.520	2.520	5.330	0.772	1.225	2.318	0.324	1.267	6.336	0.194	0.308	0.583	202,578	450,905	939,578
	2010	1.561	2.706	5.810	0.841	1.330	2.663	0.436	1.553	6.743	0.211	0.334	0.669	225,978	489,969	1,057,915
	2011	1.597	2.752	6.115	0.819	1.334	2.819	0.409	1.414	5.790	0.206	0.335	0.709	228,525	515,007	1,126,446
	2012	1.604	2.802	5.895	0.816	1.370	2.729	0.419	1.405	5.540	0.205	0.344	0.686	230,474	530,105	1,110,600
	2013	1.599	2.796	5.710	0.827	1.377	2.697	0.387	1.612	7.898	0.208	0.346	0.678	241,298	540,436	1,102,727
	2014	1.671	2.902	6.391	0.845	1.430	2.843	0.318	1.473	5.701	0.212	0.359	0.715	248,666	564,831	1,139,945
F45% (40-10) Harvest Policy	2005	2.472	3.232	4.165	1.287	1.673	2.151	0.122	0.340	1.015	0.319	0.414	0.533	355,660	482,899	632,026
	2006	1.664	2.169	2.781	0.935	1.207	1.530	0.694	2.135	7.248	0.232	0.299	0.379	253,660	370,917	507,664
	2007	1.730	2.398	4.040	0.911	1.245	1.802	0.408	1.733	7.614	0.226	0.309	0.447	218,786	366,140	581,201
	2008	1.675	2.801	5.184	0.896	1.365	2.292	0.408	1.562	7.092	0.222	0.338	0.568	210,534	410,192	737,894
	2009	1.707	2.896	5.674	0.886	1.409	2.563	0.334	1.330	5.102	0.219	0.349	0.635	218,179	453,579	860,214
	2010	1.845	3.102	5.859	0.979	1.523	2.686	0.367	1.335	7.304	0.243	0.377	0.665	246,014	479,357	888,422
	2011	1.850	3.129	6.044	0.950	1.519	2.758	0.415	1.407	4.989	0.235	0.376	0.683	241,460	488,955	917,727
	2012	1.814	2.972	5.839	0.928	1.461	2.756	0.375	1.408	4.984	0.230	0.362	0.683	236,900	479,261	916,826
	2013	1.800	2.937	5.725	0.932	1.440	2.730	0.340	1.539	6.115	0.231	0.357	0.676	237,814	472,026	941,087
	2014	1.790	2.976	5.865	0.916	1.463	2.735	0.311	1.378	5.373	0.227	0.363	0.678	236,545	474,799	922,979

Research and Data Needs: The STAR Panel concluded that the major source of uncertainty lies in the assumption regarding the acoustic survey catchability, q. In particular, the target strength relationship should be re-evaluated for possible biases and additional in situ measurements are needed. Moreover, an informed prior on q should be developed when estimating this parameter freely in the model.

INTRODUCTION

This assessment has been developed in the spirit of a treaty signed in November 2003 between the U.S. and Canada for the sharing of this trans-boundary resource. Under this agreement, not yet ratified by Congress, the stock assessment is to be reviewed by a Scientific Review Group (SRG), appointed by both parties. Prior to 1997, separate Canadian and U.S. assessments were submitted to each nation's assessment review process. In the past, this has resulted in differing yield options being forwarded to managers. Multiple interpretations of stock status made it difficult to coordinate overall management policy for this trans-boundary stock. To address this problem, the working group agreed in 1997 to present scientific advice in a single assessment, while that agreement was officially formalized in 2003. To further coordinate scientific advice, this report was submitted to a joint Canada-U.S. SRG for technical review in fulfillment of the agreement and to satisfy management responsibilities of both the U.S. Pacific Fisheries Management Council (PFMC) and the Canadian Pacific Stock Assessment Review Committee (PSARC). The Review Group meeting was held in Seattle, WA at the Northwest Fisheries Science Center, during Feb 2-4, 2005. While this report forms the basis for scientific advice to managers, final advice on appropriate yield is deferred to Canadian DFO managers by the PSARC Groundfish Sub-committee and the PSARC Steering Committee, and to the U.S. Pacific Fisheries Management Council by the Groundfish Management Team.

Stock Structure and Life History

Pacific hake (*Merluccius productus*), also called Pacific whiting, is a codlike species distributed off the west coast of North America from 25˚ N. to 51˚ N. lat. It is among 11 other species of hakes from the genus, *Merluccidae*, which are distributed in both hemispheres of the Atlantic and Pacific Oceans and constitute nearly two millions t of catches 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 hake 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 typically ranges from southern California to Queen Charlotte Sound. Spawning occurs off south-central California during January-March. Due to the difficulty of locating major spawning concentrations, 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, hake form extensive midwater aggregations near the continental shelf break, with highest densities located over bottom depths of 200-300 m (Dorn et al. 1994). The prey of hake include euphausiids, pandalid shrimp, and pelagic schooling fish (such as eulachon and herring) (Livingston and Bailey 1985). Larger hake become increasingly piscivorous, and herring are large component of hake diet off Vancouver Island. Although 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 greatest northern migration each season. During El Niños, a larger proportion of the stock migrates into Canadian waters, apparently due to intensified northward transport during the period of active migration (Dorn 1995). Range extensions to the north also occur during El Niños, as evidenced by reports of hake from S.E. Alaska during warm water years. During the warm period experienced in 1990s, there have been changes in typical patterns of 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. Because of this, juveniles may be subjected to increased predation from cannibalism and to increased vulnerability to fishing mortality. Subsequently, La Niña conditions apparently caused a southward shift in the center of the stock's distribution and a smaller portion was found in Canadian water 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, but offshore extensions of fishing activity have occurred. 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 on Pacific hake. During the mid 1970's, the 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 motherships. 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 entire quota, and no foreign fishing was allowed. Canada allocates a portion of the catch to joint-venture operation once shore-side capacity if filled.

Historically, the foreign and joint-venture fisheries produced fillets and headed and gutted products. In 1989, Japanese motherships began producing surimi from Pacific hake, using a newly developed process to inhibit myxozoan-induced proteolysis. In 1990, domestic catcher-processors and motherships 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 made Pacific hake a viable alternative. In 1991, joint-venture fishery for Pacific hake ended because of the high level of participation by domestic catcher-processors and motherships, 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 led to a rapid expansion of shore-based landings in the early 1990's.

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. experience. 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 former Soviet Union caught the majority of hake in the Canadian zone, with Poland and Japan harvesting much smaller amounts. 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. Since the demand of Canadian shore-based processors remains below the available yield, the joint-venture fishery will continue 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 are processed into surimi, fillets, or mince by processing plants at Ucluelet, Port Alberni, and Delta. 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 lat. 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 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 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 U.S. and Canadian fisheries lead to quota overruns; 1991-1992 quotas summed to 128% of the ABC, while in 1993-1999 the 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 a recent preliminary agreement between the United States and Canada (2003) 73.88% and 26.12%, respectively, of the coastwide allowable biological catch is to be allocated to the two countries. Furthermore, the agreement, yet to be ratified, states that a Joint Technical Committee will exchange data and conduct stock assessments which will be reviewed by a Scientific Review Group. This document represents the efforts of the joint US-Canada Technical Committee.

United States

Prior to 1989, catches in the U.S. zone were substantially below the harvest guideline, but since 1989 the entire harvest guideline has been caught with the exception of 2000, 2001 and 2003 which were 90%, 96% and 96% of the quota, respectively. The total U.S. catch has not significantly exceeded the harvest guideline for the U.S. zone (Table 2), indicating that in-season management procedures have been very 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. More recently, yields in the U.S. zone have been restricted to level below optimum yields due to widow bycatch in the hake fishery. At-sea processing and night fishing (midnight to one hour after official sunrise) are prohibited south of 42˚ N lat. Fishing is prohibited in the Klamath and Columbia River Conservation zones, and a trip limit of 10,000 pounds is established for 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 moved to May 15. Shore-based fishing is allowed after April 1 south of 42˚ N. lat. 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. A new allocation agreement, effective in 1997, divided the U.S. non-tribal harvest guideline between factory trawlers (34%) , vessels delivering to at-sea processors (24%), and vessels delivering to shore-based processing plants (42%).

Shortly after this 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 between 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 conducts research to support hake stock assessment. As part of this effort, PWCC sponsored a juvenile recruit survey in summer of 1998 and 2001, which is presently ongoing in collaboration with NMFS scientists.

Canada

The Canadian Department of Fisheries and Oceans (DFO) is responsible for managing the Canadian hake fishery. Prior to 1987, the quota was not reached due to low demand for hake. In subsequent years the quota has been fully subscribed, and total catch has been successfully restricted to ±5% of the quota (Table 2).

Domestic requirements are given priority in allocating yield between domestic and joint-venture fisheries. During the season, progress towards the domestic allocation is monitored and any anticipated surplus is re-allocated to the joint-venture fishery. The Hake Consortium of British Columbia coordinates the day-to-day fleet operations within the joint-venture fishery. Through 1996, the Consortium split the available yield equally among participants or pools of participants. In 1997, Individual Vessel Quotas (IVQ) were implemented for the British Columbia trawl fleet. IVQs of Pacific hake were allotted to licence holders based on a combination of vessel size and landing history. Vessels are allocated proportions of the domestic or joint-venture hake quota. There is no direct allocation to individual shoreside processors. Licence holders declare the proportion of their hake quota that will be landed in the domestic market, and shoreside processors must secure catch from vessel licence holders.

Overview of Recent Fishery and Management

<u>United States</u>

In 1998, the GMT recommended a status quo ABC of 290,000 mt for 1998 (i.e. the same as 1997). The ABC recommendation was based on a decision table with alternative recruitment scenarios for the 1994 year class, which was again considered a major source of uncertainty in current stock status. Recommendations were based on the moderate risk harvest strategy. The PFMC adopted the recommended ABC and allocated 80 percent of the ABC (232,000 mt) to U.S. fisheries.

The GMT recommended a status quo ABC of 290,000 mt for 1999 and 2000. This coastwide ABC was roughly the average coastwide yield of 301,000 mt and 275,000 mt projected for 1999 and 2000, respectively based on F40% (40-10 option) harvest policy.

In 2000, a Pacific hake assessment update was performed by Helser et al. (2001). While additional catch and age composition data were available at the time of the assessment, the 2001 coastwide acoustic survey which serves as the primary index of hake abundance was not. Using the same configuration with the updated fishery composition data and recruitment indices the assessment model showed consistent projections with the 1998 assessment. Based on this, the GMT recommended that the ABC in 2001 be set to the projected yield of 238,000 mt based on the F40% (40-10 option) harvest policy. Allowable biological catches in 2002 and 2003 were based the 2001 Pacific hake stock assessment (Helser et al. 2001) with updated fishery data and a new acoustic survey biomass estimated for 2001. Due to declining biomass and an estimated depletion level of 20% unfished biomass in the 2001 assessment the ABC in 2002 was 208,000 mt and based the F45% (40-10) harvest policy. However, the ABC in 2003 was adjusted upward to 235,000 mt under the same harvest policy to reflect projected increases in biomass from the relatively strong 1999 year class. In 2004, the coastwide ABC was estimated to be 514,441 mt based on the Fmsy proxy harvest rate of F40% applied to the model in which acoustic survey 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 very strong 1999 year-class. The final commercial US OY was set at 250,000 mt due to constraints imposed by bycatch of widow rockfish in the hake fishery. The Makah tribe was allocated 32,500 mt in 2004.

Landings of the at-sea fishery constituted roughly 54% of the total U.S. fishery catches since 1999. Significant distributional shifts in the Pacific hake population, presumably due to oceanographic conditions, has caused major fluctuations in the center of the at-sea harvesting sector. Most notable in recent years was the northward shift in 1999 at-sea fleet activity in which most catches were distributed North of the Columbia River (roughly 91% of the at-sea catches) and coincided with a strong El Nino the preceding year. At sea catches returned to more normal spatial distribution patterns in the 2000 fishing season with roughly 60% occurring north and 40% occurring south of the Columbia River. In 2001, the pattern of the at-sea catches were opposite of those seen in 1999 with only roughly 22% north of the Columbia River (Fig. 2). This coincided with a relatively strong La Nina. The at sea catch distributions for 2002 and 2003 were representative of more normal patterns with roughly 60% and 40% of the catches south and north of Newport, OR. In 2003, the at-sea catch of hake was 67,473 mt, with Motherships harvesting 39% (26,021m t) while the catcher/processor sector harvesting 61% (55,389 mt) of the hake allocation. At sea distribution of catch in 2004 showed a slightly stronger northward pattern with roughly 50% of the catch occurring north and south of Newport. The total at sea sector harvested approximately 43% (90,200 mt) of the total U.S. catch of 210,400 mt.

The total shore-based U.S. landings in 2002 and 2003 were 46,000 mt and 45,000 mt, respectively. The primary ports harvesting Pacific hake in 2002 were Newport, Oregon (18,553m t), Astoria, Oregon (12,171 mt), Coos Bay, Oregon (1,580 mt), Washington coastal ports (primarily Westport) (10,610 mt) , and Eureka, California (2,773 mt). In 2003, landings from Eureka were down roughly 50% from 2002, but up by over 2,000 mt in the Washington coastal port of Ilwaco. In aggregate, these ports accounted for more than 99% of all shore-based hake landings. The shore-based fishery began in mid June and ended on July 14 when the harvest guideline was attained. In 2004, the shore-based fishery harvested 46% (96,200 mt) of the total U.S. catch of 210,400 mt. As in previous years, the dominate ports were Newport (38,800 mt) followed by Westport (30,000 mt) and Astoria (16,000 mt).

Since 1996, the Makah Indian Tribe has conducted a separate fishing in its" Usual and Accustomed Fishing Area." The tribal fishery was allocated 15,000 mt of hake in 1996 with an increase to 25,000 mt in 1997- 1999, 32,500 mt in 1999-2000, and 20,000 mt in 2001-2003. The tribe harvested essentially all of its allocated catch between 1996-1999, however, in 2000 and 2001 the Makah Tribe only harvested 6,500 mt and 6,774 mt, respectively. In 2003, the Makah fishery began in June 13 and harvested roughly 90% of its allocated 25,000 mt. In 2004, pacific hake distribution provided a favorable fishery in the Makah tribal fishing area; the Makahs harvested approximately 74% (24,000 mt) of the Tribal allocation and 11% of total US catch.

<u>Canada</u>

DFO managers allow a 15% discrepancy between the quota and total catch. The quota may be exceeded by up to 15%, which is then taken off the quota for the subsequent year. 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. Between 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 the Canadian zone 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.

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 survey estimates of absolute abundance at age (Hollowed et al. 1988a). Since 1989, a stock synthesis model that utilizes fishery catch-at-age data and 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). The conversion from stock synthesis to AD model builder consisted of programming the population dynamics and likelihood equations in the model implementation language (a superset of C++). In that assessment, Dorn et al. (1999) provided model validation using a side-by-side comparison of model results between stock synthesis and ADMB, and then extended the approach to take advantage of AD model builder's post-convergence routines to calculate 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. Helser et al. (2001), using the same AD model builder modeling framework, conducted the Pacific hake stock assessment for 2001. That assessment included updated fishery and new survey biomass estimates, with exploration of numerous alternative model structures and assumptions. The hake assessment conducted in 2003 (Helser et al. 2004) incorporated information from a joint US/Canadian acoustic survey in the summer of 2003, which confirm the large 1999 year-class. That assessment employed several important modifications including: 1) revision of acoustic survey biomass estimates from 1977-1992 to reflect new deep-water and northern expansion factors; 2) initialization of the population age composition in 1966 (vs. 1972) including estimates of recruitment at age 2 from 1966-2003; and 3) discrete temporal changes in the acoustic survey selectivity. Due to the lengthened acoustic survey biomass trends the assessment model was able to freely estimate the acoustic survey catchability coefficient (q); on the order of .4-.5 and substantially below the assumed q=1.0 from earlier assessments. The ability to relax the q=1.0 assumption was based upon: 1) continued lengthening of the acoustic survey time series, thus allowing the survey to be treated as an index of relative abundance in the model; 2) relatively better model fits to the data when q is less than 1.0; and 3) high quality of expertise in the 2003 STAR Panel to allow critical examination of the q=1.0 assertion. As such, the 2003 assessment presented uncertainty in the final model result as a range of biomass. The lower biomass end of the range is based upon the conventional assumption that the acoustic survey catchability coefficient, q=1.0, while the higher end of the range represents the q=0.6 assumption. The assessment presented in this document represents an update based on the same model configurations the 2003 assessment. New information used in the modeling include total fishery removals, fishery age compositions, and a hake pre-recruit index through 2004. The joint US/Canadian acoustic survey is planned for the summer of 2005.

Data Sources

The data used in the stock assessment model included:

- Total catch from the U.S. and Canadian fisheries (1966-2004).

- Catch at age and average weights at age from the U.S. (1973-2004) and Canadian fisheries (1977-2004).

- Biomass and age composition from the Joint US-Canadian acoustic/midwater trawl surveys (1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998, 2001, and 2003). Note: the 1986 acoustic survey biomass index was omitted due to transducer and calibration problems.

- Indices of young-of-the-year abundance from the Santa Cruz Laboratory larval rockfish surveys (1986-2004). In this, as in the previous 2001 and 2003 assessment, the Santa Cruz Laboratory indices of young -of-the-year were used as an age-2 tuning index for stock reconstruction and for future projections (two years out from the terminal year in the assessment, i.e. 2003 and 2004).

The model also uses biological parameters to characterize the life history of hake. These parameters are used in the model to estimate spawning and population biomass, and obtain predictions of fishery and survey biomass from the parameters estimated by the model:

- Proportion mature at age.

- Weight at age and year by fishery and by survey

- Natural mortality (M)

Total catch

Table 1 gives the catch of Pacific hake for 1966-2004 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 feet increased after observers were placed on foreign vessels in the late 1970's. For 1981-2003, 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 1991-2003 are estimated by the North Pacific Groundfish Observer Program (NPGOP).

At-sea discards are included in the foreign, joint-venture, at-sea domestic catches in the U.S. zone. Discards have not been estimated for the shore-based fishery. 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.

Fishery age composition

Catch at age for the foreign fishery in the U.S. zone during 1973-1975 is given in Francis and Hollowed (1985), and was reported by Polish and Soviet scientists at bilateral meetings. Estimates of catch at age for the U.S. zone foreign and joint-venture fisheries in 1976-1990, and the at-sea domestic fishery in 1991-2003, were derived from length-frequency samples and length-stratified otolith samples collected by observers. Sample size information is provided in Table 3. In general, strata were defined by the combination of three seasonal time periods and three geographic areas. Methods and sample sizes by strata are given in Dorn (1991, 1992). During 1992-2004, at-sea catch was generally restricted to between May and August in the early part of the year (April-June) north of 42˚ N. lat., so only two spatial strata were used, and no seasonal strata were defined. Due to the migratory nature of hake spatial strata are defined each fishing year on the basis of marked changes in size/age compositions. For instance, during the 2004 fishing year, the 1999 year-class (age 5) was so ubiquitous in the at sea fishery that average size and age of hake were consistent until about 47º N latitude. North of 47º the average size/age and their variance increased. The Makah fishery (1996-2003) was defined as a separate strata because of its restricted geographic limits and different seasons.

Biological samples from the shore-based fishery were collected by port samplers at Newport, Astoria, Crescent City, and Westport from 1997-2004. A stratified random sampling design is used to estimate the age composition of the landed catch (sample size information provided in Table 3). Shore-based strata are defined on the basis of port of landing. In 1997- 2004, four strata were defined: 1) northern California (Eureka and Crescent City), 2) southern Oregon (Newport and Coos Bay), 3) northern Oregon (Astoria and Warrenton), and 4) Washington coastal ports (Illwaco and Westport). No seasonal strata have been used for the shore-based fishery due to the general brevity of the fishery; however, port samplers are instructed to distribute their otolith samples evenly throughout the fishing season.

Biological samples from the Canadian joint-venture fishery were collected by fisheries observers, placed on all foreign processing vessels in 1997-2004. Shore-based Canadian landings are sampled by port samplers. The Canadian catch at age is estimated from random otoliths samples.

Figure 3 shows the estimated age composition for the shore-based fishery by port in the U.S. zone from the three most recent years, 2002-2004. In most years, in the absence of a single dominant strong year-class, the shore-based age compositions show both temporal and spatial variation; age compositions are composed of older fish in the more northerly fishing ports, particularly Washington coastal ports. However, port specific age compositions for 2002-2004 clearly reflect the prominence of the 1999 year-class as seen as age 3, age 4, and age 5 fish in 2002, 2003 and 2004, respectively.

Figure 4 shows the estimated age composition for the at sea fishery by stratum (including Makah tribal fishing area) in the U.S. zone from 2002-2004. As in the shore-based fishery, age compositions comprise older fish in the northern stratum and the Makah area. Again, this pattern is due to the further northward migration of older/larger hake. The 1999 year class is also the dominate age in the at sea fishery catches in 2002-2004.

Table 4 (Figs. 5-6) give the estimated U.S. fishery (1973-2004) and Canadian fishery catch at age (1977-2004). The U.S. fishery catch at age was compiled from the NORPAC database maintained by the North Pacific Groundfish Observer Program, and from an additional database of shore-based biological sampling maintained by the NWFSC Age and Growth Laboratory in Newport, OR. The Canadian catch at age for 1997-2004 was compiled from a database at the Pacific Biological Station. The 1980 and 1984 year classes appear as the dominant year classes in both the U.S. fishery and Canadian fishery age compositions (Figs. 5-6). The 1970 and 1977 year classes, and more recently the 1999 year class, are also evident.

Since aging Pacific hake was transferred 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 197 otoliths from the 2003 acoustic survey between the Northwest Fisheries Science Center (NWFSC) and Department of Fisheries and Oceans (DFO). Overall agreement between NWFSC/DFO was 50%, and for ages assigned that were aged within one and two years, the agreement was 86% and 96%, respectively. As would be expected, agreement between the three labs was better for younger fish than for older fish. These cross-calibration results were somewhat better than 2001 comparisons between NWFSC/DFO, but poorer than 1998 comparisons between AFSC (Alaska Fishery Science Center) and DFO. It should be noted, however, that agreement between two age readers at NWFSC was closer to 87%, with 98% agreement within one year of age. Agreement for ages 3-4 and ages 5-7 was 82% and 40%, respectively, for NWFSC between reader comparisons, with similar results for NWFSC/DFO comparisons. Also, when ages did not agree between the three labs agers at the NWFSC tended to assign older ages than DFO. Additional comparisons are needed to further calibrate ageing criteria between agencies.

Triennial Acoustic Survey (Biomass and Age Composition)

The integrated acoustic and trawl surveys, used to assess the distribution, abundance and biology of coastal Pacific hake, *Merluccius productus*, along the west coasts of the United States and Canada have been historically conducted triennially by Alaska Fisheries Science Center (AFSC) since 1977 and annually along the Canadian west coast since 1990 by Pacific Biological Station (PBS) scientists. The triennial surveys in 1995, 1998, and 2001 were carried out jointly by AFSC and DFO. Following 2001, the responsibility of the US portion of the survey was transferred to Fishery Resource Analysis and Monitoring (FRAM) Division scientists at the Northwest Fisheries Science Center (NWFSC). The joint 2003 survey was conducted by FRAM and PBS scientists, marking not only the change in the US participants but also shortens the frequency between surveys.

The 2003 survey was conducted by joint US and Canadian science teams aboard the vessel CCGS *W.E. Ricker* from 29 June to 1 September 2003, covering the length of the west coast from south of Monterey California (36.1° N) to the Dixon Entrance area (54.4° N). A total of 115 line transects, generally oriented east-west and spaced at 10 nm intervals, were completed (Fig. 7). During the 2003 acoustic survey, aggregations of hake were found along the continental shelf break from just north of San Francisco Bay (38° N) to Queen Charlotte Sound (52° N). Peak concentrations of hake were observed north of Cape Mendocino, California (ca. 43° N), in the area spanning the US-Canadian border off Cape Flattery and La Perouse Bank (ca. 48.5° N), and in Queen Charlotte Sound (ca. 51° N). Along transect 44 (42.9° N), hake were found in a continuous aggregation that extended to over 2500 meters of water and 20 nm further offshore than seen previously in this area. By contrast, no hake were found north of transect 98 in Queen Charlotte Sound (52° N). As revealed by the associated midwater and bottom trawl samples, the majority of the coastal stock is currently dominated by the 1999 year-class (age 4), with most fish at an average size of 43-44 cm in tows south of 48° N, are larger hake found further north.

Hake distribution during the 2003 acoustic survey appeared to be more representative of normal years. Aggregations of Pacific hake showed a marked contrast in 1998 and 2001 relative to the 2003 acoustic survey (Fig. 7 continued). In 1998, major aggregations were observed off Oregon between Cape Blanco and Coos Bay; near the US-Canada border, between northern Vancouver Island and southern Queen Charlotte Sound, and to lesser extent along the west side of the Queen Charlotte Islands, northern Hecate Strait, and Dixon Entrance. Hake were found as far north as 58° N. lat. in the Gulf of Alaska. There was also a large northward shift in the distribution of biomass compared to previous surveys. In contrast, most of the biomass of hake in the 2001 acoustic survey was distributed south of Newport, Oregon (Fig 7). Aggregations of hake in the 2001 acoustic survey were observed off northern California between Cape Mendocino and San Francisco Bay and off southern Oregon near Cape Blanco. The most notable differences between the 1998 and 2001 survey was the presence of hake aggregations south of Cape Blanco and the absence of hake off the Washington coast in the 2001 survey.

The 2001 and 2003 acoustic survey were similar in that 80% and 86%, respectively, of the total hake biomass occurred south of 47˚30'N (i.e., Monterey, Eureka, and Columbia INPFC areas). In contrast, only 35% of the total biomass in 1998 was observed south of 47˚30'N. The biomass in Canadian waters in 1998 was nearly triple the level reported in 1995. In 2001 and 2003, age 3+ hake biomass was split 80/20 between the U.S. and Canadian zone.

The 1998 survey results indicate a moderate decline of about 15% in hake biomass relative to the previous coastwide survey in 1995, however the 2001 acoustic survey dropped 62% relative to the 1998 survey. In contrast, the 2003 biomass estimate (1843 million mt) increased 120% over the 737,000 mt of the 2001 survey. The strong 1999 year class shown entering the population as age 4 fish in 2003 is principally responsible for the increase.

Revision of the Acoustic Survey Biomass and Age Composition

In 1996, research on hake acoustic target strength (Traynor 1996) resulted in a new target strength model of TS = 20 log L - 68. Target strength (TS) is a measure of the acoustic reflectivity of the fish and is necessary to scale measured backscattering to produce absolute estimates of abundance. Biomass estimates for the 1977-89 acoustic surveys were re-estimated using the new target strength. Relative to the more recent surveys (1992-2003) in which hake aggregations were found further offshore and in more northerly latitudes, the 1977-1989 surveys were corrected for the limited geographic coverage by calculating deep water and northern expansion factors used to adjust the total acoustic backscatter (Dorn 1996). Dorn's (1996) revised acoustic time series, which averaged 31% higher than the original time series for 1977-89, had been used in subsequent stock assessments until 2001. The 2003 assessment included a revision of deepwater and northern expansion factors (See Helser et al. 2004 for details) which were based on additional acoustic surveys not included in Dorn's analysis. In addition, the Helser et al. (2004) analysis also included adjusted age compositions that reflect changes in biomass and thus numbers at age. Comparison of acoustic survey biomass trends shown in Figure 8 illustrate the relative differences between the analyses, along with the final age compositions used in the assessment (Table 5). Despite attempts to corrected for incomplete spatial coverage of the earlier acoustic surveys, these years are still uncertain than compared to more recent surveys. As such, larger coefficient of variation s (CVs) as assigned to reflect additional levels of uncertainty in the earlier surveys and time averaged expansion factors (CV~0.5). Overall CVs, calculated by application of post survey stratification of the 2003 acoustic survey, was in the 0.35 range (Fleischer et al. 2004).

Triennial Shelf Trawl Survey (Hake distribution)

The Alaska Fisheries Science Center has conducted a triennial bottom trawl survey along the west coast of North America between 1977-2001 (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. More over, bottom trawl used in the survey is limited in its effectiveness at catching mid-water schooling hake. In the context of this assessment we examine the spatial distribution of hake in this survey relative to that found in the acoustic survey.

The most recent survey conducted by the NWFSC was carried out from May 5 to July 28, 2004 from south of Point Conception (33° N. lat.) to the U.S./Canadian border (approx. 48°30′ N. lat.) aboard four chartered commercial trawlers (See Turk et al. 2001 for details). The vessels were equipped with the FRAM Division's standardized Aberdeen bottom trawls and net mensuration equipment. Pacific hake were caught at 353 of the 383 successfully sampled stations. Catch rates of hake were highest in the Columbia and Vancouver INPFC areas followed by Eureka (Figure 9). Catch rates over the entire survey area increased with depth.

Santa Cruz Laboratory Midwater Trawl Recruit Survey

The Santa Cruz Laboratory of the Southwest Fisheries Science Center has conducted annual surveys since 1983 to estimate the relative abundance of pelagic juvenile rockfish off central California. Although not specifically designed to sample juvenile hake, young-of-the-year juvenile hake occur frequently in the midwater trawl catches. In this assessment as in the previous 2001 assessment, the index is used as a tuning index for recruitment to age-2 and to project the relative strength of recruitment two years into the future (Table 8, fig 10). This index was obtained using from a generalized linear model (GLM) fit to the log-transformed CPUEs (Ralston et al. 1998; Sakuma and Ralston 1996). Specifically, the year effect from the GLM was back-transformed to obtain an index of abundance. Only the Monterey outside stratum was used because of its higher correlation with hake recruitment. Also, Dorn et al. (1999) showed that the juvenile index was significantly correlated to the predicted recruitment two years later in the stock assessment model. The index in 1999 suggested that age-2 recruitment in 2001 may be above average, which has largely been confirmed by other data sources such as numbers at age in the fishery catches and acoustic survey. Except for the 2001 larval index (representing age 2 recruitment in 2003) which appears to be average, the most recent 2002 and 2003 indexes are among the lowest observed since 1986. As will be discussed below, the PWCC recruit survey shows a marked contrast to the 2003 survey index. Most recently, the 2004 index, which appears to be about the same strength as 1999, also indicates the potential for a larger than average recruitment in 2006. The PWCC pre-recruit survey is also consistent with the Santa Cruz survey for 2004. The Santa Cruz series average CV, estimated from the GLM, was calculated to be approximately 0.50. Relative accuracy of the Santa Cruz and PWCC pre-recruit surveys will be evaluated following the 2005 coastwide acoustic survey.

PWCC-NMFS midwater trawl survey

The Pacific Whiting Conservation Cooperative (PWCC) and the National Marine Fisheries Service, Northwest Science Center (NWFSC) and Santa Cruz Laboratory (SCL), Southwest Fisheries Science Center has been conducting a cooperative survey of juvenile hake and rockfish relative abundance and distribution off Oregon and California since 1999. This survey is an expansion of the Santa Cruz Laboratory's juvenile survey conducted in between Monterrey Bay and Pt. Reyes, California. Prior to 2001 results between the PWCC survey and the SCL survey were not comparable because of trawl gear differences. Since 2001, the gear has been comparable and side-by-side comparisons were made between the PWCC vessel *Excalibur* and the SCL vessel *David Starr Jordan.*

The PWCC Pacific whiting prerecruit survey is conducted in May at stations across the continental shelf between Newport Oregon (44º30'N) and Point Arguello California (34º 30' N). Several stations were sampled on transects located at 30 nm intervals. Transect stations were located over waters between 50 m and approximately 1200 m depth. A total of 113 trawl samples were taken during the survey.

A modified anchovy midwater trawl with an 86' headrope and ½" codend with a 1/4" liner was used to obtain samples of juvenile hake and rockfish. Trawling was done at night with the head rope at 30 m at a speed of 2.7 kt. Some trawls were made prior to dusk to compare day/night differences in catch. Trawls sets of 15 minutes duration at target depth were conducted along transects located at 30 nm intervals along the coast (Figure 1). Stations were located along each transect from 50m bottom depth seaward to 700 m with hauls taken over bottom depths of 50, 100, 200, 300, and 500 meters at each transect.

The hake YOY were primarily distributed between 40 and 41 N. Lesser amounts of YOY hake were encountered in the Monterey Bay area relative to earlier years, and fewer hake YOY were captured at the southern extreme of the survey area. The total number of YOY hake captured in the 2003 PWCC/NMFS survey was much greater than in prior years. In 2001, 5,610 hake YOY were captured, and in 2002 a total of 6,359 were captured, while in 2003 the number increased to 42,541. The absolute variance was higher in 2003 with a high proportion of YOY hake in a few hauls; however the coefficient of variation was nearly similar between years, indicating that 2003 results were not anomalous. Abundance of YOY hake from the most recent 2004 survey indicated a 3-fold increase over 2003.

The Santa Cruz survey results indicate that 2001 hake year class is near the long-term mean of the index, but that 2002 is a relatively weak year class, and 2003 estimated abundance is the lowest observed. The PWCC index, on the other hand, indicates that the 2001 and 2002 are both near average year-classes and 2003 a strong year class. The conclusion of two near average year classes is based on a comparison of 2001 and 2002 results. In 2001, the Santa Cruz index was average and the PWCC coast wide distribution of hake YOY showed Monterrey Canyon as the center of abundance. However, in 2002, the center of abundance in the PWCC survey was further north, and proportionally less hake YOY occurred in the Monterrey Bay area.

In 2003 the difference in number of hake YOY between the PWCC and Santa Cruz surveys was more pronounced, although both surveys were relatively consistent in 2004. The PWCC survey had a nearly seven fold increase in estimated abundance over the previous two years, while the Santa Cruz survey found the lowest number in the time series. This discrepancy may in large part be due to the fact that the PWCC survey encountered numerous pre-recruit hake above 40º N latitude; above the northern-most boundary of the Santa Cruz survey.

The PWCC hake prerecruit survey results are interesting in that they show an inconsistent trend in some years than the Santa Cruz survey over the same time period. The PWCC survey indicates 2001 and 2002 abundance to be about the same magnitude and 2003 to be significantly higher. The Santa Cruz Survey, on the other hand, suggests that the 2003 index to be the least abundant year class of the series, while the index for 2004 somewhat consistent between the two surveys. However, until a longer time series is established, or a calibration can be achieved with the Santa Cruz juvenile rockfish survey it is difficult to determine what the results mean in terms of future abundance levels of the measured year class. As the year classes in question accrue to the catch the question of relative year class size will be established. The expansion of the hake recruitment index beyond the traditional NMFS Santa Cruz Lab survey area raises questions of consistency in hake larval distribution. The results of the 2003, and particularly 2004 PWCC survey suggest that transport of larvae may be spatially varying with larvae reaching the outer shelf, north of the Monterey index area in some years. However, it is possible that the larvae follow a set transport pattern, but vary temporally. If there is a temporal component there may be some evidence in larval daily growth or an environmental signal. With additional data, it may be possible to model and predict the distribution of YOY and better deploy survey effort.

Weight at age

Year-specific weights at age are used in all years for each fishery and survey and for the population because significant variation in Pacific hake weight at age has been observed (Table 9) (Dorn 1995). In particular, weight at age declined substantially during the 1980's, then remained fairly constant to 1998. Interestingly, average weights at age increased substantially in 2000 and 2001 in both the fishery and surveys, suggesting more favorable growth in recent years. Weights at age, however, have declined in both the fishery and survey in 2003. Weight at age is inversely correlated with sea-surface temperature and (to a lesser extent) adult biomass (Dorn 1992). Weight at age estimates for 1977-87 are given in Hollowed et al. (1988b). Weight-at-age vectors since 1987 were derived from the length-weight relationship for that year and unbiased length at age calculated using age length keys (Dorn 1992). In some cases, a linear interpolation of the weight at age of the strong year classes was used for the weaker year classes whose weight at age was poorly estimated or not available due to small sample sizes. This was necessary only for the older or less abundant age groups. Population weight at age, used to calculate spawning biomass, was assumed to be equal to the nearest AFSC acoustic survey weight-at-age.

Age at Maturity

Dorn and Saunders (1997) estimate female maturity at age with a logistic regression using ovary collections and visual maturity determinations by observers as

Age														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.000	0.176	0.661	0.890	0.969	0.986	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Natural mortality

The natural mortality currently used for Pacific hake stock assessment and population modeling is 0.23. 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 for Merluciids worldwide, 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).

Model Development

Population dynamics

The age-structured model for hake describes the relationships between population numbers by age and year. The modeled population includes individuals from age 2 to age 15, with age 15 defined as a "plus" group, i.e., all individuals age 15 and older. The model extends from 1966 to 2003. The Baranov (1918) catch equations are assumed, so that

$$c_{ijk} = N_{ij} \frac{F_{ijk}}{Z_{ij}} [1 - \exp(-Z_{ij})]$$

$$N_{i+1\ j+1} = N_{ij} \exp(-Z_{ij})$$

$$Z_{ij} = \sum_k F_{ijk} + M$$

except for the plus group, where

$$N_{i+1,15} = N_{i,14} \exp(-Z_{i,14}) + N_{i,15} \exp(-Z_{i,15})$$

where N_{ij} = population abundance at the start of year *I* for age *j* fish, F_{ijk} = fishing mortality rate in year *I* for age *j* fish in fishery *k*, and c_{ijk} = catch in year *I* for age *j* fish in fishery *k*. A constant natural mortality rate, *M*, irrespective of year and age, is assumed.

The U.S. and Canadian fisheries are modeled as distinct fisheries. Fishing mortality is modeled as a product of year-specific and age-specific factors (Doubleday 1976)

$$F_{ijk} = s_{jk} f_{ik}$$

where s_{jk} = age-specific selectivity in fishery *k*, and f_{ik} = the annual fishing mortality rate for fishery *k*. To ensure that the selectivities are well determined, we require that $\max(s_{jk}) = 1$ for each fishery. Following previous assessments, a scaled double-logistic function (Dorn and Methot 1990) was used to model age-specific selectivity

$$s_j^{/} = \left(\frac{1}{1 + \exp[-\beta_1(j - \alpha_1)]} \right) \left(1 - \frac{1}{1 + \exp[-\beta_2(j - \alpha_2)]} \right)$$

$$s_j = s_j^{/} \; / \; \max_j \; (s_j^{/})$$

where α_1 = inflection age, β_1 = slope at the inflection age for the ascending logistic part of the equation, and α_2 , β_2= the inflection age and slope for the descending logistic part. The subscript k , used to index a fishery or survey, has been suppressed in the above and subsequent equations in the interest of clarity.

Measurement error

Model parameters were estimated by maximum likelihood (Fournier and Archibald 1982, Kimura 1989, 1990, 1991). Fishery observations consist of the total annual catch in tons, C_i, and the proportions at age in the catch, p_{ij}. Predicted values from the model are obtained from

$$\hat{C}_i = \sum_j w_{ij} \; c_{ij}$$

$$\hat{p}_{ij} = c_{ij} \; / \; \sum_j \; c_{ij}$$

where w_{ij} is the weight at age j in year I . Year- and fishery-specific weights at age are used because of the changes in weight at age during the modeled time period.

Log-normal measurement error in total catch and multinomial sampling error in the proportions at age give a log-likelihood of

$$\log \; L_k = -\sum_i [\log(C_i) - \log(\hat{C}_i)]^2 \; / \; 2\sigma_i^2 + \sum_i \; m_i \sum_j \; p_{ij} \; \log(\; \hat{p}_{ij} \; / \; p_{ij})$$

where σ_i is standard deviation of the logarithm of total catch (~ CV of total catch) and m_i is the size of the age sample. In the multinomial part of the likelihood, the expected proportions at age have been divided by the observed proportion at age, so that a perfect fit to the data for a year gives a log likelihood value of zero (Fournier and Archibald 1982). This formulation of the likelihood allows considerable flexibility to give different weights (i.e. emphasis) to each estimate of annual catch and age composition. Expressing these weights explicitly as CVs (for the total catch estimates), and sample sizes (for the proportions at age) assists in making reasonable assumptions about appropriate weights for estimates whose variances are not routinely calculated.

Survey observations from age-structured survey (acoustic survey) consist of a total biomass estimate, B_i, and survey proportions at age π_{ij}. Predicted values from the model are obtained from

$$\hat{B}_i = q \sum_j w_{ij}\; s_j\; N_{ij}\; \exp[-\phi_i\; Z_{ij}]$$

where q = survey catchability, s_j = selectivity at age for the survey, and ϕ_i = fraction of the year to the mid-point of the survey. Survey selectivity was modeled using a double-logistic function of the same form used for fishery selectivity. The expected proportions at age in the survey in the *i*th year are given by

$$\hat{\pi}_{ij} = s_j\; N_{ij}\; \exp[-\phi_i\; Z_{ij}] \;/\; \Sigma_j\; s_j\; N_{ij}\; \exp[-\phi_i\; Z_{ij}]$$

Log-normal errors in total biomass and multinomial sampling error in the proportions at age give a log-likelihood for survey *k* of

$$\log\; L_k = -\sum_i [\log(B_i) - \log(\hat{B}_i)]^2 \;/\; 2\sigma_i^2 + \sum_i\; m_i \sum_j\; \pi_{ij}\; \log(\; \hat{\pi}_{ij} \;/\; \pi_{ij})$$

where σ_i is the standard deviation of the logarithm of total biomass (~ CV of the total biomass) and m_i is the size of the age sample from the survey.

For surveys that produce only an index of recruitment at age 2, R_i , predicted values from the model are

$$\hat{R}_i = q\; N_{i2}$$

Log-normal measurement error in the survey index gives a log-likelihood of

$$\log\; L_k = -\sum_i [\log(R_i) - \log(\hat{R}_i)]^2 \;/\; 2\sigma_i^2$$

where σ_i is the standard deviation of the logarithm of recruitment index. Since the recruitment surveys occur several years before recruitment at age 2, the indices need to be shifted forward the appropriate number of years.

Process error and Bayes priors

Process error refers to random changes in parameter values from one year to the next. Annual variation in recruitment and fishing mortality can be considered types of process error (Schnute and Richards 1995). In the hake model, these are estimated as free parameters, with no additional error constraints. We use a process error to describe changes in fisheries selectivity over time using a random walk (Gudmundsson 1996).

To model temporal variation in a parameter γ , the year-specific value of the parameter is given by

$$\gamma_i = \bar{\gamma} + \delta_i$$

where $\bar{\gamma}$ is the mean value (on either a log scale or linear scale), and δ_i is an annual deviation subject to the constraint $\sum \delta_i = 0$. For a random walk process error where annual *changes* are normally distributed, the log-likelihood becomes

$$\log\ L_{Proc.\ Err.} = -\sum \frac{(\delta_i - \delta_{i+1})^2}{2\sigma_i^2}$$

where σ_i is the standard deviation of the annual change in the parameter. We use a process error model for all four parameters of the U.S. fishery double-logistic curve. For the Canadian fishery double-logistic curve, a process error model was used only for the two parameters of the ascending part of the curves. Since the descending portion is almost asymptotic, little improvement in fit can be obtained by including process error for those parameters.

Bayesian methods offer a number of conceptual and methodological advantages in stock assessment (Punt and Hilborn 1997). We adopt an incremental approach of adding Bayes priors to what is essentially a maximum likelihood model. In non-linear optimization, the usual practice is to place upper and lower bounds on estimated parameters (a feature of both stock synthesis and AD model builder). From a Bayesian perspective, placing bounds on the possible values of a parameter corresponds to using a uniform prior for that parameter. Additional constraints are imposed on a parameter γ by adding the log likelihood for a log-normal prior,

$$\log\ L_{Prior} = \frac{-[\log(\gamma) - \log(\tilde{\gamma})]^2}{2\sigma^2}$$

where $\tilde{\gamma}$ is the prior mean, and σ is the standard deviation of the logarithm of the prior. In this assessment, we continue to use a prior for the slope of the ascending part of the acoustic survey double-logistic function.

The total log likelihood is the sum of the likelihood components for each fishery and survey, plus terms for process error and priors,

$$Log\ L = \sum_k Log\ L_k + \sum_p Log\ L_{Proc.\ Err.} + Log\ L_{Prior}\ .$$

Likelihood components and variance assumptions for the base-run assessment model are given in the following table:

Likelihood component	Error model	Variance assumption
U.S. fishery total catch	Log-normal	CV = 0.05
U.S. age composition	Multinomial	Sample size = 300
Canadian fishery total catch	Log-normal	CV = 0.05
Canadian fishery age composition	Multinomial	Sample size = 130
Acoustic survey biomass (q=1.0)	Log-normal	CV = 0.10, CV = 0.20 for 1977-89
Acoustic survey biomass (q=0.6)	Log-normal	CV = 0.30, CV = 0.50 for 1977-89
Acoustic survey age composition	Multinomial	Sample size = 60 (77-04)
Santa Cruz Laboratory larval rockfish survey	Log-normal	CV = 1.1
Fishery selectivity random walk process error	Slope: Log-normal	CV = 0.25
	Inflection age: Normal	SE = 1.0
Prior on acoustic survey slope	Log-normal	Prior mean = 0.9, Prior CV = 0.2

Ageing error

The model was configured to accumulate the marginal age groups at different ages to prevent obvious instances of aging error from affecting the model fit. This approach was used most frequently when a portion of an incoming strong year classes was misaged into an adjacent year class. We also used this approach to obtain reliable estimates of initial age composition. Marginal age groups were combined in the following situations:

- Accumulate the older fish at age 13 in 1973 at age 14 in 1974. Rationale: an age 12+ group is estimated for the initial age composition in 1972 (or 1966 with the 2003 basemodel).

- Accumulate the older fish in the fishery and survey data at age 7 in 1978, age 8 in 1979, age 9 in 1980, etc.. The Canadian age data was only accumulated in 1978 and 1979, but not in subsequent years. Rationale: large numbers of the strong 1970 year class were misaged into the 1971 year class starting in 1978.

- Accumulate the younger fish at age-3 fish in 1979. Rationale: The strong 1977 year class appeared as 3-year-old fish in 1979 due to a small sample size in the age-length key for that year.

- Accumulate the younger fish to age 4 in 1984 and age 5 in 1985 in the Canadian fishery age composition. Rationale: The strong 1980 year class was misaged into the 1981 year class.

- Accumulate the younger fish to age 3 in the 1986 U.S. fishery age composition. Rationale: The strong 1984 year class (2-year-old fish) was misaged into the 1983 year class (3-year-old fish).

- Accumulate the younger fish to age 5 in 1995 and age 6 in 1996 in the Canadian fishery age composition. Rationale: In the 1995 Canadian age composition, the number of 4-year-old fish was greater than the number of 5-year-old fish. In 1996, the age 5-fish were 75% as abundant as the age-6 fish in the Canadian fishery age composition, but only 35% as abundant in the U.S. fishery age composition. The 1991 year class (4-year-old fish in 1995) has been much less common in U.S. fishery samples than the 1990 year class (5-year-old fish in 1995) in each year during 1992-95. It is likely that the 4-year-old fish in the Canadian age composition data are misaged fish from the 1990 year class.

Optimization algorithm and convergence criteria

The optimizer in AD model builder is a quasi-Newton routine that uses auto-differentiation to obtain the gradient (Press et al. 1972). The model is determined to have converged when the maximum gradient component is less than a small constant (set to 1×10^{-4} for the hake model). Optimization occurs over a number of phases, in which progressively more parameters are estimated. Typically the initial phase consists of a catch curve analysis (Ricker 1973) to obtain rough estimates of mean recruitment and fishing mortality. The intermediary stages correspond to separable age-structured models (Deriso et al 1987), while the final stages also include the parameters for time varying selectivity. Thus the model mimics the entire historical development of quantitative stock assessment during a single estimation run. Identical parameter estimates (to 5 decimal places) were obtained when the initial values for mean recruitment and mean fishing mortality were halved and doubled (R = 0.5, 1.0, 2.0 billion, F = 0.1, 0.2, 0.4), suggesting that final parameter estimates were independent of initial values. After the model converges, the Hessian is estimated using finite differences. Standard errors are obtained using the inverse Hessian method. We also assess uncertainty using AD model builder routines for obtaining likelihood profiles and Markov chain Monte Carlo samples from the likelihood function.

Model parameters, as in the previous 2003 assessment model, can be classified as follows:

Population process modeled	Number of parameters estimated	Estimation details
Initial age structure (1966)	Age 2 recruitment dev in 1966 = 1 Age 3-12 (not estimated)	Estimated as log deviance from the log mean. Age 3-12 = $ave.Re^{-M+initF}$ (note: ave R is bias corrected).
Recruitment	Years 1967-04 = 39 (38 devs + 1 log mean)	Estimated as log deviances from the log mean
Average selectivity to fisheries and age-structured surveys	4 * (No. of fisheries + No. of surveys) = 4 * (2 + 1) = 12	Slope parameters estimated on a log scale, a prior is used for the acoustic survey ascending slope parameter.
Annual changes in fishery selectivity	4 * (No. of fisheries) * (No. of yrs -1) = 4 * 1.5 * 32(28) = 184	Estimated as deviations from mean selectivity and constrained by random walk process error

Year and age-specific selectivity for the 1994 & 1997 year class	U.S fishery: 1996 & 1997 = 2 Canadian fishery: 1999- 2002 = 4	Bounded by (0,1)
Survey catchability	No. of surveys = 2	Acoustic survey catchability not estimated, SWFSC catchabilities estimated on a log scale
Natural mortality	Age- and year-invariant = 1	Not estimated
Fishing mortality	No. of fisheries * (No. of yrs) + means = 2 * 39 + 2 = 80	Estimated as log deviances from the log mean
Total	134 conventional parameters + 190 process error parameters + 3 fixed parameters = 327	

Model Structure and Assumptions

This assessment presents only an update of the 2003 model. As such, it includes updated 2004 fishery removals, 2004 fishery weights at age and age composition data, and indices of Santa Cruz pre-recruit abundance 1986-2004 inclusive. The model structure and assumptions used are identical to that of the 2003 assessment model. The only exception was the addition of a bias correction added to average recruitment for calculation of unfished spawning biomass (Bzero). Since bias correction was applied to average recruitment for calculation of initial equilibrium conditions in 1966, we felt it should be applied to calculation of Bzero as well for consistency. This reconciled the somewhat small difference between calculation of Bzero and the initial year's calculated female spawning biomass. Comparative runs with and with out application of bias correction to the calculation of Bzero using only data from last year's assessment show only nominal differences. For instance, without bias correction: Bzero=2.7, 1966 B/Bzero=.93 and 1993B/Bzero=0.48. With bias correction: Bzero=2.6, 1966 B/Bzero=1.0 and 1993B/Bzero=0.50. As can be seen from these numbers, biomass during 1966 starts out in equilibrium with Bzero (1966B/Bzero=1.0) in comparison to 0.93 without bias correction. Moreover, application of bais correction had little impact of estimates of 2003 spawning biomass and depletion.

This assessment, as the previous assessment models, were built upon the AD model builder software and Dorn et al. (1999) confirmed consistency with the previous assessment prior to 1998 which used the stock synthesis program. Until the 2003 assessment, all past assessment results and recommendations have been based upon fixing the acoustic survey q=1.0; thus asserting that the acoustic survey estimate of biomass is an absolute measure of biomass and not just a relative measure. This was in large part based upon the best expert opinions and inability to quantitatively estimate it. This assessment, as well as the 2003 assessment, have explored relaxation of this assumption. The ability to relax the q=1.0 assumption was based upon: 1) continued lengthening of the acoustic survey time series, thus allowing the survey to be treated as an index of relative abundance in the model; 2) relatively better model fits to the data when q is less than 1.0; and 3) high quality of expertise in the 2003 STAR Panel to allow critical examination of the q=1.0 assertion. Accordingly, two models (q=0.6 and q=1.0 as specified in the 2003 assessment) are asserted as representing plausible extremes in the state of nature and therefore uncertainty in the final model result is represented by a range of biomass. The lower biomass end of the range is based upon the conventional assumption that the acoustic survey catchability coefficient, q=1.0, while the higher end of the range represents the q=0.6 assumption.

The basic model structure and assumptions, as shown in the above table, included: 1) initialization of the 1966 age composition (first year in assessment) as deviation from mean log recruitment for age 2, with numbers at ages 3-12 decayed from mean recruitment (bias corrected) as a function of M and initial F (not estimated), 2) recruitments estimated 1966-2004 as deviations from mean log recruitment, 3) acoustic survey biomass series with higher CVs during 1977-1989 to better reflect uncertainty in the earlier years, 4) an index of recruitment to age 2 based on the Santa Cruz larval rockfish survey, 1986-2004, with a CV=1.1, 5) use of time varying fishery selectivity functions modeled as a random walk process error, and 6) use of a prior on the ascending limb slope parameter of the acoustic survey selectivity. The addition of the random walk process error was to account for changes in fishery selectivity which was strongly influenced by El Niño (1983, 1992, 1997-98) driven distribution changes in the hake population as well as aperiodic strong year classes in the fishery (while not necessarily biased, this formulation may represent an over-parameterization based on a recent simulation-estimation study, See Appendix A). In addition, it was clear that the 1997 year class was unusually abundant as age-2 and age-3 fish in the 1999 and 2000 Canadian catch at age data, respectively (fig. 6). This pattern in the age composition data was unlike any other year and apparently due to the extreme northward extension of juvenile hake in 1997. Since age-specific selectivity is estimated as smooth functions over time the model was unable to accommodate this rapid shift in catch at age. Thus, we estimated year- and age-specific selectivity patterns for the 1997 year class in the 1999 - 2002 Canadian fishery. Dorn et al. (1999) provided similar model accommodation by estimating year- and age-specific selectivity parameters for the 1994 year class in the 1996 and 1997 U.S. fishery. The remaining differences between model configuration used are:

Model q=1.0: Acoustic survey is fixed at 1.0, but acoustic survey CV=0.2 (1977-1989) and CV=0.1 (1992-2003). The 1986 acoustic survey biomass omitted.

Model q=0.6: Acoustic survey is fixed at 0.6, but acoustic survey CV=0.5 (1977-1989) and CV=0.3 (1992-2003). The 1986 acoustic survey biomass omitted.

Model Results

Parameter estimates and model output for model assumption q=10 and q=0.6 are presented in a series of tables and figures. Results of both models are presented to bracket the uncertainty in model configurations, specifically related to different assumptions of acoustic survey q. Residual plots were prepared to examine the goodness of fit of the model to the age composition data. The Pearson residuals for a multinomial distribution are

$$r_i = \frac{p_i - \hat{p}_i}{\sqrt{(\hat{p}_i(1 - \hat{p}_i)/m)}} ,$$

where p_i is the observed proportion at age, and m is the nominal sample size (McCullagh and Nelder 1983). Figures 11-13 show Pearson residuals of the fit to the U.S. fishery, Canadian fishery, and acoustic survey age compositions. Although there are large residuals for some ages and years, no severe pattern of residuals is evident in the fishery age composition. There is a moderate residual pattern of positive residuals for the strong year classes and negative residuals for the weak year classes, particularly for the older fish. This pattern is strongest in the Canadian fishery age composition, but is also present to some degree in the U.S. fishery age composition. A tendency for age readers to prefer the strong year classes as fish become older and more difficult to age could account for this pattern (Kimura et al. 1992).

Estimated selectivity for the U.S. and Canadian fisheries is shown in Figure 14 and Table 10. U.S. fishery selectivity was strongly dome-shaped in the early years (<1980) with ages 6-12 being fully selected by the fishery. Over time the age-specific selectivity in the U.S. fishery increased on both younger and older fish. Average selectivity in recent years (1998-2004) is 20% on age-2, 70% on age-3 and 90% on age-4 fish. Changes in Canadian fishery selectivity is equally pronounced over time and generally shows the same pattern with increasing selectivity toward younger fish. The descending limb of the Canadian fishery selectivity was time-invariant and thus selectivity on the oldest age groups remained constant through time. Both models were q=1.0 and q=0.6 show qualitatively the same fishery selectivity and hence only those patterns associated with model q=1.0 are shown.

Selectivity of the acoustic survey is given in Table 10 and shown in Figure 15. Selectivity in the acoustic survey was high on age-2 through age-4 fish relative to the fishery selectivity, but both reached maximum selectivity on ages 5-9. Acoustic survey selectivity from model q=1.0 was higher on younger ages relative to model q=0.6, and is in part due to the lower value of survey q assumed. Expected acoustic survey biomass from both models fit the observed biomass values relatively well between 1992 and 2003 (Figure 15). Relatively poorer fits were observed for the remaining acoustic survey biomasses, except for 1980 where the q=1.0 model had a slightly better fit than the q=0.6 model. This may not be unexpected since model q=0.6 had slightly larger CVs for the early survey years comparted to Model q=1.0 and thus expected values allowed to deviated from the observed values to a greater degree.

Expected acoustic survey age compositions fit the observed survey age compositions fairly well (Figure 16). More notable discrepancies between the predicted and observed age compositions appeared to occur in the 1995 and 1998 survey years, with pattern of residuals generally opposite between models q=1.0 and q=0.6.

Results of the above model runs are given in Tables 11-13 and Figure 17-18. Although not directly comparable because of different weights on the data components, Model q=0.6 fit better compared to the model q=1.0 because it assumes a lower fixed value of q (Note: equal weight with both models still results in an improvement of approximately 13 likelihood units just by assuming different q) (Table 11). Improvement in model fits appears to occur in the acoustic survey biomass and age composition data with qs less than one (Table 11). As in previous model runs, the alternative models fit poorly to the early acoustic biomass due to the large CVs on the earlier surveys (1977-1989) and also because the age composition data predict greater biomass during the mid 1980s (due to the strong 1980 and 1984 year class) than would be predicted by the trend in survey biomass. Models fits (i.e. q=0.6 or freely estimated) with lower values of q attempt to better reconcile the difference in expected biomass between the age composition data and the trend in acoustic biomass better because a q less than 1.0 would allow for biomass to be scaled higher than the observed trend. Thus, the acoustic survey biomass would be considered a relative index.

Table 12 provides estimated time series of population 3+ biomass, female spawning biomass, age-2 recruitment, and percent utilization of the total age 3+ biomass by the U.S. and Canadian fisheries for 1966-2004 for models q=1.0 and q=0.6 (see also Fig. 17). Both models show largely the same biomass and recruitment trajectories through time with the exception that model q=0.6 has absolute estimates elevated above those of model q=1.0. In the early 1970s to early 1980s biomass was relatively stable with low levels of recruitment punctuated infrequently by more moderate year classes (Fig. 17). Biomass increased substantially during the middle 1980s as the 1980 (1982 recruitment) and 1984 (1986 recruitment) year classes recruited to the population. The time series peak 1987 biomass ranges between 7 and 11 million mt for model q=1.0 and q=0.6, respectively. During this period spawning biomass briefly exceeded unfished biomass levels and as such, depletion levels at this period in time were in excess of 100% unfished (this can happen when recruitment events that are substantially above average recruit into the spawning biomass). Population biomass then declined after 1987 as the 1980 and 1984 year class were replaced by more moderate year classes and the 1980 and 1984 year classes were exploited. In more recent years (1997 -2001), biomass declined to its lowest level in the time series of 1.3 and 2.7 million mt in 2001 for models q=1.0 and q=0.6, respectively. As such, depletion levels (percent unfished) approached 25% unfished levels in 2000-2001. However, as the 1999 year class, estimated to be the fourth largest, recruited into the population biomass increase substantially since 2001. While slightly lower than 2003, spawning biomass is currently (as of 2004) estimated to be above 40% of an unfished stock; ranging between 1.6 million mt and 2.0 million mt for model q=1.0 and q=0.6, respectively.

Uncertainty and Sensitivity Analyses

Uncertainty in current stock size and other state variables were explored using a Markov Chain Monte Carlo 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. It has the advantage of producing the true marginal likelihood (ore marginal distributions) of the parameter, rather than the conditional mode, as with the likelihood profile. We ran the MCMC routine in ADMB drawing 2,500,000 samples in which the first 25% of the samples were discarded (as the burn-in) and every 1000th sample saved to reduce autocorrelation in the chain sequence. Initial MCMC runs revealed significant autocorrelation among sequential draws of the chain even after a lag of 100. Results of the MCMC simulation were evaluated for nonconvergence to the target posterior distribution. The final samples from the MCMC were used to develop the probability distributions of the target marginal posterior. MCMC diagnostic results are only shown for model q=1.0 since results were qualitatively similar for both final models.

Convergence diagnostics of selected parameters from the MCMC simulation suggests that no severe problems of non-convergence is present for the 2004 q=1.0 model (Fig. 19 and 20). Trace plots (panels A) of two selected model state variables, Bzero or unfished biomass and 2004 spawning biomass, illustrate that these variables are quite stable over the thinned chain sequence and that the percentiles (panels C) shown suggest reasonable stationarity. In addition, autocorrelations between 1000th draws of the chain sequence drop below +/- 0.10 after the first lag indicating that thinning the chain at a rate of every 1000th draw should substantially reduce between draw correlation. Kernel density plots for these variables are also shown in Figure 19 (panel D). Figure 20 provides a more thorough summary of 46 parameters (and state variables) from the MCMC simulation. Except for a few parameters with autocorrelation above 0.15, most of the 46 parameters examined achieve autocorrelations of less than 0.10 after chain sequence thinning rate of every 1000th draw. Furthermore, most of the 46 parameters examined have a Geweke statistic of less than +/- 1.96 indicating stationarity of the mean of the parameter. Finally, all 46 parameters passed the Heidelberger-Welch statistic test. If passed the retained sample is deemed to estimate the posterior mean with acceptable precision, while if failed, it 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.

Sensitivity to survey catchability assumptions

A decision analysis was conducted to evaluate the consequences of assuming a harvest rate policy associated with lower or higher acoustic survey q (assumed state on nature) when in fact the converse was true (true state on nature). This analysis defines a 2x2 matrix with two assumed states of nature (q=1.0 and q=0.6) and two true states of nature (q=1.0 and q=0.6) under both the F 40%(40-10) and F45%(40-10) harvest rate policy. It should be noted that *q*=1.0 and *q*=0.6 have slightly different specifications in terms of CVs assumed for the acoustic survey biomasses. Projected spawning biomass, depletion level (% unfished biomass), and exploitation rates in 2005-2014 were examined (Table 14). Results of this analysis suggest that more dire consequences occur when assuming harvest rate policies consistent with the *q*=0.6 model assumption when in fact the *q*=1.0 model assumption turns out to be the true state of nature (lower left diagonal of Table14), than when the converse is the case. For instance, if yields consistent with the *q*=0.6 harvest rate policy were assumed under a *q*=1.0 "true state of nature", then female spawning biomass declines to 521 million mt in 2007 with a corresponding depletion level of 20% of an unfished stock (lower left diagonal). In contrast, female spawning biomass declines to 1.1 million mt (29% unfished) when the harvest rate of *q*=0.6 is assumed and is the true state of nature. Under the more conservative scenario when harvest rates are consistent with the *q*=1.0 model assumption and the *q*=0.6 model assumption turns out to be the true state of nature (upper right diagonal of Table 14) the depletion level reaches 31% compared to 27% when the harvest policy assumed is consistent with the true state of nature. In general, these results suggest rather significant differences between which model is assumed for setting harvest rates and the resulting risks involved because survey acoustic *q* determines directly the assumed absolute level of harvest from the exploitable stock biomass.

To further evaluate uncertainty, models *q*=1.0 and *q*=0.6 were run in which acoustic survey Q was freely estimated (Note: here q is freely estimated with the only difference in models being the CVs on acoustic survey biomasses). To explore the uncertainty from these configurations acoustic survey *q* was freely estimated and then uncertainty was characterized using the samples drawn from a Markov Chain Monte Carlo simulation of the posterior distribution. Acoustic survey Q was estimated to be much lower for Final Models *q*=1.0 and *q*=0.6; *q*=0.38 and *q*=0.26, respectively, than has been assumed from past assessments. In the case of model *q*=0.6, a lower emphasis on the acoustic survey biomass for all years caused survey *q* to be lower in order to scale biomass up to a level of magnitude consistent with that predicted by the age compositions. Correspondingly when higher emphasis was placed on survey biomass (i.e. model *q*=1.0) survey *q* was estimated to be higher because greater weight was given to the model to fit the survey biomass relative to the age compositions. It should be noted that estimated biomass and recruitment translate into substantially higher biomass for models when q is assumed to be less than 1.0. (Both the STAT and STAR conceded that acoustic survey catchability substantially less than 0.6 seems unplausible).

Uncertainty in 2004 stock size and female spawning biomass

The results of the MCMC based on 2,500,000 simulations was then plotted to evaluate the uncertainty of the state variables of interest. Results show that 2004 female spawning biomass was estimated to be 1.2 million mt and 2.0 million mt for final models *q*=1.0 and *q*=0.6, respectively (Fig. 22). Based on the marginal posterior distributions 2004 female spawning biomass has greater than a 70% probability of exceeding the 40% unfished biomass level for both model alternatives (Fig. 22). Uncertainty in the 2004 depletion level was also examined. The posterior mode of the depletion level (B_{2004}/B_{zero}) was estimated to be approximately 50% of unfished biomass for both models *q*=1.0 and *q*=0.6, with less than a 5% chance of being below 40%B0 (Fig. 22).

TARGET FISHING MORTALITY RATES

To evaluate harvesting strategies and target fishing mortality rates for projections, we employed the 40-10 option that provides a more gradual response to declining stock sizes by reducing *catches* linearly, rather than fishing mortality. The 40-10 option can be expressed approximately in fishing mortality as

$$F_{ABC} = F_{40\%} \frac{B_{40\%}}{B} \left[\frac{B - B_{10\%}}{B_{40\%} - B_{10\%}} \right],$$

Dorn et al. (1999) evaluated the 40-10 option relative to the hybrid F strategy (Shuter and Koonce, 1985) that was formerly used to manage the hake stocks and found approximately the same overall reduction in harvest rates. In general, they concluded that as a control law the general form of 40-10 policy was an improvement over the hybrid F strategy. Moreover, using a Bayesian meta-analysis of Merluciid stock recruit relationships, Dorn et al. (1999) showed that F40-F45% may be appropriate proxies for F_{MSY} depending of the level of risk aversion.

The following estimates of F40% and F45% under the 40-10 option were obtained using the life history vectors in Table 15. The Canadian F multiplier is used to scale the Canadian fishing mortality so that the mean yield per recruit for the U.S. and Canadian fisheries corresponds to the historical distribution of catches (~26%). Previous work has demonstrated that overall yield per recruit is relatively insensitive to the allocation of yield within the range in dispute. Unfished spawning biomass was based on mean (bias adjusted) 1966-2004 recruitment (1.9 and 2.8 billion for models *q*=1.0 and *q*=0.6, respectively) and SPR at F=0 (1.233 kg/recruit).

Model *q*=1.0

SPR rate	U.S. Fishing mortality	Canadian F	Equilibrium harvest rate
F40%	0.225	0.122	13.0%
F45%	0.181	0.098	11.0%
Unfished female spawning biomass	2.5 million t		
B40%	1.0 million t		

Model *q*=0.6

SPR rate	U.S. Fishing mortality	Canadian F	Equilibrium harvest rate
F40%	0.217	0.118	13.1%
F45%	0.177	0.096	10.1%
Unfished female spawning biomass	3.7 million t		
B40%	1.5 million t		

HARVEST PROJECTIONS

For harvest projections, model estimates of population numbers at age in 2004 and their variance were projected forward for the years 2005-2014. Estimates of future recruitment, N_{i2}, are also needed for the projections. Survey indices of age-0 abundance in 2003 and 2004 available from the Santa Cruz Laboratory larval rockfish survey are used to represent projected recruitment in 2005 and 2006. Recruitment estimates projected in future years were modeled to account for two sources of variability: random variation in recruitment (process error), and sampling variability of the index (measurement error). For example, if recruitment itself is not highly variable, an index that shows an extremely low or high value should be shrunk towards the mean, particularly if it is known that sampling variability for that index is large. The appropriate tradeoff between these different sources of uncertainty is obtained by adding a log likelihood term for future recruitments in the final estimation phase. Assuming that both recruitment variability and sampling variability are log normal,

$$\log L_{Fut.\ Recr.} = -\frac{1}{2\sigma_r^2}\sum_i\left[\log(N_{i2}) - \overline{\log(N_2)}\right]^2 - \sum_k \frac{1}{2\sigma_k^2}\sum_i\left[\log(q_k N_{i2}) - \log(R_i)\right]^2$$

where $\overline{\log(N_2)}$ is the mean log recruitment as estimated by the base-run model, σ_r is the standard deviation of log recruitment, and σ_k is the standard deviation of the log index from survey k, which can be estimated using the prediction error of the index in the assessment model. These parameters were fixed at the values estimated by the two final model alternatives. The standard deviations for log recruitment ($Model1b{:}\sigma_r = 1.15 Model1c{:}\sigma_r = 1.23$) and the log index ($Model1b{:}\sigma_k = 1.41 Model1c{:}\sigma_k = 1.48$) of the Santa Cruz Laboratory recruitment survey were similar implying that estimates of future recruitment should be roughly an average of the log mean recruitment from the assessment model run and the Santa Cruz Laboratory survey prediction. In years when no indices are available, as in 2007-2014, the estimated log recruitment will be drawn toward the mean log recruitment from the assessment model and thus uncertainty will be equal to the process error in recruitment. As with other state variables, the uncertainty in short-term projections were evaluated using MCMC simulation. Use of MCMC for projections would be particularly appropriate since the MCMC draws from a log-normal distribution and, as such, produces biomass levels more like that generated from the arithmetic mean recruitment.

Results of projections are given in Table 16 and state variables are summarized in terms of 10%, 50% and 90% of 2,500,000 MCMC samples for each of the harvest rates policies (Also see Fig. 23-24). Under both model alternatives q=1.0 and q=0.6 (and under F40% and F45% harvest rates policies), female spawning biomass is projected to decline to within the precautionary zone of 25%-40% unfished biomass between 2006 and 2010, due to attrition of the 1999 year-class and lower than average recruitment expected from the Santa Cruz Laboratory recruit index. Both model alternatives q=1.0 and q=0.6 show essentially the same levels of projected depletion, although their actual biomass levels differ. However, the decline in spawning biomass is somewhat dependent upon the harvest policy chosen; under the F45% (40-10) option the 2006 depletion level falls to 28%B0 as compared to 27%B0 under the F40% option for the q=1.0 model (Table 16). Despite the short- term decline, spawning biomass is projected to increase slightly to between 35% and 40%B0 by 2014 depending upon the model and harvest rate policy, as the assumed low 2002 and 2003 year classes are replaced by long-term average recruitment. Information on recruitment from the NMFS-PWCC survey is not yet of sufficient duration to include in this assessment, but it suggests that the 2003 year class may not be as low as indicated by the Tiburon index.

Projected 2005 Coastwide yield varies substantially between the two model alternatives *q*=1.0 and *q*=0.6. Under model *q*=1.0, 2005 coastwide yield ranges from a low of 302,300 mt to 364,100 mt under the F45% (40-10) and F40% (40-10) harvest rate policy, respectively (Table 16, Fig. 24). Contrastingly, higher 2005 coastwide yields are estimated from model *q*=0.6 ranging from 482,800 mt to 597,600 mt under the F45% (40-10) and F40% (40-10) harvest rate policy, respectively (Table 16, Fig. 24). As with spawning biomass, coastwide yield is projected to decline in the short-term (2006-2008), but increase over the medium term (2011-2014), with higher expected gains in yield from the F45%(40-10) harvest rate policy.

ACKNOWLEDGMENTS

Stock assessments draw upon many sources. The following individuals contributed information, data, or ideas: Mark Blaisdell, Julie Pearce, Mike Guttormsen, Chris Wilson, and Mark Wilkins (NMFS, Alaska Fisheries Science Center); Steven Ralston (NMFS, Southwest Fisheries Science Center); Lara Hutton, Patrick McDonald (Oregon Department of Fish and Wildlife) Robert LeGoff (Washington Department of Fish and Wildlife); Larry Quirollo (California Department of Fish and Game); Vidar Wespestad (Pacific Whiting Conservation Cooperative); Andre Punt and Ian Stewart (University of Washington); John Wallace (NMFS; Northwest Fisheries Science Center); Robert Kronlund and Ken Cooke (DFO, Pacific Biological Station). Their assistance is gratefully acknowledged. Special thanks to Larry Hufnagle, Rebecca Thomas, Steve Deblois, and Patrick Ressler for the timely production of the 2003 acoustic survey biomass data. The STAT team also extends its thanks to the STAR panel for insightful suggestions and discussion.

LITERATURE CITED

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

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

Baranov, F.I. 1918. On the question of the biological basis of fisheries. Nauchn. Issed. Ikhtiologicheskii Inst. Izv. 1:81-128.

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

Deriso, R.B., T.J. Quinn II, and P.R. Neal. 1985. Catch-age analysis with auxiliary information. Can. J. Fish. Aquat. Sci. 42: 815-824.

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

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

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

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

Dorn, M. W., and R. D. Methot. 1991. Status of the coastal Pacific whiting resource in 1990. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-204, 97 p.

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

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

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

Doubleday, W.G. 1976. A least-squares approach to analyzing catch at age data. Res. Bull. Int. Comm. Northw. Atl. Fish. 12:69-81.

Fleischer, G.W., K.D. Cooke, P.H. Ressler, R.E. Thomas, S.K. de Blois, L.C. Hufnagle, A.R. Kronlund, J.A. Holmes, and C.D. Wilson. In Review. Integrated Acoustic and Trawl Survey of Pacific Hake, Merluccius productus, in U.S. and Canadian Waters off the Pacific Coast in 2003. NOAA Technical Memorandum.

Fournier, D. and C. P. Archibald. 1982. A general theory for analyzing catch at age data. Can. J. Fish. Aquat. Sci. 39:1195-1207.

Fournier, D. 1996. An introduction to AD model builder for use in nonlinear modeling and statistics. Otter Research Ltd. PO Box 2040, Sidney, B.C. V8L 3S3 Canada.

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

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

Gelman, A., Carlin, J.B., Stern, H.S., and Rubin, D.B. 1995. Bayesian data analysis. Chapman and Hall, New York.

Gudmundsson, G. 1994. Time series analysis of catch-at-age observations. Appl. Statist. 43:117-126.

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

Helser, T.E, R.D. Methot, and G. W. Fleischer. 2004. Pacific whiting assessment update for 20003 In Pacific Fishery Management Council, Status of the Pacific Coast groundfish fishery through 2001 and recommended acceptable biological catches in 2002 (Document prepared for the Council and its advisory entities.) Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

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

Hollowed, A.B., R. D. Methot, and M. W. Dorn. 1988b. Status of the Pacific whiting resource in 1988 and recommendation to management in 1989. In Pacific Fishery Management Council, Status of the Pacific Coast groundfish fishery through 1988 and recommended acceptable biological catches in 1989, p. A1-A50. (Document prepared for the Council and its advisory entities.) Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Kimura, D.K. 1989. Variability, tuning, and simulation for the Doubleday-Deriso catch-at-age model. Can. J. Fish. Aquat. Sci. 46:941-949.

Kimura, D.K. 1990. Approaches to age-structured separable sequential population analysis. Can. J. Fish. Aquat. Sci. 47:2364-2374.

Kimura, D.K. 1991. Improved methods for separable sequential population analysis. Unpublished. Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, Washington 98115.

Kimura, D.K., J.J. Lyons, S.E. MacLellan, and B.J. Goetz. 1992. Effects of year-class strength on age determination. Aust. J. Mar. Freshwater Res. 43:1221-8.

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

McCullagh, P., and J. A. Nelder. 1983. Generalized linear models. Chapman and Hall, London. 261 p.

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

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery. 1992. Numerical recipes in C. Second ed. Cambridge University Press. 994 p.

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

Ralston, S., Pearson, D., and Reynolds, J. 1998. Status of the Chillipepper Rockfish stock in 1998. In Pacific Fishery Management Council, Appendix: Status of the Pacific Coast groundfish fishery through 1998 and recommended acceptable biological catches in 1999: Stock assessment and fishery evaluation. Pacific Fishery Management Council, 2130 SW Fifth Avenue, Suite 224, Portland, OR 97201.

Ricker, W. E. 1975. Computation and interpretation of biological statistic of fish populations. Bull. Fish. Res. Board. 191:382 p.

Sakuma, K. M. and S. Ralston. 1996. Vertical and horizontal distribution of juvenile Pacific whiting (*Merluccius productus*) in relation to hydrography of California. Calif. Coop. Oceanic Fish. Invest. Rep. 38:137:146.

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

Schnute J.T. and L.J. Richards. 1995. The influence of error on population estimates from catch-age models. Can. J. Fish. Aquat. Sci. 52:2063-2077.

Shuter, B. J., and J. F. Koonce. 1985. A review of methods for setting catch quotas on fish stocks. Unpubl. manuscr., 78 p. Research Section Fisheries Branch, Ontario Ministry of Natural Resources, P.O. Box 50, Maple, Ontario, L0J 1E0. (Contribution to Assessment of Stock and Prediction of Yield Workshop, Thunder Bay, Ontario, Canada, August 1985.)

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

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

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

Wespestad V. G. and A. M. Shimada. 1998. Pacific Whiting Conservation Cooperative National Marine Fisheries Service 1998 Pacific whiting cooperative survey report. Pacific Whiting Conservation Cooperative, 1200 Westlake N. Suite 900, Seattle WA 98109.

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

Wilson, C. D. and M. A. Guttormsen. 1997. Echo integration-trawl survey results for Pacific whiting (*Merluccius productus*) along the Pacific coast of the US and Canada during summer, 1995. NOAA Tech. Memo. NMFS-AFSC-74.

Table 1. Annual catches of Pacific whiting (1,000 t) in U.S. and Canadian management zones by foreign, joint venture (JV), domestic at-sea, domestic shore-based, and tribal fisheries, 1966-2004.

	U.S.						Canada				U.S. and Canada
			Domestic								
Year	Foreign	JV	At-sea	Shore	Tribal	Total	Foreign	JV	Shore	Total [1]	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	90.490	251.188
1989	0.000	203.578	0.000	7.418	0.000	210.996	29.753	62.618	2.563	99.532	310.528
1990	0.000	170.972	4.713	8.115	0.000	183.800	3.814	68.313	4.022	76.680	260.480
1991	0.000	0.000	196.905	20.600	0.000	217.505	5.605	68.133	16.178	104.522	322.027
1992	0.000	0.000	152.449	56.127	0.000	208.576	0.000	68.779	20.048	86.370	294.946
1993	0.000	0.000	99.103	42.119	0.000	141.222	0.000	476.422	12.355	58.783	200.005
1994	0.000	0.000	179.073	73.656	0.000	252.729	0.000	85.162	23.782	106.172	358.901
1995	0.000	0.000	102.624	74.965	0.000	177.589	0.000	26.191	46.193	70.418	248.007
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	55.335	20.684	143.492	0.000	0.000	62.090	62.090	205.582
2004	0.000	0.000	90.258	96.229	23.997	210.484	0.000	58.892	65.345	124.237	334.721
Average 1966-2004						156.909				53.642	210.551

[1] Canadian fishery total catch revised 1996-2001.

Table 2. Harvest strategies, coastwide ABCs, quotas or havest guidelines for U.S. and Canadian zones, and Pacific whiting catches (t) in the U.S. and Canadian zone (1978-2004).

Year	Harvest strategy	Acceptable Biological Catch (t) (coastwide)	U.S. harvest guideline or quota (t)	U.S. catch (t)	% of U.S. harvest guideline utilized	Canadian scientific recommendations, low to high risk (t), (CAN) = Canadian zone only	Canadian quota (t)	Canadian catch (t)	% of Canadian quota utilized	Total Catch (t)	% of ABC harvested
1978	N/A	---	130,000	98,372	75.7	NA	NA	5,267	NA	103,639	---
1979	N/A	---	198,900	124,681	62.7	35,000 (CAN)	35,000	12,435	35.5	137,116	---
1980	N/A	---	175,000	72,353	41.3	35,000 (CAN)	35,000	17,584	50.2	89,937	---
1981	N/A	---	175,000	114,762	65.6	35,000 (CAN)	35,000	24,361	69.6	139,123	---
1982	N/A	---	175,500	75,578	43.1	35,000 (CAN)	35,000	32,157	91.9	107,735	---
1983	N/A	---	175,500	73,151	41.7	35-40,000 (CAN)	45,000	40,774	90.6	113,925	---
1984	N/A	270,000	175,500	96,381	54.9	35-40,000 (CAN)	45,000	42,109	93.6	138,490	51.3
1985	N/A	212,000	175,000	85,440	48.8	45-67,000 (CAN)	50,000	24,962	49.9	110,402	52.1
1986	N/A	405,000	295,800	154,963	52.4	75-150,000 (CAN)	75,000	55,653	74.2	210,616	52.0
1987	N/A	264,000	195,000	160,449	82.3	75-150,000 (CAN)	75,000	73,699	98.3	234,148	88.7
1988	Variable effort	327,000	232,000	160,690	69.3	98-176,000 (CAN)	98,000	90,490	92.3	251,180	76.8
1989	Variable effort	323,000	225,000	210,992	93.8	87-98,000 (CAN)	98,000	99,532	101.6	310,524	96.1
1990	Variable effort - high risk	245,000	196,000	183,800	93.8	32-70,000 (CAN)	73,500	76,680	104.3	260,480	106.3
1991	Hybrid -mod. risk	253,000	228,000	217,505	95.4	175-311,000	98,000	104,522	106.7	322,027	127.3
1992	Hybrid -mod. risk	232,000	208,800	208,576	99.9	160-288,000	90,000	86,370	96.0	294,946	127.1
1993	Hybrid -mod. risk	178,000	142,000	141,222	99.5	122-220,000	61,000	58,783	96.4	200,005	112.4
1994	Hybrid-low risk	325,000	260,000	252,729	97.2	325-555,000	110,000	106,172	96.5	358,901	110.4
1995	Hybrid-low risk	223,000	178,400	176,107	98.7	223-382,000	76,500	70,418	92.0	246,525	110.5
1996	Hybrid-low risk	265,000	212,000	212,900	100.4	161-321,000	91,000	88,240	97.0	301,140	113.6
1997	Hybrid-moderate risk	290,000	232,000	233,423	100.6	161-321,000	99,400	90,630	91.2	324,053	111.7
1998	Hybrid-moderate risk	290,000	232,000	232,509	100.2	116-233,000	80,000	86,738	108.4	319,247	110.1
1999	40-10 option-moderate risk	290,000	232,000	242,522	104.5	90,300	90,300	86,637	95.9	329,159	113.5
2000	40-10 option-moderate risk	290,000	232,000	208,418	89.8	90,300	90,300	22,257	24.6	230,675	79.5
2001	40-10 option-moderate risk	238,000	190,400	182,377	95.8	81,600	81,600	53,257	65.3	235,634	99.0
2002	40-10 option-moderate risk	208,000	129,600	129,993	100.3			50,796		180,789	86.9
2003	40-10 option-moderate risk	235,000	148,200	141,506	95.5			62,090		203,596	86.6
2004	40-10 option-moderate risk	514,441	250,000	210,500	84.2	134,475	134,475	124,237	92.4	334,737	65.1

Table 3. Length and age sample sizes for estimates of Pacific whiting age composition for U.S. surveys and fisheries. A. Triennial acoustic survey, B. U.S. shore-based fishery, C. U.S. at-sea fishery.

A. Triennial acoustic survey

Year	No. hauls	No. lengths	No. aged
1977	116	11,695	4,262
1980	72	8,296	2,952
1983	38	8,614	1,327
1986	48	12,702	2,074
1989	25	5,606	1,730
1992	62	15,852	2,184
1995	95	22,896	2,118
1998	108	33,347	2,417
2001	90	16,442	2,536
2003	106	19,357	3,007

B. U.S. shore-based fishery

Year	No. samples	No. aged
1990	15	660
1991	26	934
1992	47	1,062
1993	36	845
1994	50	1,457
1995	51	1,441
1996	34	1,123
1997	58	1,759
1998	66	2,021
1999	61	1,452
2000	75	1,314
2001	39	1,983
2002	71	1,582
2003	79	1,561
2004	72	1,440

C. U.S. at-sea fishery

Year	No. hauls	No. lengths	No. aged
1973		NA	
1974		NA	
1975		NA	
1976	279	53,429	4,077
1977	1,103	142,971	7,698
1978	832	124,771	5,839
1979	1,156	173,356	3,124
1980	682	102,248	5,336
1981	905	135,740	4,268
1982	1,145	171,816	4,258
1983	1,112	166,858	3,232
1984	1,625	243,684	3,310
1986	3,161	474,107	3,070
1987	2,876	431,454	3,175
1988	2,801	420,144	3,043
1989	2,666	368,807	3,041
1990	2,101	268,083	3,112
1991	1,022	112,477	1,335
1992	848	78,626	2,175
1993	423	33,100	1,196
1994	645	47,917	1,775
1995	434	30,285	690
1996	530	33,209	1,333
1997	632	49,592	1,147
1998	744	47,789	998
1999	284	49,246	1,047
2000	237	48,143	1,257
2001	287	48,426	1,104
2002	258	23,433	1,970
2003	264	24,420	1,770
2004	337	30,019	1,667

Estimation methods:
A. Acoustic survey. Age-length keys by geographic strata (Wilson and Guttormsen 1997)
B. U.S. shore-based fishery. Stratified random design with strata based on port groups.
C. U.S. at-sea fishery. Age-length keys by geographic strata (Dorn 1991). Number of hauls are those where length samples were taken.

Table 4. Catch at age (millions of fish) for the Pacific whiting fisheries, 1973-2004. Separate tables are given for U.S. and Canadian fisheries. The aggregate catch from all foreign, joint venture, domestic fisheries is included in these estimates.

	Age															
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
								U.S. fisheries								
1973	0.00	0.00	55.92	9.67	21.72	40.22	25.16	23.01	21.51	10.33	4.51	1.94	1.08	0.00	0.00	215.07
1974	29.31	1.30	0.98	150.14	20.52	35.50	44.29	25.73	11.40	3.58	1.63	0.98	0.33	0.00	0.00	325.69
1975	0.00	88.43	2.69	3.70	128.11	21.86	23.54	38.00	17.15	7.40	3.70	1.35	0.34	0.00	0.00	336.27
1976	0.00	0.33	36.85	29.29	29.62	185.27	27.65	13.82	4.93	0.99	0.33	0.00	0.00	0.00	0.00	329.09
1977	0.00	1.81	3.80	54.35	11.23	19.93	68.11	11.05	5.80	2.72	1.45	0.73	0.18	0.00	0.00	181.16
1978	0.01	0.02	4.56	8.58	51.87	9.48	20.32	38.57	5.74	2.48	1.28	0.52	0.20	0.05	0.01	143.69
1979	0.00	4.34	8.74	17.41	10.15	48.01	15.47	29.48	20.82	4.25	1.70	0.50	0.22	0.05	0.03	161.17
1980	0.00	0.13	24.67	2.16	6.90	7.16	20.11	9.57	11.99	9.92	1.74	1.35	1.01	0.59	0.14	97.44
1981	13.38	1.25	2.30	97.62	6.89	9.64	6.77	23.33	6.26	7.24	7.05	0.95	0.48	0.12	0.13	183.41
1982	0.00	27.51	1.93	1.57	57.88	5.02	5.78	5.02	11.96	2.43	2.53	4.64	0.34	0.13	0.03	126.77
1983	0.00	0.00	86.60	7.22	3.63	36.79	4.68	3.72	3.32	5.24	1.62	1.00	1.00	0.16	0.14	155.12
1984	0.00	0.00	2.59	164.97	7.18	5.18	17.54	2.17	1.24	0.82	1.34	0.21	0.20	0.31	0.03	203.78
1985	2.27	0.55	1.32	12.36	113.50	9.74	4.30	6.75	0.61	0.34	0.24	0.36	0.00	0.00	0.00	152.34
1986	0.00	62.92	12.88	1.85	9.34	171.79	21.55	10.76	12.45	1.53	1.05	0.38	0.79	0.15	0.05	307.49
1987	0.00	0.00	124.20	6.58	1.68	2.72	151.56	7.89	3.09	14.87	0.57	0.15	0.15	1.25	0.00	314.71
1988	0.00	1.22	1.31	172.76	8.02	1.40	2.60	96.93	5.16	0.72	8.32	0.15	0.24	0.00	0.65	299.48
1989	0.00	8.65	9.57	3.88	257.20	7.80	2.46	2.74	106.63	6.62	0.87	5.37	0.03	0.12	0.57	412.51
1990	0.00	5.69	85.34	10.97	1.92	152.02	2.56	1.14	0.71	95.97	0.47	0.00	6.07	0.00	0.41	363.27
1991	0.00	0.95	43.96	98.32	19.35	6.00	151.49	6.63	1.31	0.93	60.10	2.11	0.00	9.74	0.65	401.54
1992	0.97	18.53	9.94	51.95	109.58	10.27	5.09	131.94	4.84	2.38	0.79	42.06	0.63	0.20	1.88	391.05
1993	0.00	1.90	70.49	9.07	42.90	59.65	3.75	3.06	81.86	1.81	0.43	0.20	20.95	0.12	2.47	298.66
1994	0.00	0.23	16.48	121.89	4.82	76.93	104.64	3.29	2.04	115.38	0.46	2.06	0.22	29.13	3.65	476.31
1995	0.20	1.02	0.41	19.96	114.38	3.32	27.40	66.22	3.09	0.53	58.19	1.09	0.91	0.10	18.55	315.36
1996	0.00	102.26	71.90	6.75	34.60	97.87	1.81	17.17	46.84	0.90	0.17	50.38	0.00	0.49	14.81	445.94
1997	0.00	2.00	173.73	163.98	3.01	27.17	48.41	3.05	10.71	18.59	0.39	0.77	17.33	0.47	8.38	477.97
1998	0.00	26.97	117.63	103.21	133.25	16.56	20.27	41.66	4.83	2.35	17.29	1.52	0.48	11.85	3.32	501.20
1999	0.00	47.58	112.329	100.72	91.74	54.50	16.20	19.69	19.86	3.94	6.16	9.99	1.34	1.68	9.92	495.66
2000	2.13	15.24	34.58	50.95	46.19	62.31	40.85	21.48	13.48	7.83	6.52	6.74	2.83	2.72	7.44	321.30
2001	0.00	52.82	59.10	40.31	59.74	29.69	25.99	15.21	3.99	4.54	3.64	2.31	1.80	1.55	2.86	303.57
2002	0.00	0.00	156.354	36.31	15.63	12.58	8.08	6.75	5.32	1.26	1.16	1.36	0.50	0.32	1.04	246.68
2003	0.03	1.40	9.57	198.18	30.70	6.74	8.30	7.00	4.18	2.86	1.42	0.59	0.88	0.31	0.62	272.78
2004	0.03	1.71	33.32	39.09	272.09	21.39	5.85	12.72	5.38	1.91	1.83	1.26	0.63	0.18	0.94	398.33

Table 4. Continued. Canadian catch at age.

	Age															
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
								Canadian fisheries								
1977	0.00	0.01	0.01	0.25	0.09	0.30	1.83	0.53	0.50	0.42	0.40	0.35	0.16	0.00	0.00	4.85
1978	0.00	0.00	0.00	0.20	0.35	0.28	1.06	1.31	1.12	0.62	0.48	0.21	0.18	0.09	0.00	5.90
1979	0.00	0.00	0.00	0.21	0.62	1.30	1.14	2.10	3.02	1.10	0.79	0.37	0.25	0.17	0.12	11.19
1980	0.00	0.00	0.00	0.00	0.47	0.62	2.46	0.92	1.18	6.74	1.27	0.62	0.62	0.20	0.00	15.10
1981	0.00	0.00	0.00	1.01	0.27	1.41	1.38	4.28	0.85	2.36	6.18	1.49	0.60	0.85	0.00	20.68
1982	0.00	0.00	0.00	0.69	13.35	1.10	1.44	1.41	4.41	1.00	0.78	6.04	0.59	0.47	0.00	31.28
1983	0.00	0.06	14.02	1.03	1.80	32.15	1.29	1.87	1.67	5.59	0.77	0.26	3.41	0.26	0.13	64.31
1984	0.00	0.00	1.11	13.27	1.73	9.26	20.86	2.04	2.35	1.54	4.81	0.93	0.80	2.65	0.37	61.72
1985	0.00	0.06	0.06	2.45	8.03	1.65	3.25	9.62	0.49	0.55	0.55	1.65	0.37	0.00	1.59	30.32
1986	0.00	0.14	0.14	0.28	3.97	38.41	2.41	2.41	11.48	1.28	0.57	0.99	1.42	0.43	1.42	65.35
1987	0.00	0.00	0.90	0.60	0.15	2.56	70.71	2.86	2.86	10.38	0.60	0.45	1.20	0.90	1.20	95.37
1988	0.00	0.00	0.31	15.28	0.62	1.13	2.36	66.66	2.26	1.44	7.90	0.51	0.21	0.21	0.62	99.51
1989	0.00	0.00	0.20	0.59	35.55	0.20	0.39	0.59	69.34	1.76	1.37	8.59	0.39	0.20	1.17	120.34
1990	0.00	0.00	2.80	2.08	0.21	48.67	0.73	0.21	0.00	27.50	0.42	0.00	1.25	1.04	2.08	86.99
1991	0.00	0.00	0.11	6.11	2.46	0.43	70.60	0.54	0.00	0.21	47.47	0.21	0.11	2.25	0.11	130.61
1992	0.00	0.00	0.67	7.63	17.81	3.55	0.40	56.83	0.27	0.00	0.13	30.79	0.07	0.13	1.21	119.49
1993	0.00	0.07	0.77	2.52	12.91	17.54	1.89	0.21	40.62	0.21	0.14	0.14	12.49	0.21	0.21	89.93
1994	0.00	0.00	0.70	2.87	3.07	15.20	26.86	4.20	0.80	67.45	0.87	0.27	0.13	22.73	1.33	146.48
1995	4.88	0.04	0.53	6.31	5.03	3.21	10.72	15.96	3.25	0.67	33.81	0.68	0.04	0.15	9.41	94.70
1996	0.00	12.46	2.89	1.44	12.03	16.06	4.31	14.28	17.05	2.84	1.10	34.27	0.06	0.00	10.01	128.80
1997	0.00	0.81	22.17	19.19	2.52	17.21	16.22	2.25	11.08	14.42	3.24	0.54	18.65	1.35	4.06	133.73
1998	0.14	0.14	9.15	39.39	38.25	3.56	13.74	14.27	1.64	7.74	7.17	0.99	0.67	5.50	1.91	144.26
1999	1.45	26.28	9.65	18.35	40.74	25.71	1.94	8.39	8.47	2.65	3.66	4.26	0.56	0.19	4.05	156.36
2000	0.00	0.11	9.45	1.96	2.38	7.03	4.16	0.53	1.94	1.07	0.34	0.79	0.49	0.25	0.79	31.28
2001	0.00	0.04	0.86	12.32	3.24	5.06	14.31	7.54	1.70	2.37	2.72	0.95	1.69	1.41	1.61	55.81
2002	0.00	0.00	0.55	4.24	14.59	4.85	5.37	10.57	5.81	0.85	1.15	1.53	0.20	0.59	1.68	51.98
2003	0.00	0.00	0.54	28.66	16.21	6.24	10.16	5.88	6.52	4.63	1.60	0.65	0.96	0.24	0.53	82.81
2004	0.00	0.08	3.89	3.80	116.69	24.77	7.36	12.77	7.19	5.33	4.14	1.10	0.68	0.68	0.51	188.98

Table 5. AFSC 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 $50^o30'$ 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 no age one fish were captured in survey trawls.

Year	Total biomass at 20 log l - 68 (1,000 t)	Number at age (million)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1977	1596.422	0.22	135.48	121.24	718.01	63.29	87.41	745.78	106.23	78.20	40.90	39.47	21.80	8.49	2.18	2.25
1980	1701.482	0.00	14.45	1641.32	151.15	91.20	70.79	326.83	110.38	248.08	97.65	60.94	9.71	16.66	3.71	2.89
1983	1364.656	0.00	1.23	2918.17	50.86	20.64	304.29	31.84	34.78	26.00	51.01	12.46	13.39	14.84	2.69	0.00
1986	2397.386	0.00	3610.65	91.38	17.56	112.09	1701.85	179.58	131.65	181.21	21.62	21.03	1.47	10.37	2.35	0.00
1989	1805.603	0.00	571.25	200.82	39.29	1864.35	38.91	15.27	24.54	626.89	30.64	2.77	53.71	0.00	0.00	2.00
1992	1417.327	190.54	227.03	45.97	235.77	502.09	57.21	19.85	994.22	28.52	16.85	6.93	323.37	17.19	0.00	14.81
1995	1385.205	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	1185.932	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	737.743	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	1842.627	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

Estimates of numbers at age based on year-specific deep-water and northern expansion factors applied to 1977-1992.

Year	Total biomass at 20 log l - 68 (1,000 t)	Number at age (million)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1977	1915.01	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	2115.09	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	1646.68	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	2857.06	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	1237.69	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	2169.20	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	1385.00	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	1185.00	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	737.00	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	1840.00	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

Table 6. AFSC trawl survey estimates of Pacific whiting biomass (1,000 t) and age composition (million). The biomass estimates for 1977 and 1986, when the trawl survey did not extend into the Canadian zone, were adjusted as described in Dorn et al. (1991). In 1995, 53,730 t of age-1 fish is not included in the biomass estimate. In 1998, 20,658 t of age-1 fish is not included in the biomass estimate. Age composition data for 2001 should be considered preliminary. AFSC acoustic survey age-length key was applied to trawl survey length compositions to derive numbers and biomass at age.

	Area-swept biomass estimate (1,000 t)	Number at age (million)														
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1977	76.307	0.57	7.96	4.05	16.87	3.28	7.46	33.45	7.70	6.11	3.96	2.21	1.14	0.41	0.02	0.08
1980	188.299	0.30	1.80	234.42	6.91	12.53	11.37	22.31	14.32	16.93	11.96	4.63	2.28	1.20	0.99	1.43
1983	128.808	0.11	0.27	201.77	7.40	1.43	34.06	8.53	6.63	8.57	10.71	4.36	3.16	2.20	0.24	0.43
1986	254.566	0.00	203.50	8.95	2.81	1.33	202.20	10.37	5.21	59.96	2.23	2.20	0.55	8.88	0.20	0.69
1989	379.810	114.10	44.57	14.09	11.93	172.32	10.24	15.84	4.97	270.64	9.69	1.43	36.48	0.14	0.33	2.65
1992	352.538	56.14	47.95	5.72	28.12	78.63	9.10	3.32	202.78	3.60	3.25	2.61	74.35	3.43	0.00	4.85
1995	529.527	592.70	171.38	22.12	20.88	97.14	6.48	49.25	233.89	0.00	0.00	181.53	0.00	4.61	0.00	142.41
1998	476.459	212.14	442.40	285.14	132.36	151.01	12.48	34.31	72.23	12.36	7.24	46.03	0.68	4.55	33.74	14.03
2001	379.276	36.74	398.62	93.26	50.07	78.97	45.24	55.03	27.47	11.10	12.92	6.52	4.31	4.46	1.30	0.86
2003	Not Available															

Table 7. DFO acoustic survey estimates of Pacific whiting biomass (1,000 t) and age composition (proportion in numbers) in the Canadian zone. The biomass and age composition in 1995 are from the U.S.-Canadian joint survey of the Canadian zone, and is reported in Wilson and Guttormsen (1997).

	Total biomass at -35 dB/kg (1,000 t)	Number at age (million)														
Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1990	317.338	0.00	0.00	37.40	10.33	0.98	287.37	2.95	0.00	0.00	145.16	1.97	0.00	3.94	0.00	0.98
1991	563.308	0.00	0.00	2.96	54.46	10.69	1.48	448.06	1.48	0.00	1.48	346.79	3.49	1.48	23.97	0.00
1992	1101.328	0.00	0.00	8.58	88.95	214.54	54.69	1.04	840.57	3.24	0.00	0.00	351.39	0.52	4.29	7.77
1993	638.906	0.00	0.35	12.34	14.79	97.23	154.49	24.32	9.55	421.22	4.03	1.86	2.49	173.32	1.44	7.66
1994	224.907	0.00	1.44	5.96	7.87	8.34	36.86	53.37	10.35	2.33	138.50	1.08	0.00	0.00	37.16	0.74
1995	374.400	112.05	0.00	0.00	1.49	71.19	7.40	29.33	144.78	2.84	0.00	181.00	0.00	10.15	0.00	38.41
1996	447.410	1.18	77.89	21.83	7.08	79.07	61.96	29.51	57.83	92.06	18.88	8.26	175.26	17.11	3.54	41.31
1997	649.793	0.00	1.30	179.48	143.06	15.61	120.95	115.75	13.01	72.83	94.94	10.40	5.20	146.97	1.30	24.71

Table 8. Tiburon Midwater trawl laval rockfish survey estimates of log whiting abundance (Sakuma and Ralston 1997).

		All Strata		Monterey outside stratum only	
Year class	Year of recruitment	log(numbers)	SE	log(numbers)	SE
1986	1988	1.679	0.192	3.131	0.501
1987	1989	3.129	0.172	6.258	0.481
1988	1990	3.058	0.161	4.921	0.468
1989	1991	0.979	0.170	2.008	0.481
1990	1992	1.323	0.173	3.553	0.481
1991	1993	2.134	0.167	3.769	0.481
1992	1994	0.583	0.166	2.507	0.501
1993	1995	3.095	0.173	7.048	0.481
1994	1996	2.152	0.177	3.470	0.481
1995	1997	0.768	0.173	1.940	0.481
1996	1998	1.968	0.174	4.594	0.501
1997	1999	1.487	0.197	3.034	0.532
1998	2000	0.602	0.177	1.557	0.501
1999	2001	-	-	4.589	0.481
2000	2002	-	-	2.584	0.501
2001	2003	-	-	3.415	0.481
2002	2004	-	-	2.089	0.520
2003	2005	-	-	0.508	0.481
2004	2006	-	-	4.547	0.481

Table 9. Weight at age (kg) used in the stock assessment model.

U.S. fishery weight at age [1]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1966-78	0.119	0.264	0.407	0.514	0.610	0.656	0.696	0.743	0.812	0.880	0.956	0.993	1.065	1.093	1.125
1979	0.143	0.264	0.456	0.570	0.667	0.734	0.793	0.831	0.905	0.944	1.016	1.088	1.156	1.071	1.208
1980	0.141	0.298	0.470	0.559	0.646	0.722	0.790	0.825	0.867	0.899	0.995	1.046	1.050	1.040	1.159
1981	0.137	0.286	0.429	0.547	0.632	0.697	0.760	0.809	0.858	0.888	0.934	1.000	1.055	1.075	1.176
1982	0.143	0.253	0.396	0.509	0.605	0.669	0.730	0.788	0.856	0.877	0.901	0.976	1.053	1.061	1.016
1983	0.150	0.253	0.328	0.447	0.525	0.589	0.637	0.680	0.721	0.791	0.806	0.850	0.878	1.005	0.999
1984	0.187	0.293	0.387	0.434	0.550	0.607	0.658	0.712	0.753	0.798	0.863	0.906	0.934	0.952	1.113
1985	0.213	0.321	0.412	0.491	0.545	0.619	0.679	0.796	0.777	0.831	0.920	0.961	1.023	1.004	1.111
1986	0.192	0.294	0.386	0.464	0.518	0.538	0.617	0.663	0.735	0.755	0.816	0.877	0.919	0.928	1.094
1987	0.187	0.297	0.394	0.460	0.517	0.546	0.563	0.627	0.681	0.720	0.748	0.834	0.856	0.893	0.975
1988	0.197	0.303	0.395	0.466	0.520	0.570	0.572	0.596	0.641	0.702	0.733	0.803	0.874	0.886	0.955
1989	0.192	0.232	0.320	0.402	0.454	0.502	0.538	0.565	0.577	0.584	0.668	0.752	0.826	0.900	0.854
1990	0.195	0.248	0.364	0.418	0.515	0.522	0.553	0.559	0.542	0.589	0.616	0.759	0.707	0.779	0.851
1991	0.195	0.291	0.374	0.461	0.505	0.527	0.576	0.629	0.604	0.566	0.641	0.601	0.802	0.866	0.887
1992	0.216	0.275	0.367	0.472	0.513	0.554	0.579	0.581	0.600	0.581	0.600	0.617	0.763	0.521	0.797
1993	0.196	0.283	0.348	0.402	0.468	0.511	0.509	0.524	0.557	0.556	0.569	0.603	0.587	0.636	0.615
1994	0.196	0.236	0.357	0.428	0.458	0.518	0.562	0.613	0.563	0.612	0.566	0.638	0.765	0.656	0.645
1995	0.120	0.277	0.468	0.488	0.493	0.514	0.591	0.590	0.601	0.619	0.636	0.617	0.651	0.655	0.669
1996	0.120	0.278	0.378	0.451	0.519	0.547	0.568	0.574	0.599	0.583	0.760	0.629	0.625	0.647	0.630
1997	0.097	0.340	0.421	0.471	0.536	0.532	0.572	0.584	0.603	0.625	0.746	0.657	0.684	0.623	0.716
1998	0.204	0.238	0.364	0.452	0.490	0.506	0.535	0.549	0.560	0.780	0.620	0.719	0.630	0.689	0.687
1999	-	0.244	0.338	0.414	0.505	0.527	0.548	0.572	0.638	0.582	0.722	0.698	0.846	0.750	0.780
2000	0.184	0.401	0.478	0.556	0.630	0.687	0.707	0.730	0.810	0.782	0.825	0.770	0.883	0.818	0.906
2001	-	0.319	0.485	0.591	0.632	0.681	0.740	0.749	0.767	0.826	0.780	0.823	0.838	0.801	0.825
2002	-	0.435	0.443	0.547	0.679	0.684	0.743	0.847	0.810	0.756	0.876	0.813	0.821	0.929	0.925
2003	0.429	0.420	0.472	0.500	0.539	0.585	0.609	0.620	0.641	0.664	0.669	0.697	0.674	0.685	0.760
2004	0.385	0.419	0.448	0.491	0.525	0.585	0.639	0.633	0.657	0.702	0.677	0.692	0.712	0.808	0.985

[1] U.S. Fishery mean weights age age revised 1998-2001.

Canadian fishery weight at age [2]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1972-76	0.135	0.370	0.606	0.742	0.827	0.861	0.905	0.987	1.221	1.111	1.163	1.206	1.222	1.213	1.247
1977	0.143	0.355	0.570	0.744	0.824	0.871	0.875	0.957	1.020	1.104	1.164	1.222	1.240	1.207	1.273
1978	0.133	0.313	0.502	0.658	0.783	0.818	0.825	0.858	0.922	0.992	1.072	1.153	1.171	1.132	1.205
1979	0.141	0.332	0.532	0.701	0.830	0.916	0.935	0.969	0.989	1.046	1.137	1.175	1.266	1.237	1.299
1980	0.140	0.319	0.496	0.655	0.780	0.869	0.979	0.955	0.970	1.037	1.073	1.180	1.229	1.225	1.301
1981	0.136	0.309	0.479	0.660	0.741	0.829	0.891	0.985	0.961	0.977	1.137	1.096	1.172	1.204	1.272
1982	0.126	0.288	0.449	0.584	0.674	0.779	0.842	0.902	0.904	0.959	0.987	1.028	1.097	1.127	1.269
1983	0.120	0.264	0.399	0.515	0.607	0.630	0.730	0.785	0.824	0.789	0.890	0.926	0.883	0.960	1.091
1984	0.137	0.296	0.439	0.557	0.643	0.710	0.723	0.816	0.856	0.896	0.911	0.975	0.987	0.957	1.076
1985	0.142	0.311	0.465	0.584	0.712	0.740	0.792	0.871	0.889	0.931	0.978	1.048	1.037	1.012	1.067
1986	0.125	0.281	0.431	0.548	0.633	0.659	0.742	0.795	0.888	0.880	0.932	0.986	1.143	0.988	1.048
1987	0.149	0.314	0.457	0.566	0.643	0.692	0.706	0.768	0.801	0.827	0.877	0.919	0.943	0.940	0.978
1988	0.120	0.315	0.655	0.608	0.754	0.652	0.767	0.801	0.909	1.066	1.054	0.766	1.159	1.111	1.305
1989	0.192	0.315	0.521	0.666	0.657	0.690	0.924	0.807	0.806	1.071	0.950	1.049	0.779	0.852	1.515
1990	0.195	0.315	0.567	0.603	0.598	0.659	0.709	0.660	0.753	0.745	0.738	0.805	0.938	0.852	1.225
1991	0.195	0.315	0.521	0.629	0.751	0.777	0.712	0.891	0.753	0.782	0.758	0.794	0.779	0.957	0.923
1992	0.216	0.315	0.550	0.561	0.633	0.684	0.689	0.713	0.710	0.782	0.722	0.754	0.779	0.890	0.958
1993	0.196	0.315	0.440	0.515	0.530	0.558	0.588	0.567	0.600	0.589	0.834	0.805	0.619	0.852	0.923
1994	0.196	0.315	0.557	0.594	0.648	0.692	0.714	0.745	0.719	0.772	0.720	0.788	0.779	0.792	0.921
1995	0.120	0.315	0.668	0.652	0.663	0.728	0.741	0.766	0.800	0.909	0.805	0.757	0.779	0.852	0.847
1996	0.120	0.329	0.481	0.568	0.628	0.632	0.671	0.676	0.693	0.762	0.676	0.739	0.779	0.852	0.786
1997	0.120	0.496	0.536	0.574	0.658	0.700	0.687	0.717	0.739	0.746	0.754	0.811	0.782	0.836	0.819
1998	-	0.351	0.448	0.570	0.580	0.607	0.676	0.667	0.669	0.699	0.717	0.756	0.809	0.794	0.775
1999	-	0.284	0.413	0.494	0.620	0.616	0.645	0.715	0.713	0.729	0.778	0.810	0.779	0.850	0.802
2000	-	0.528	0.524	0.604	0.695	0.782	0.764	0.831	0.851	0.837	0.811	0.931	0.882	0.892	0.951
2001	-	0.315	0.766	0.812	0.842	0.909	1.020	1.016	1.047	1.099	1.102	1.120	1.053	1.045	1.150
2002	-	0.315	0.697	0.897	0.980	0.953	1.058	1.113	1.091	1.119	1.124	1.104	1.367	1.149	1.192
2003	-	0.400	0.606	0.656	0.709	0.848	0.785	0.813	0.898	0.84	0.9	0.982	0.845	0.899	1.134
2004	-	0.253	0.467	0.571	0.619	0.662	0.789	0.764	0.783	0.833	0.813	0.795	0.816	0.965	0.958

Table 9. Weight at age (kg) used in the stock assessment model (cont).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AFSC acoustic survey weight at age [1]															
1977	0.123	0.256	0.388	0.492	0.589	0.662	0.724	0.796	0.860	0.892	0.949	1.008	1.057	1.093	1.119
1980	0.107	0.261	0.455	0.561	0.672	0.759	0.861	0.894	0.948	1.003	1.081	1.122	1.170	1.176	1.205
1983	0.122	0.228	0.308	0.457	0.570	0.667	0.723	0.776	0.826	0.891	0.917	0.935	0.985	1.034	1.032
1986	0.165	0.262	0.367	0.465	0.532	0.558	0.658	0.715	0.815	0.823	0.865	0.908	1.006	0.995	1.069
1989	0.143	0.321	0.387	0.461	0.521	0.561	0.599	0.621	0.634	0.638	0.682	0.729	0.870	0.984	1.069
1992	0.119	0.205	0.357	0.508	0.554	0.578	0.654	0.642	0.688	0.655	0.758	0.705	0.697	0.734	0.800
1995	0.097	0.220	0.344	0.438	0.548	0.605	0.639	0.624	0.630	0.682	0.717	0.701	0.727	0.752	0.728
1998	0.081	0.189	0.343	0.527	0.534	0.587	0.658	0.631	0.645	0.766	0.709	0.830	0.735	0.744	0.790
2001	-	0.250	0.419	0.505	0.617	0.708	0.795	0.845	0.894	1.211	1.038	1.101	0.941	0.875	1.056
2003	0.139	0.264	0.411	0.515	0.544	0.716	0.687	0.728	0.788	0.754	0.769	0.820	0.780	0.815	0.841
AFSC bottom trawl survey weight at age															
1977	0.123	0.256	0.388	0.492	0.589	0.662	0.724	0.796	0.860	0.892	0.949	1.008	1.057	1.093	1.119
1980	0.107	0.261	0.455	0.561	0.672	0.759	0.861	0.894	0.948	1.003	1.081	1.122	1.170	1.176	1.205
1983	0.122	0.228	0.308	0.457	0.570	0.667	0.723	0.776	0.826	0.891	0.917	0.935	0.985	1.034	1.032
1986	0.165	0.262	0.367	0.465	0.532	0.558	0.658	0.715	0.815	0.823	0.865	0.908	1.006	0.995	1.069
1989	0.143	0.321	0.387	0.461	0.521	0.561	0.599	0.621	0.634	0.638	0.682	0.729	0.870	0.984	1.069
1992	0.119	0.205	0.357	0.508	0.554	0.578	0.654	0.642	0.688	0.655	0.758	0.705	0.697	0.734	0.800
1995	0.091	0.204	0.279	0.408	0.476	0.530	0.609	0.659	0.682	0.704	0.727	0.730	0.733	0.706	0.679
1998	0.097	0.189	0.339	0.480	0.502	0.532	0.534	0.575	0.583	0.655	0.669	0.639	0.762	0.670	0.710
2001	-	0.189	0.339	0.480	0.502	0.532	0.534	0.575	0.583	0.655	0.669	0.639	0.762	0.670	0.710
DFO acoustic survey weight at age															
1990	0.119	0.205	0.533	0.575	0.592	0.647	0.623	0.646	0.646	0.669	0.656	0.957	0.957	0.957	0.957
1991	0.119	0.205	0.533	0.560	0.592	0.641	0.615	0.633	0.633	0.650	0.656	0.657	0.657	0.657	0.657
1992	0.119	0.205	0.629	0.600	0.653	0.685	0.686	0.705	0.657	0.698	0.698	0.739	0.744	0.744	0.810
1993	0.196	0.283	0.541	0.595	0.624	0.641	0.688	0.718	0.704	0.827	0.847	0.624	0.741	0.685	0.995
1994	0.196	0.567	0.585	0.614	0.654	0.694	0.720	0.782	0.775	0.761	1.083	0.935	0.935	0.787	0.810
1995	0.098	0.235	0.371	0.508	0.642	0.778	0.739	0.740	0.691	0.739	0.787	0.769	0.752	0.771	0.790
1996	0.330	0.403	0.482	0.582	0.655	0.650	0.665	0.693	0.686	0.688	0.684	0.705	0.779	0.798	0.671
1997	0.330	0.488	0.572	0.598	0.673	0.710	0.722	0.731	0.746	0.785	0.749	0.713	0.761	0.689	0.742
Population weight at age															
1972-78	0.123	0.256	0.388	0.492	0.589	0.662	0.724	0.796	0.860	0.892	0.949	1.008	1.057	1.093	1.119
1979-81	0.107	0.261	0.455	0.561	0.672	0.759	0.861	0.894	0.948	1.003	1.081	1.122	1.170	1.176	1.205
1982-84	0.122	0.228	0.308	0.457	0.570	0.667	0.723	0.776	0.826	0.891	0.917	0.935	0.985	1.034	1.032
1985-87	0.165	0.262	0.367	0.465	0.532	0.558	0.658	0.715	0.815	0.823	0.865	0.908	1.006	0.995	1.069
1988-90	0.143	0.321	0.387	0.461	0.521	0.561	0.599	0.621	0.634	0.638	0.682	0.729	0.870	0.984	1.069
1991-93	0.119	0.205	0.357	0.508	0.554	0.578	0.654	0.642	0.688	0.655	0.758	0.705	0.697	0.734	0.800
1994-96	0.097	0.220	0.344	0.438	0.548	0.605	0.639	0.624	0.630	0.682	0.717	0.701	0.727	0.752	0.728
1997-99	0.081	0.189	0.343	0.527	0.534	0.587	0.658	0.631	0.645	0.766	0.709	0.830	0.735	0.744	0.790
1999-01	-	0.250	0.419	0.505	0.617	0.708	0.795	0.845	0.894	1.211	1.038	1.101	0.941	0.875	1.056
2002-04	0.139	0.264	0.411	0.515	0.544	0.716	0.687	0.728	0.788	0.754	0.769	0.820	0.780	0.815	0.841
Female multiplier for spawning biomass															
All yrs.	0.511	0.510	0.511	0.510	0.512	0.522	0.525	0.535	0.543	0.547	0.569	0.568	0.572	0.581	0.589

[1] Mean weights at age from 2001 acoustic survey revised.

Table 10. Selectivity at age for Pacific whiting fisheries and surveys for final models 1b and 1c (See text for description). The fisheries and surveys were modeled using double logistic selectivity functions, with random walk process error for the U.S. and Canadian fisheries. The fishery selectivity coefficients reported below are the average of the annual selectivity coefficients for all years (1966-2004), and for the last ten years (1995-2004) under acoustic survey assumption *q* =1.0 and *q* =0.6.

Age	U.S. fishery, all years		U.S. fishery, 1995-04		Canadian fishery, all years		Canadian fishery, 1995-04		Acoustic survey (all years)	
Model	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*
2	0.100	0.104	0.127	0.134	0.016	0.018	0.042	0.047	0.320	0.414
3	0.405	0.437	0.506	0.549	0.062	0.075	0.162	0.204	0.518	0.661
4	0.765	0.805	0.866	0.902	0.140	0.169	0.256	0.332	0.728	0.860
5	0.937	0.963	0.985	1.000	0.359	0.421	0.538	0.674	0.893	0.966
6	0.986	0.996	1.000	0.999	0.629	0.690	0.721	0.833	0.982	1.000
7	0.990	0.983	0.999	0.975	0.855	0.891	0.906	0.962	1.000	0.989
8	0.963	0.935	0.992	0.931	0.957	0.972	0.976	0.994	0.961	0.947
9	0.900	0.845	0.977	0.860	0.991	0.997	0.996	1.000	0.876	0.876
10	0.792	0.705	0.948	0.752	1.000	1.000	1.000	0.997	0.755	0.776
11	0.629	0.517	0.889	0.610	0.996	0.985	0.995	0.980	0.611	0.653
12	0.441	0.325	0.776	0.451	0.963	0.920	0.961	0.915	0.463	0.517
13	0.275	0.185	0.572	0.305	0.815	0.719	0.813	0.715	0.330	0.384
14	0.145	0.104	0.316	0.193	0.449	0.376	0.448	0.374	0.224	0.270
15	0.066	0.058	0.141	0.116	0.132	0.126	0.132	0.125	0.146	0.180

Table 11. Configuration, error assumptions and output (likelihoods and derived parameters) from various final model alternatives explored in the 2004 Pacific hake assessment. See text for description of model configurations.

	Model			
Parameters	Q=1.0	Q=0.6	Free Q	Free Q
q	1.000	0.600	0.370	0.276
Sigmas				
Acoustic: 77-89	0.20	0.50	0.20	0.50
Acoustic: 92-03	0.10	0.30	0.10	0.30
Tiburon	1.10	1.10	1.10	1.10
US Fishery effective sample	300	300	300	300
Canada Fishery effective sample	130	130	130	130
Acoustic survey effective sample	60	60	60	60
Likelihoods				
US Fishery: catch	-0.10	-0.01	-0.04	0.00
US Fishery:age	-252.19	-249.84	-247.56	-247.62
Canadian Fishery: catch	-0.02	0.00	0.00	0.00
Canadian Fishery: age	-171.49	-162.07	-165.16	-161.06
Acoustic survey biomass	-32.47	-6.36	-33.94	-5.71
Acoustic survey age	-39.28	-31.58	-33.16	-29.95
Tiburon survey index	-8.95	-9.49	-9.50	-10.11
Acoustic survey slope	-0.39	-0.01	-0.09	0.00
Recruits	-19.44	-20.59	-18.76	-19.67
Random walk	-32.54	-32.24	-32.38	-32.55
Forecast	-2.09	-2.16	-2.15	-2.15
Total likelihood	-558.95	-514.34	-542.73	-508.83
Derived Parameters				
B0 (millions mt)	2.69	3.50	4.07	6.03
Spawning Biomass 2004 (millions mt)	1.26	1.92	3.07	4.25
Ratio	46.7%	54.9%	75.4%	70.5%
US Fishery 2005 catch (X1000 mt)	258.9	406.7	610.2	858.8
US Fishery 2005 F	0.20	0.21	0.21	0.22
Canada Fishery 2005 catch (X 1000 mt)	91.5	143.8	215.8	303.6
Canada Fishery 2005 F	0.08	0.07	0.06	0.06
Total Catch 2005 (X 1000 mt)	350.4	550.5	826.0	1162.4

Table 12. Time series of estimated biomass, recruitment, and utilization for 1966-2004 for models q =1.0 and q =0.6 (See text for description). U.S. and Canadian exploitation rate is the catch in biomass divided by the total biomass of age 3+ fish at the start of the year. Population biomass is in millions of tons of age-3 and older fish at the start of the year. Recruitment is given in billions of age-2 fish.

Year	Population biomass (million t)		Female spawning biomass		Recruits (billion)		U.S. exploitation rate		Canada exploitation rate		Total exploitation rate		Depletion	
Model	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*	*q=1.0*	*q=0.6*
1966	4.813	7.008	2.489	3.643	2.502	4.495	2.8%	2.2%	0.0%	0.0%	2.9%	2.2%	99.2%	99.8%
1967	4.875	7.423	2.482	3.751	2.276	4.040	3.6%	2.8%	0.8%	0.6%	4.4%	3.3%	98.9%	102.8%
1968	4.817	7.648	2.449	3.856	2.264	4.018	1.3%	0.9%	1.3%	1.0%	2.5%	1.9%	97.6%	105.7%
1969	4.868	7.961	2.484	4.034	2.736	4.865	1.8%	1.3%	1.9%	1.4%	3.7%	2.7%	99.0%	110.5%
1970	5.010	8.448	2.502	4.188	1.567	2.717	3.2%	2.3%	1.5%	1.1%	4.7%	3.4%	99.7%	114.7%
1971	4.736	8.186	2.405	4.139	1.239	2.068	2.7%	2.0%	0.6%	0.4%	3.3%	2.4%	95.8%	113.4%
1972	4.429	7.758	2.407	4.196	6.593	10.849	1.7%	1.2%	1.0%	0.7%	2.7%	1.9%	95.9%	115.0%
1973	5.815	10.056	2.706	4.707	0.782	1.294	2.5%	1.8%	0.3%	0.2%	2.8%	2.0%	107.8%	129.0%
1974	5.385	9.390	2.703	4.726	0.712	1.139	3.6%	2.6%	0.3%	0.2%	3.9%	2.8%	107.7%	129.5%
1975	4.829	8.524	2.538	4.485	2.237	3.582	4.3%	3.1%	0.3%	0.2%	4.6%	3.3%	101.1%	122.9%
1976	4.687	8.317	2.375	4.238	0.488	0.801	4.9%	3.6%	0.1%	0.1%	5.1%	3.6%	94.6%	116.1%
1977	4.031	7.292	2.108	3.828	0.517	0.856	3.2%	2.2%	0.1%	0.1%	3.3%	2.3%	84.0%	104.9%
1978	3.545	6.480	1.880	3.450	0.302	0.505	2.8%	2.0%	0.1%	0.1%	2.9%	2.1%	74.9%	94.5%
1979	3.408	6.292	1.918	3.534	4.026	6.670	3.7%	2.6%	0.4%	0.3%	4.0%	2.8%	76.4%	96.8%
1980	4.226	7.630	2.018	3.691	0.554	0.901	1.7%	1.2%	0.4%	0.3%	2.1%	1.5%	80.4%	101.1%
1981	3.862	6.976	1.982	3.609	0.823	1.299	3.0%	2.1%	0.6%	0.4%	3.6%	2.6%	79.0%	98.9%
1982	2.973	5.395	1.855	3.298	15.484	23.597	2.5%	1.8%	1.1%	0.8%	3.6%	2.6%	73.9%	90.4%
1983	6.357	10.481	2.657	4.486	0.461	0.683	1.2%	0.8%	0.6%	0.5%	1.8%	1.3%	105.9%	122.9%
1984	6.655	10.865	3.198	5.276	0.145	0.211	1.4%	1.1%	0.6%	0.5%	2.1%	1.5%	127.4%	144.5%
1985	5.819	9.521	2.977	4.900	0.329	0.462	1.5%	1.1%	0.4%	0.3%	1.9%	1.4%	118.6%	134.3%
1986	4.914	8.078	2.812	4.576	10.485	14.176	3.2%	2.3%	1.1%	0.8%	4.3%	3.2%	112.0%	125.4%
1987	7.272	11.154	3.278	5.149	0.173	0.226	2.2%	1.7%	1.0%	0.8%	3.2%	2.4%	130.6%	141.1%
1988	6.041	9.229	3.018	4.665	0.463	0.586	2.7%	2.0%	1.5%	1.1%	4.2%	3.1%	120.2%	127.8%
1989	5.106	7.836	2.724	4.191	3.053	3.754	4.1%	3.1%	1.9%	1.5%	6.1%	4.6%	108.5%	114.8%
1990	4.940	7.435	2.481	3.794	1.420	1.683	3.7%	2.8%	1.6%	1.2%	5.3%	4.0%	98.8%	103.9%
1991	4.691	6.965	2.382	3.598	0.282	0.329	4.6%	3.5%	2.2%	1.7%	6.9%	5.2%	94.9%	98.6%
1992	3.656	5.478	1.948	2.945	2.018	2.352	5.7%	4.2%	2.4%	1.8%	8.1%	6.0%	77.6%	80.7%
1993	3.348	4.939	1.698	2.559	0.770	0.921	4.2%	3.1%	1.8%	1.3%	6.0%	4.5%	67.7%	70.1%
1994	2.846	4.198	1.467	2.204	0.328	0.390	8.9%	6.6%	3.7%	2.8%	12.6%	9.4%	58.4%	60.4%
1995	2.178	3.302	1.182	1.813	1.709	2.032	8.2%	5.9%	3.2%	2.3%	11.4%	8.2%	47.1%	49.7%
1996	2.060	3.056	1.050	1.595	1.718	2.046	10.3%	7.5%	4.5%	3.3%	14.9%	10.8%	41.8%	43.7%
1997	2.109	3.086	1.029	1.553	0.903	1.128	11.1%	8.1%	4.4%	3.2%	15.4%	11.2%	41.0%	42.6%
1998	1.813	2.695	0.904	1.379	0.850	1.104	12.8%	9.2%	4.8%	3.5%	17.7%	12.6%	36.0%	37.8%
1999	1.495	2.315	0.747	1.185	0.550	0.739	15.0%	10.3%	5.8%	4.0%	20.9%	14.3%	29.8%	32.5%
2000	1.371	2.243	0.705	1.174	0.933	1.366	15.2%	9.9%	1.6%	1.1%	16.8%	11.0%	28.1%	32.2%
2001	1.272	2.151	0.729	1.226	5.336	7.605	14.3%	9.1%	4.2%	2.7%	18.5%	11.8%	29.0%	33.6%
2002	2.819	4.474	1.149	1.889	0.530	0.721	4.7%	3.1%	1.8%	1.2%	6.5%	4.4%	45.8%	51.8%
2003	2.710	4.297	1.289	2.074	0.718	0.890	5.3%	3.5%	2.3%	1.5%	7.6%	5.1%	51.3%	56.8%
2004	2.535	4.024	1.248	2.015	0.344	0.507	8.3%	5.5%	4.9%	3.2%	13.2%	8.7%	49.7%	55.2%
Avg. 1966-04	4.059	6.631	2.051	3.375	2.016	3.016	5.1%	3.6%	1.7%	1.2%	6.8%	4.8%	81.7%	92.5%

Table 13. Numbers at age (billions of fish) for the coastal stock of Pacific whiting estimated by the base-run model, 1966-2004.

	Age													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1966	2.54	1.54	1.23	0.97	0.77	0.61	0.49	0.39	0.31	0.24	0.19	0.15	0.12	0.42
1967	2.30	2.01	1.21	0.95	0.74	0.58	0.46	0.37	0.29	0.23	0.19	0.15	0.12	0.43
1968	2.29	1.82	1.57	0.93	0.71	0.55	0.43	0.34	0.27	0.21	0.17	0.14	0.12	0.44
1969	2.76	1.82	1.44	1.23	0.72	0.55	0.42	0.32	0.26	0.20	0.16	0.13	0.11	0.44
1970	1.58	2.19	1.43	1.12	0.94	0.54	0.41	0.31	0.24	0.19	0.15	0.12	0.10	0.43
1971	1.25	1.25	1.72	1.10	0.84	0.70	0.40	0.30	0.22	0.18	0.14	0.12	0.10	0.42
1972	6.63	0.99	0.98	1.33	0.84	0.63	0.52	0.30	0.22	0.17	0.13	0.11	0.09	0.41
1973	0.79	5.26	0.78	0.77	1.03	0.64	0.48	0.40	0.23	0.17	0.13	0.10	0.09	0.40
1974	0.72	0.62	4.13	0.60	0.58	0.77	0.48	0.36	0.30	0.17	0.13	0.10	0.08	0.38
1975	2.25	0.57	0.49	3.14	0.45	0.43	0.57	0.36	0.27	0.23	0.13	0.10	0.08	0.37
1976	0.49	1.71	0.43	0.37	2.36	0.34	0.32	0.43	0.27	0.21	0.18	0.10	0.08	0.36
1977	0.52	0.39	1.32	0.31	0.26	1.69	0.24	0.24	0.33	0.21	0.16	0.14	0.08	0.35
1978	0.30	0.41	0.30	1.00	0.23	0.20	1.27	0.18	0.19	0.26	0.17	0.13	0.11	0.34
1979	4.05	0.24	0.32	0.23	0.75	0.17	0.15	0.96	0.14	0.15	0.21	0.13	0.10	0.36
1980	0.56	3.21	0.19	0.24	0.17	0.55	0.13	0.11	0.72	0.11	0.11	0.16	0.10	0.37
1981	0.83	0.44	2.53	0.15	0.18	0.13	0.41	0.10	0.08	0.55	0.08	0.09	0.13	0.37
1982	15.59	0.66	0.35	1.92	0.11	0.14	0.09	0.30	0.07	0.06	0.42	0.07	0.07	0.40
1983	0.46	12.37	0.52	0.27	1.46	0.08	0.10	0.07	0.22	0.05	0.05	0.32	0.05	0.37
1984	0.15	0.37	9.74	0.40	0.21	1.10	0.06	0.08	0.05	0.17	0.04	0.04	0.25	0.33
1985	0.33	0.12	0.29	7.58	0.31	0.16	0.84	0.05	0.06	0.04	0.13	0.03	0.03	0.46
1986	10.54	0.26	0.09	0.23	5.91	0.24	0.12	0.64	0.04	0.04	0.03	0.10	0.02	0.38
1987	0.17	8.31	0.20	0.07	0.17	4.48	0.18	0.09	0.48	0.03	0.03	0.02	0.08	0.32
1988	0.46	0.14	6.49	0.15	0.05	0.13	3.35	0.13	0.07	0.36	0.02	0.03	0.02	0.32
1989	3.06	0.37	0.11	4.98	0.12	0.04	0.10	2.51	0.10	0.05	0.27	0.02	0.02	0.26
1990	1.42	2.42	0.28	0.08	3.69	0.09	0.03	0.07	1.83	0.07	0.04	0.21	0.01	0.22
1991	0.28	1.12	1.85	0.21	0.06	2.73	0.06	0.02	0.05	1.36	0.06	0.03	0.16	0.19
1992	2.02	0.22	0.85	1.37	0.16	0.04	1.97	0.05	0.02	0.04	0.99	0.04	0.02	0.26
1993	0.77	1.59	0.17	0.62	0.98	0.11	0.03	1.39	0.03	0.01	0.03	0.72	0.03	0.22
1994	0.33	0.61	1.20	0.12	0.45	0.70	0.08	0.02	1.00	0.02	0.01	0.02	0.54	0.20
1995	1.70	0.26	0.47	0.84	0.08	0.29	0.45	0.05	0.01	0.64	0.02	0.01	0.01	0.55
1996	1.72	1.35	0.20	0.35	0.57	0.05	0.19	0.29	0.03	0.01	0.42	0.01	0.00	0.42
1997	0.90	1.27	1.01	0.14	0.23	0.36	0.03	0.12	0.18	0.02	0.01	0.27	0.01	0.32
1998	0.84	0.71	0.85	0.66	0.09	0.14	0.22	0.02	0.07	0.11	0.01	0.00	0.18	0.25
1999	0.55	0.64	0.46	0.52	0.39	0.05	0.08	0.13	0.01	0.04	0.07	0.01	0.00	0.32
2000	0.94	0.39	0.40	0.27	0.29	0.22	0.03	0.05	0.07	0.01	0.02	0.04	0.00	0.24
2001	5.31	0.74	0.27	0.25	0.17	0.18	0.13	0.02	0.03	0.04	0.00	0.01	0.02	0.19
2002	0.53	4.17	0.53	0.16	0.16	0.10	0.10	0.07	0.01	0.02	0.02	0.00	0.01	0.16
2003	0.76	0.42	3.17	0.38	0.11	0.11	0.07	0.07	0.05	0.01	0.01	0.02	0.00	0.13
2004	0.60	0.60	0.32	2.31	0.27	0.07	0.07	0.04	0.04	0.03	0.00	0.01	0.01	0.10

Table 14. Decision table evaluating the consequences of assuming a harvest rate policy associated with lower or higher acoustic survey Q (assumed state on nature) when in fact the converse was true (true state on nature). This analysis defines a 2x2 matrix with two assumed states of nature (*q*=1.0 and *q*=0.6, respectively) and two true states of nature (*q*=1.0 and *q*=0.6) under both the F40%(40-10) and F45%(40-10) harvest rate policies. Projected spawning biomass (millions mt), depletion level (% unfished biomass), and exploitation rates in 2005-2014 are given.

			True State of Nature					
Assumed			***q = 1.0***			***q = 0.6***		
State of Nature	**Year**	**OY Assumed**	**Spawning Biomass**	**Percent Unfished**	**Exploitation Rate**	**Spawning Biomass**	**Percent Unfished**	**Exploitation Rate**
q = 1.0								
	2005	364,197	0.997	0.383	0.185	1.673	0.414	0.113
	2006	258,507	0.696	0.268	0.198	1.268	0.314	0.113
	2007	248,323	0.707	0.272	0.164	1.382	0.343	0.092
	2008	278,576	0.779	0.300	0.166	1.557	0.386	0.087
F40% (40-10)	**2009**	321,665	0.838	0.322	0.173	1.621	0.402	0.096
	2010	353,427	0.921	0.354	0.177	1.824	0.452	0.096
	2011	371,392	0.936	0.360	0.179	1.833	0.454	0.099
	2012	369,845	0.934	0.359	0.183	1.800	0.446	0.101
	2013	363,418	0.909	0.350	0.185	1.824	0.452	0.099
	2014	365,660	0.919	0.353	0.182	1.862	0.461	0.097
q = 0.6								
	2005	597,625	0.997	0.383	0.306	1.673	0.414	0.113
	2006	422,115	0.578	0.222	0.413	1.185	0.298	0.195
	2007	382,138	0.521	0.200	0.361	1.140	0.286	0.159
	2008	408,865	0.550	0.212	0.350	1.192	0.300	0.163
F40% (40-10)	**2009**	450,905	0.594	0.229	0.350	1.225	0.308	0.171
	2010	489,969	0.641	0.246	0.367	1.330	0.334	0.172
	2011	515,007	0.639	0.246	0.364	1.334	0.335	0.174
	2012	530,105	0.623	0.240	0.385	1.370	0.344	0.179
	2013	540,436	0.577	0.222	0.433	1.377	0.346	0.184
	2014	564,831	0.562	0.216	0.445	1.430	0.359	0.179

Table 14. Continued……

Assumed State of Nature	Year	OY Assumed	True State of Nature: q = 1.0 Spawning Biomass	Percent Unfished	Exploitation Rate	q = 0.6 Spawning Biomass	Percent Unfished	Exploitation Rate
q = 1.0								
	2005	302,305	0.997	0.383	0.154	1.673	0.414	0.094
	2006	230,359	0.729	0.280	0.168	1.300	0.322	0.098
	2007	225,028	0.753	0.289	0.141	1.428	0.354	0.081
	2008	251,998	0.831	0.319	0.141	1.609	0.399	0.077
F45% (40-10)	**2009**	290,260	0.896	0.345	0.146	1.675	0.415	0.084
	2010	318,141	0.997	0.383	0.149	1.896	0.470	0.084
	2011	336,497	1.020	0.392	0.152	1.909	0.473	0.086
	2012	338,863	1.022	0.393	0.154	1.881	0.466	0.089
	2013	336,312	1.008	0.388	0.156	1.910	0.473	0.088
	2014	338,300	1.018	0.391	0.155	1.955	0.485	0.086
q = 0.6								
	2005	482,899	0.997	0.383	0.247	1.673	0.414	0.149
	2006	370,917	0.637	0.245	0.327	1.207	0.299	0.167
	2007	366,140	0.601	0.231	0.301	1.245	0.309	0.139
	2008	410,192	0.625	0.240	0.312	1.365	0.338	0.138
F45% (40-10)	**2009**	453,579	0.655	0.252	0.322	1.409	0.349	0.148
	2010	479,357	0.697	0.268	0.334	1.523	0.377	0.149
	2011	488,955	0.689	0.265	0.324	1.519	0.376	0.151
	2012	479,261	0.677	0.260	0.326	1.461	0.362	0.154
	2013	472,026	0.648	0.249	0.340	1.440	0.357	0.154
	2014	474,799	0.656	0.252	0.342	1.463	0.363	0.152

Table 15. Life history and fishery vectors used to estimate spawning biomass per recruit (SPR) fishing mortalities.

Age	Natural mortality	U.S. fishery selectivity (Avg. 1995-2004)		Canadian fishery selectivity (Avg 1995-2004)		U.S. fishery weight at age (kg) (Avg. 1978-2004)	Canadian fishery weight at age (kg) (Avg. 1976-2004)	Population weight at age (kg) (Avg. 1977-2004)	Proportion of mature females	Multiplier for female weight at age
		q =1.0	*q* =0.6	*q* =1.0	*q* =0.6					
2	0.23	0.1300	0.1361	0.042	0.040	0.299	0.334	0.300	0.176	0.510
3	0.23	0.5154	0.5389	0.162	0.173	0.403	0.530	0.430	0.661	0.511
4	0.23	0.8744	0.8858	0.256	0.289	0.482	0.627	0.552	0.890	0.510
5	0.23	0.9890	0.9998	0.538	0.610	0.548	0.702	0.655	0.969	0.512
6	0.23	1.0000	1.0000	0.721	0.812	0.590	0.749	0.843	0.986	0.522
7	0.23	0.9985	0.9810	0.906	0.959	0.632	0.789	0.716	0.996	0.525
8	0.23	0.9939	0.9486	0.976	0.995	0.666	0.826	0.834	1.000	0.535
9	0.23	0.9838	0.8965	0.996	1.000	0.694	0.858	0.965	1.000	0.543
10	0.23	0.9620	0.8151	1.000	0.994	0.722	0.894	0.753	1.000	0.547
11	0.23	0.9138	0.6933	0.995	0.969	0.765	0.919	1.042	1.000	0.569
12	0.23	0.8080	0.5269	0.961	0.881	0.793	0.954	1.076	1.000	0.568
13	0.23	0.6007	0.3424	0.813	0.650	0.840	0.970	0.833	1.000	0.572
14	0.23	0.3330	0.1933	0.448	0.322	0.843	0.985	0.827	1.000	0.581
15+	0.23	0.1479	0.1020	0.132	0.108	0.906	1.086	1.255	1.000	0.589

Table 16. Projections of Pacific hake biomass, yield and depletion rates for 2005-2014 under different harvest rate policies from final models q =1.0 and q =0.6. Shown are Bayesian credibility intervals (10%, 50%, and 90%) generated from 2,500,000 MCMC samples.

Model *q* =1.0

		3+ Bioimass (millions mt)			SpawningBioimass (million mt)			Age-2 Recruits (billion)			Depletion Rate			Coastwide yield (t)		
	Year	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
	2005	1.638	1.952	2.338	0.842	0.997	1.184	0.092	0.259	0.736	0.324	0.383	0.455	294,258	364,197	438,815
	2006	1.042	1.252	1.554	0.577	0.696	0.850	0.477	1.448	4.631	0.222	0.268	0.327	192,114	258,507	345,172
	2007	1.051	1.418	2.484	0.542	0.707	1.064	0.285	1.134	4.000	0.208	0.272	0.409	159,956	248,323	425,987
F40% (40-10)	2008	0.993	1.619	3.019	0.535	0.779	1.335	0.249	1.114	4.731	0.206	0.300	0.513	150,452	278,576	529,730
Harvest Policy	2009	1.061	1.742	3.558	0.539	0.838	1.578	0.232	0.954	3.906	0.207	0.322	0.607	154,230	321,665	641,017
	2010	1.103	1.860	3.829	0.598	0.921	1.723	0.336	1.087	4.593	0.230	0.354	0.663	180,131	353,427	682,167
	2011	1.211	1.949	3.867	0.606	0.936	1.798	0.292	0.931	3.717	0.233	0.360	0.691	190,821	371,392	713,404
	2012	1.155	1.944	3.675	0.589	0.934	1.736	0.303	1.035	3.853	0.227	0.359	0.667	190,315	369,845	705,711
	2013	1.177	1.877	3.727	0.612	0.909	1.704	0.240	0.989	4.313	0.235	0.350	0.655	200,654	363,418	689,173
	2014	1.171	1.864	3.948	0.607	0.919	1.818	0.197	1.099	4.732	0.234	0.353	0.699	194,951	365,660	725,154
	2005	1.638	1.952	2.338	0.842	0.997	1.184	0.092	0.259	0.736	0.324	0.383	0.455	244,229	302,305	363,377
	2006	1.093	1.315	1.629	0.605	0.729	0.887	0.477	1.448	4.631	0.233	0.280	0.341	172,562	230,359	304,634
	2007	1.125	1.505	2.574	0.580	0.753	1.119	0.285	1.134	4.000	0.223	0.289	0.430	149,984	225,028	368,429
	2008	1.080	1.723	3.154	0.580	0.831	1.408	0.249	1.114	4.731	0.223	0.319	0.541	142,603	251,998	457,461
F45% (40-10)	2009	1.138	1.853	3.724	0.577	0.896	1.676	0.232	0.954	3.906	0.222	0.345	0.645	145,064	290,260	560,357
Harvest Policy	2010	1.193	2.003	4.044	0.643	0.997	1.853	0.336	1.087	4.593	0.247	0.383	0.713	166,897	318,141	604,656
	2011	1.309	2.115	4.157	0.658	1.020	1.942	0.292	0.931	3.717	0.253	0.392	0.747	179,031	336,497	639,758
	2012	1.265	2.123	3.991	0.644	1.022	1.900	0.303	1.035	3.853	0.248	0.393	0.730	179,943	338,863	639,545
	2013	1.289	2.062	4.048	0.674	1.008	1.869	0.240	0.989	4.313	0.259	0.388	0.719	189,901	336,312	632,219
	2014	1.303	2.065	4.256	0.673	1.018	1.965	0.197	1.099	4.732	0.259	0.391	0.756	190,028	338,300	650,107

Model *q* =0.6

		3+ Bioimass (million mt)			SpawningBioimass (million mt)			Age-2 Recruits (billion)			Depletion Rate			Coastwide yield (t)		
	Year	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
	2005	2.445	3.356	4.323	1.287	1.673	2.151	0.106	0.349	1.034	0.320	0.437	0.562	418,345	597,625	791,728
	2006	1.587	2.123	2.771	0.900	1.185	1.500	0.661	2.054	6.483	0.226	0.298	0.377	278,998	422,115	590,706
	2007	1.640	2.240	3.652	0.861	1.140	1.662	0.342	1.428	6.156	0.216	0.286	0.418	242,757	382,138	640,772
F40% (40-10)	2008	1.588	2.399	4.580	0.840	1.192	2.063	0.340	1.537	6.902	0.211	0.300	0.519	218,160	408,865	794,166
Harvest Policy	2009	1.520	2.520	5.330	0.772	1.225	2.318	0.324	1.267	6.336	0.194	0.308	0.583	202,578	450,905	939,578
	2010	1.561	2.706	5.810	0.841	1.330	2.663	0.436	1.553	6.743	0.211	0.334	0.669	225,978	489,969	1,057,915
	2011	1.597	2.752	6.115	0.819	1.334	2.819	0.409	1.414	5.790	0.206	0.335	0.709	228,525	515,007	1,126,446
	2012	1.604	2.802	5.895	0.816	1.370	2.729	0.419	1.405	5.540	0.205	0.344	0.686	230,474	530,105	1,110,600
	2013	1.599	2.796	5.710	0.827	1.377	2.697	0.387	1.612	7.898	0.208	0.346	0.678	241,298	540,436	1,102,727
	2014	1.671	2.902	6.391	0.845	1.430	2.843	0.318	1.473	5.701	0.212	0.359	0.715	248,666	564,831	1,139,945
	2005	2.472	3.232	4.165	1.287	1.673	2.151	0.122	0.340	1.015	0.319	0.414	0.533	355,660	482,899	632,026
	2006	1.664	2.169	2.781	0.935	1.207	1.530	0.694	2.135	7.248	0.232	0.299	0.379	253,660	370,917	507,664
	2007	1.730	2.398	4.040	0.911	1.245	1.802	0.408	1.733	7.614	0.226	0.309	0.447	218,786	366,140	581,201
	2008	1.675	2.801	5.184	0.896	1.365	2.292	0.408	1.562	7.092	0.222	0.338	0.568	210,534	410,192	737,894
F45% (40-10)	2009	1.707	2.896	5.674	0.886	1.409	2.563	0.334	1.330	5.102	0.219	0.349	0.635	218,179	453,579	860,214
Harvest Policy	2010	1.845	3.102	5.859	0.979	1.523	2.686	0.367	1.335	7.304	0.243	0.377	0.665	246,014	479,357	888,422
	2011	1.850	3.129	6.044	0.950	1.519	2.758	0.415	1.407	4.989	0.235	0.376	0.683	241,460	488,955	917,727
	2012	1.814	2.972	5.839	0.928	1.461	2.756	0.375	1.408	4.984	0.230	0.362	0.683	236,900	479,261	916,826
	2013	1.800	2.937	5.725	0.932	1.440	2.730	0.340	1.539	6.115	0.231	0.357	0.676	237,814	472,026	941,087
	2014	1.790	2.976	5.865	0.916	1.463	2.735	0.311	1.378	5.373	0.227	0.363	0.678	236,545	474,799	922,979

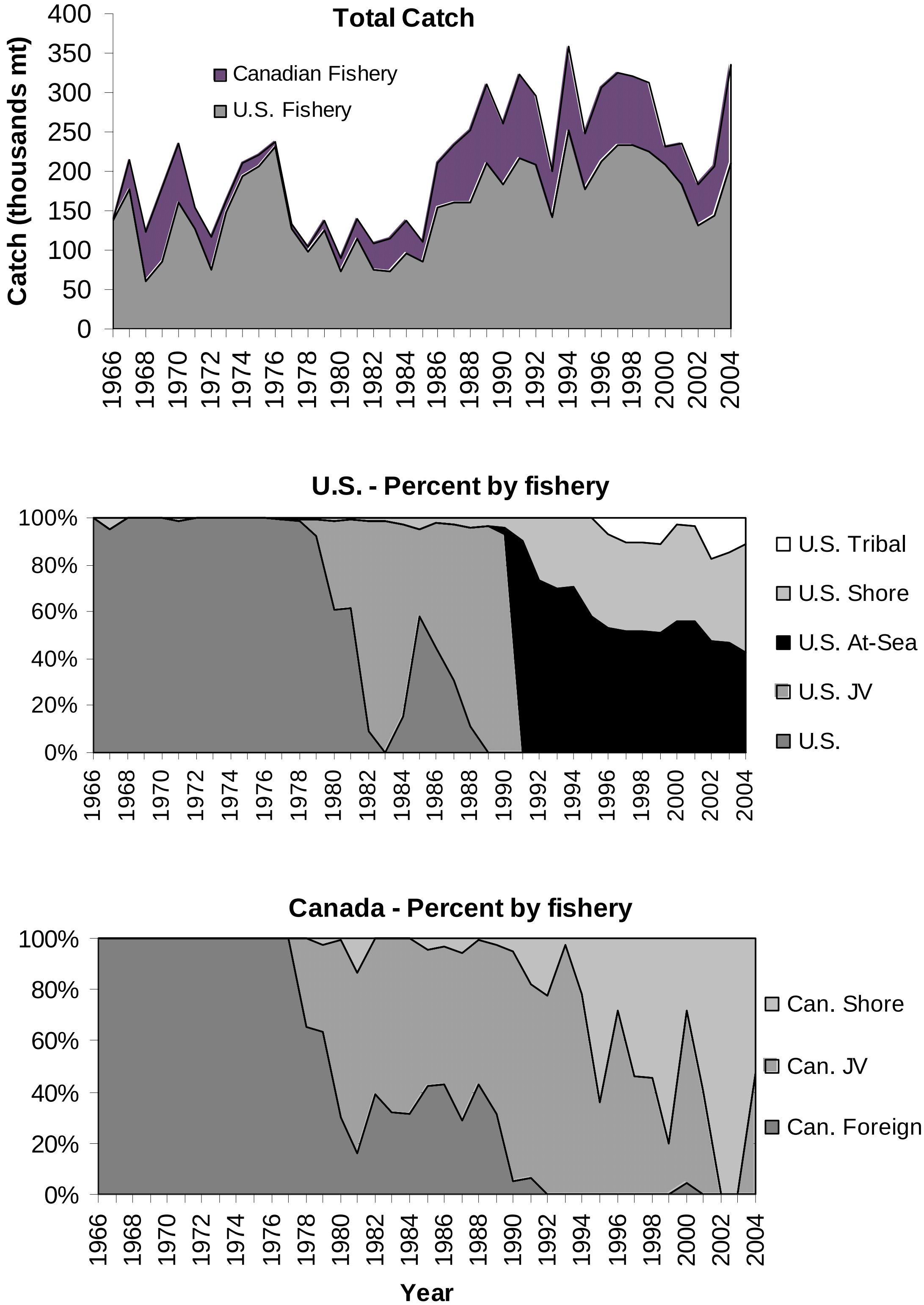


Figure 1. Total catch of Pacific hake in the U.S. and Canadian zones (1966-2004) (upper panel). Percent catch by fishery within each zone (lower panels).

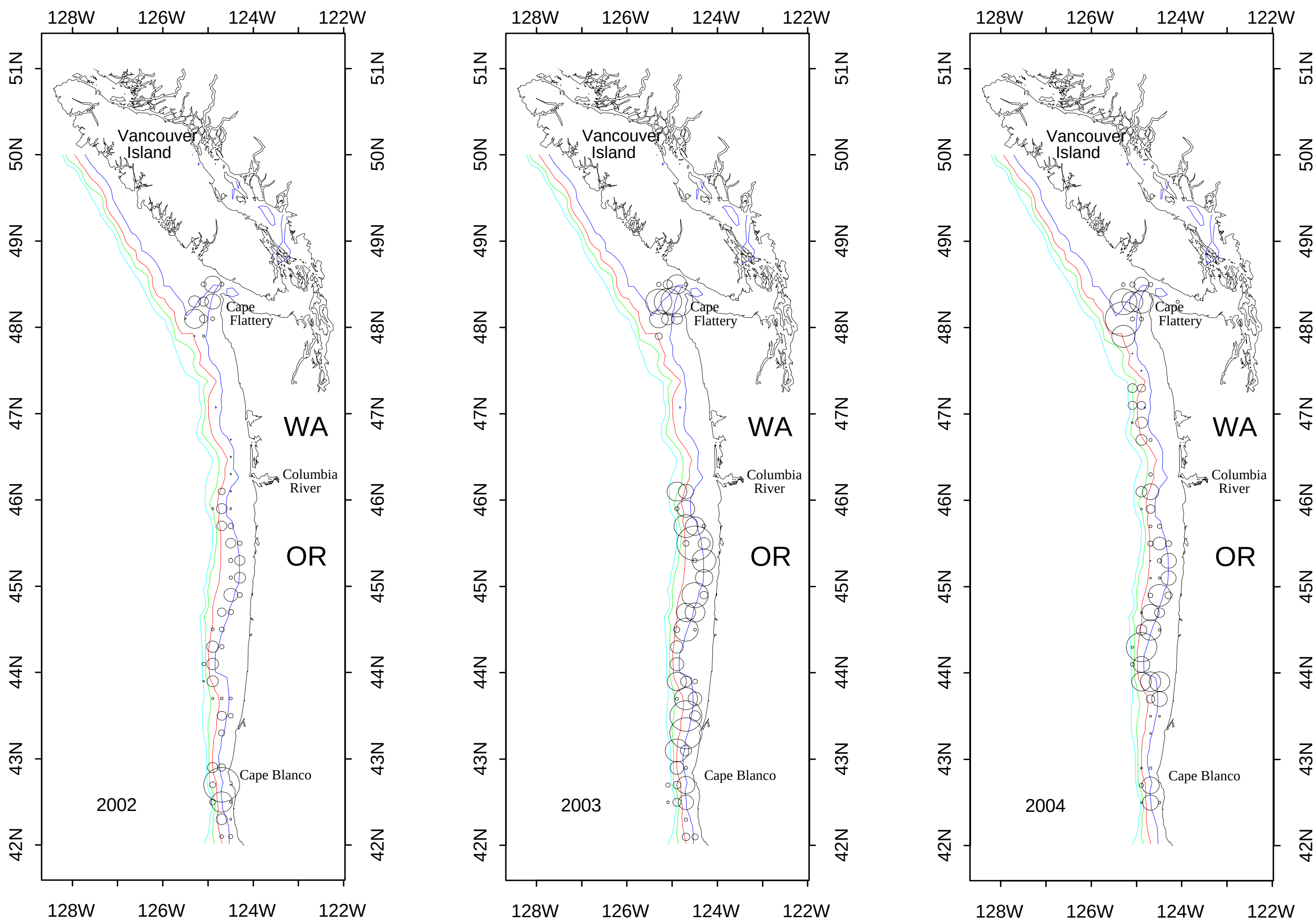


Figure 2. Catch by 20 km^2 block for factory and catcher boats in the 2002-2004 at-sea fishery for Pacific hake. Area of circle is proportional to the total catch within the block.

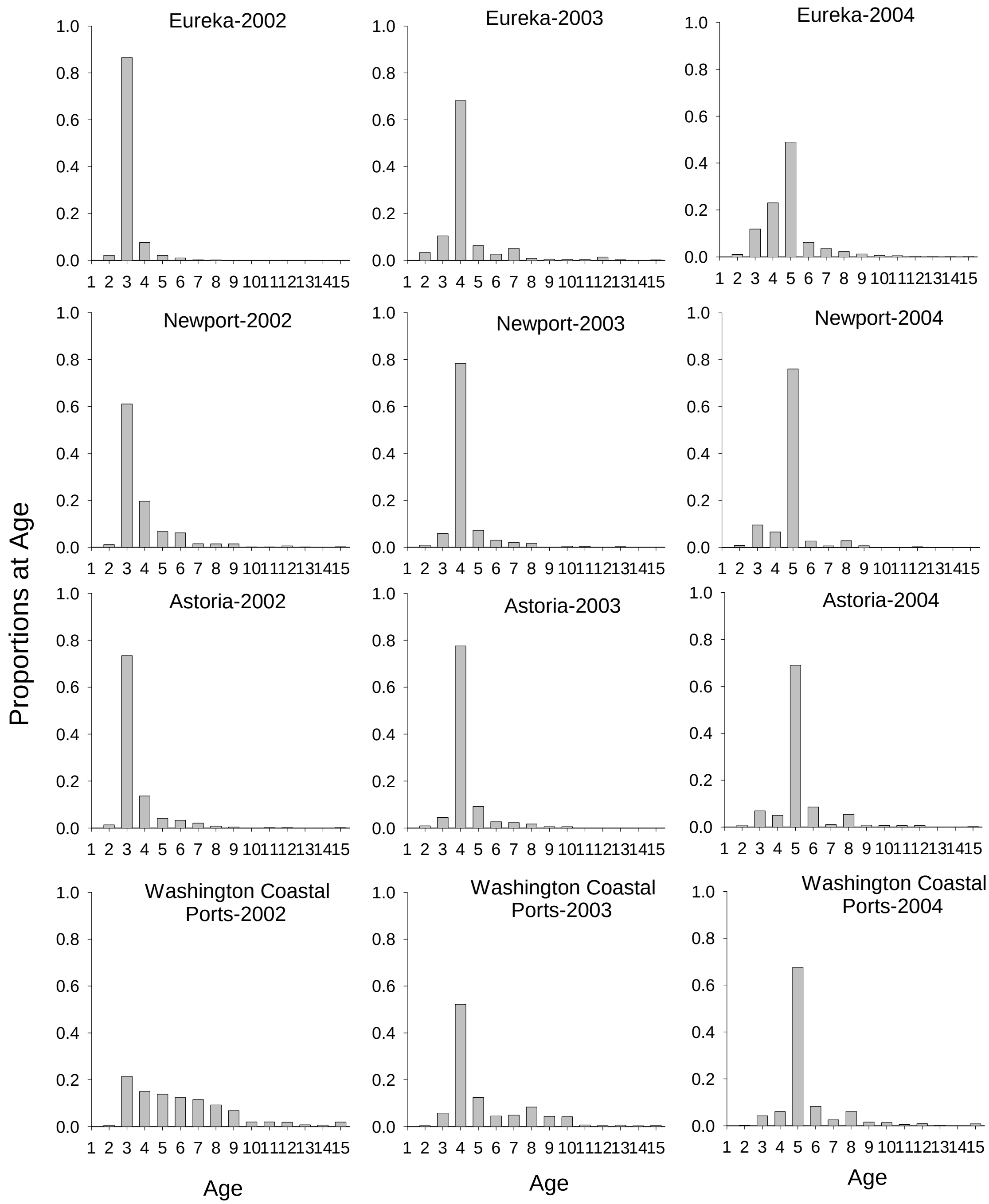


Figure 2. Pacific whiting proportion by age from shore-based landings in the U.S. zone, 1999-2001.

Figure 3. Pacific hake proportion by age from shore-based landings in the U.S. zone, 2002-2004.

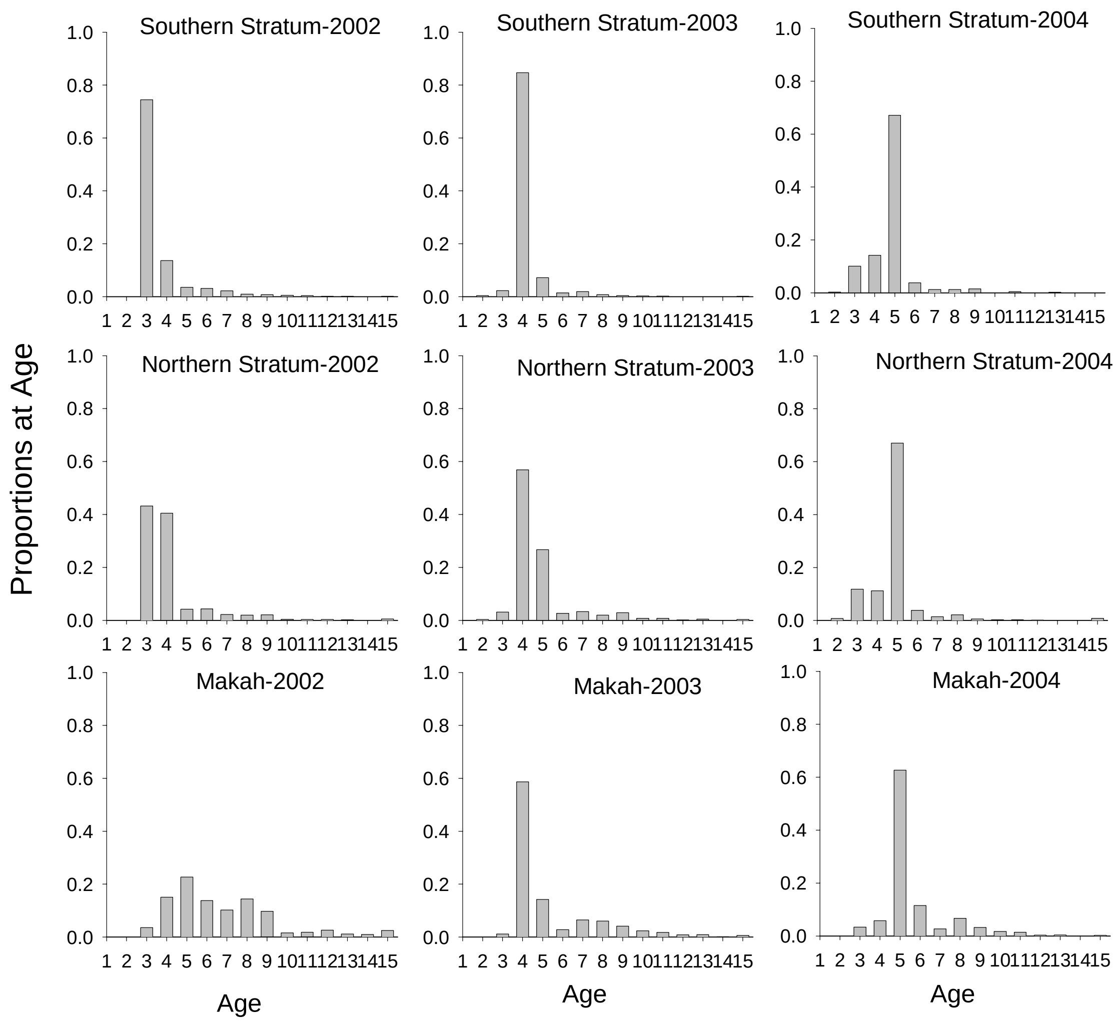


Figure 4. Pacific hake proportion by age from at sea fishery catches in the U.S. zone, 2002-2004.

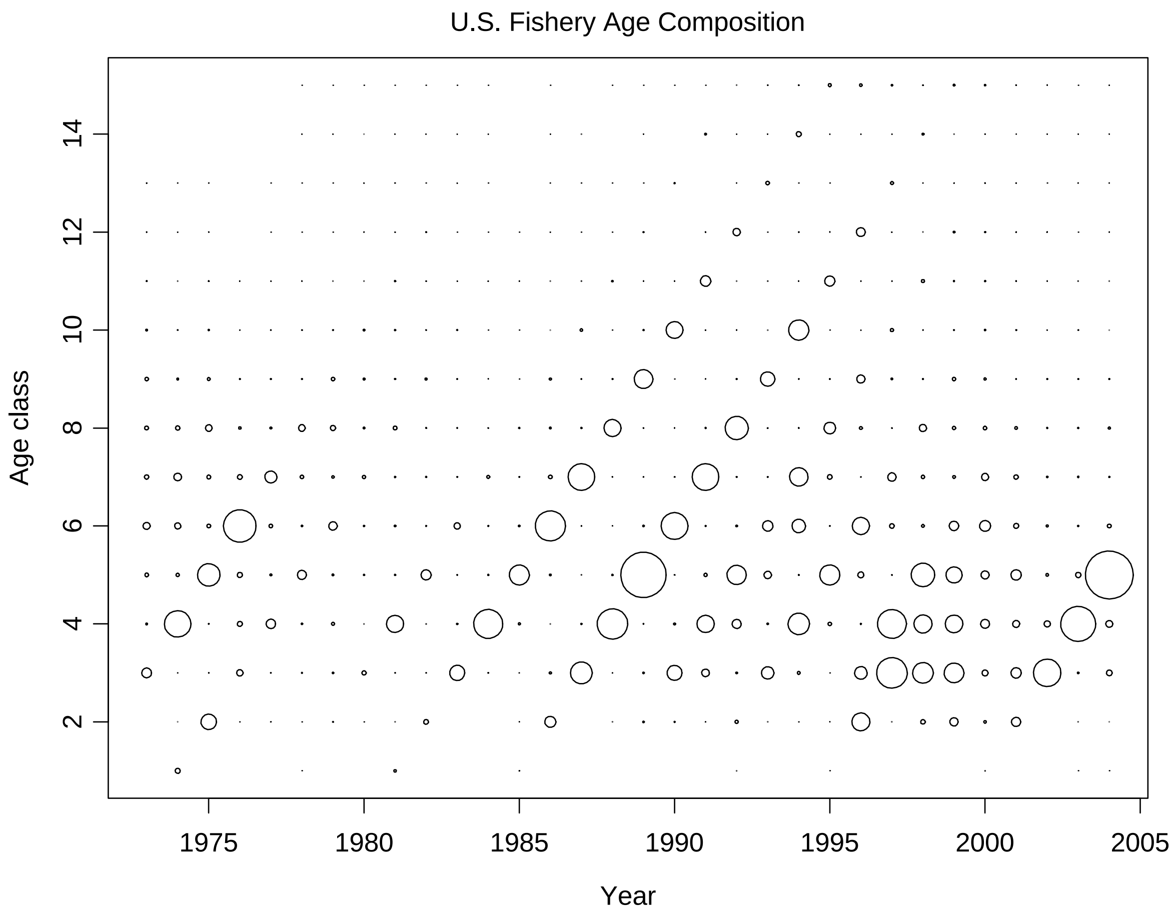


Figure.5. Catch at age of Pacific hake in the U.S. fisheries during 1973-2004. The diameter of the circle is proportional to the catch at age

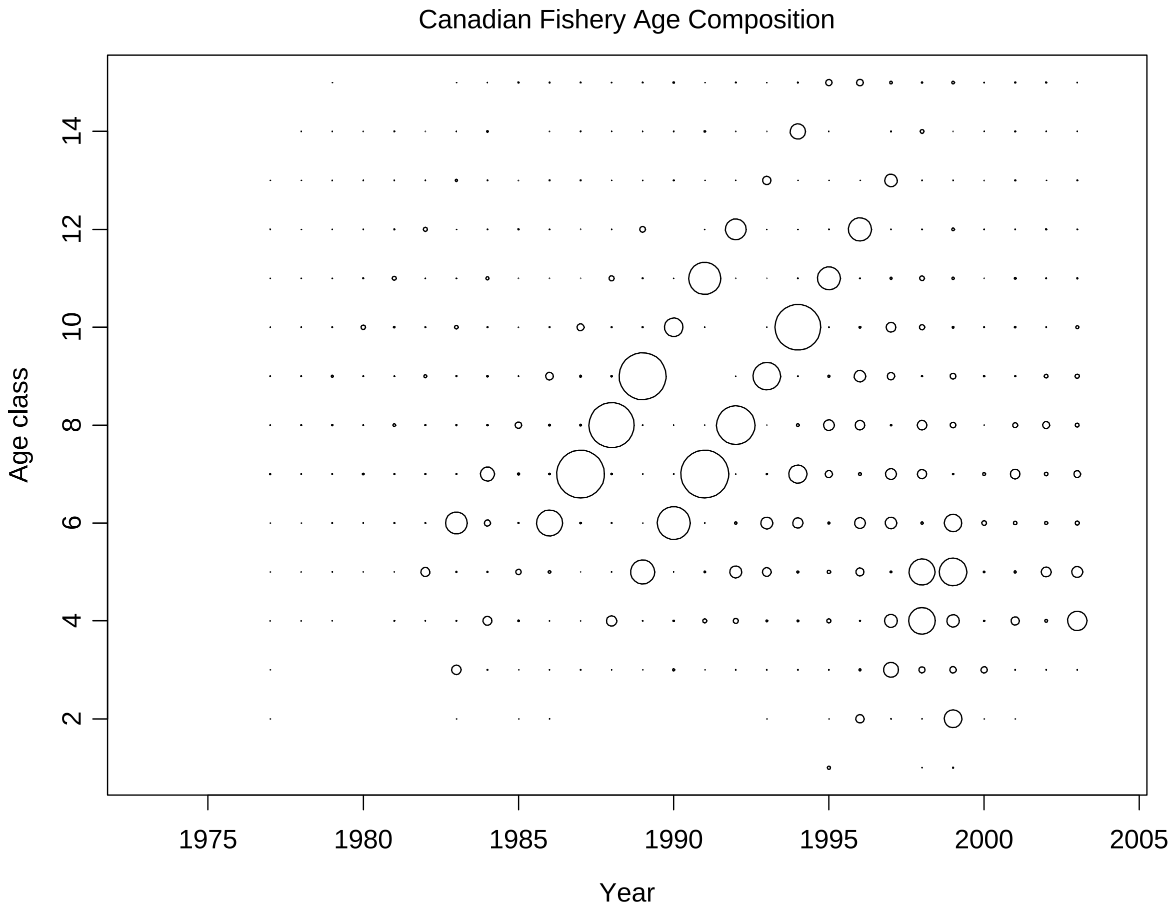


Figure 6. Catch at age of Pacific hake in the Canadian fisheries during 1977-2004. The diameter of the circle is proportional to the catch at age

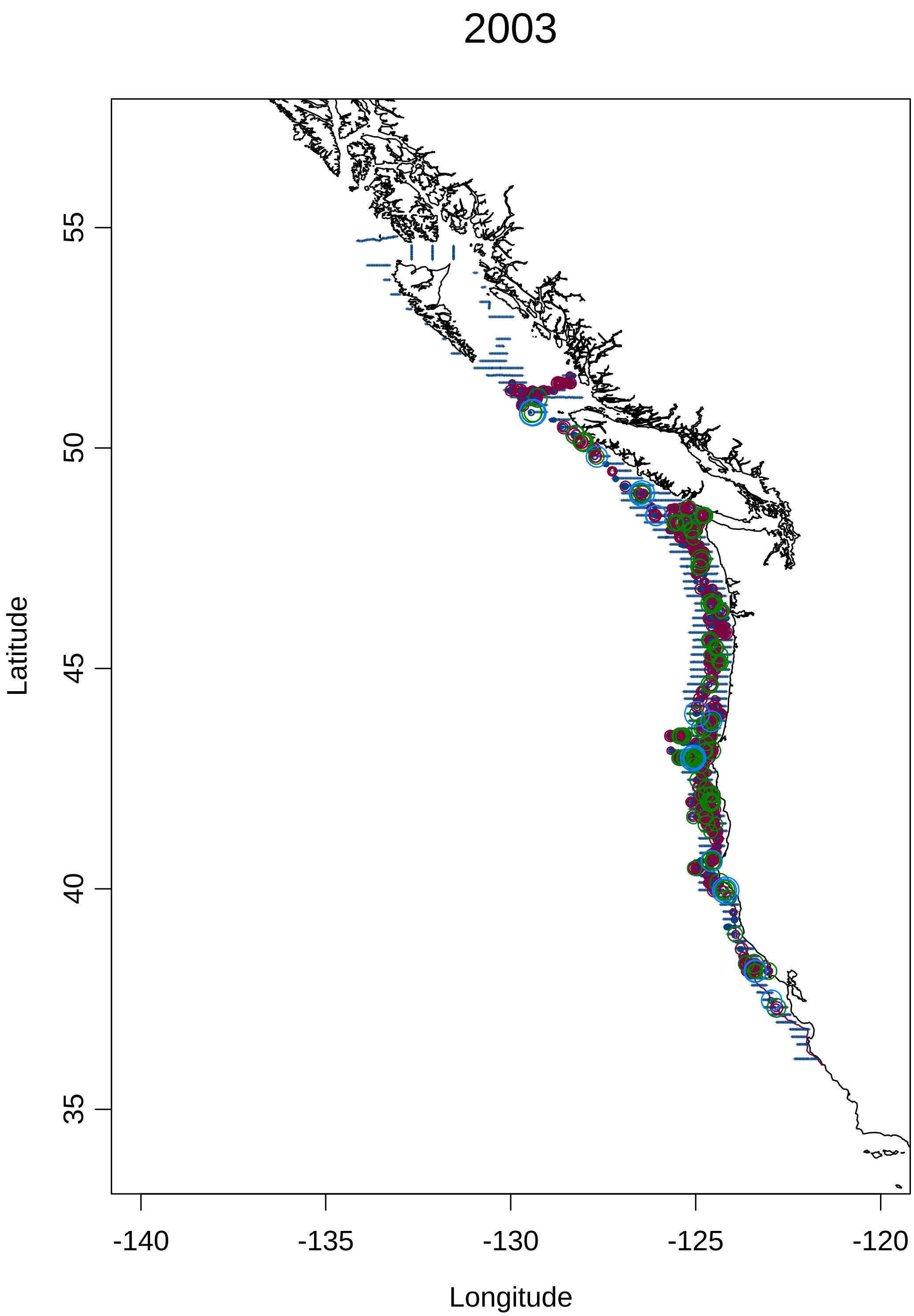
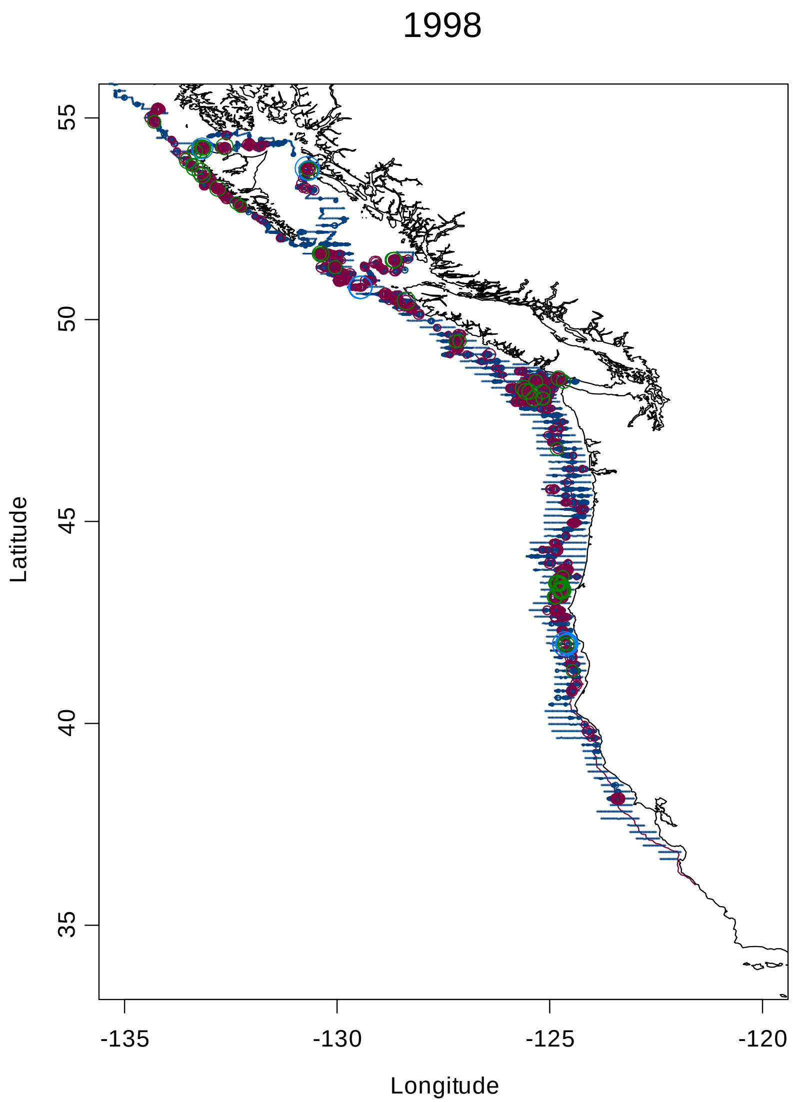


Figure 7. Acoustic backscattering (SA) attributed to Pacific hake along transects off the U.S. and Canada west coast shelf and slope between Monterey, CA, and Newport, OR, during the 2003 acoustic echo integration-trawl survey.



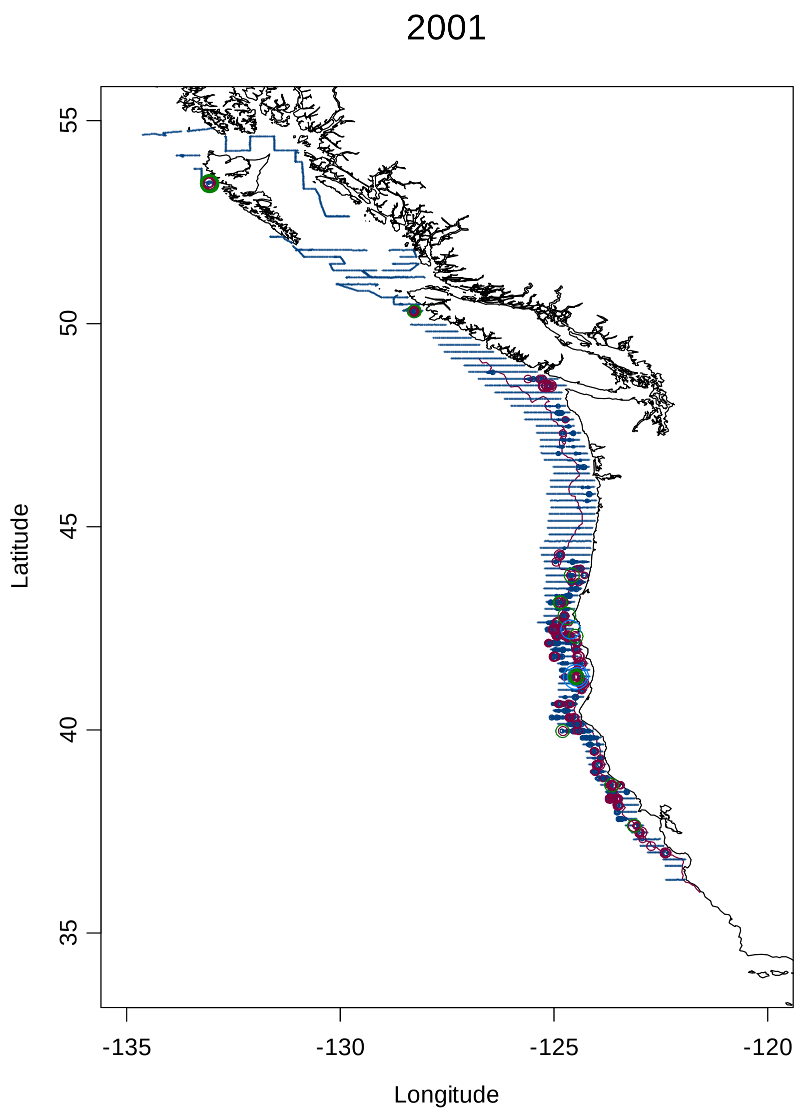
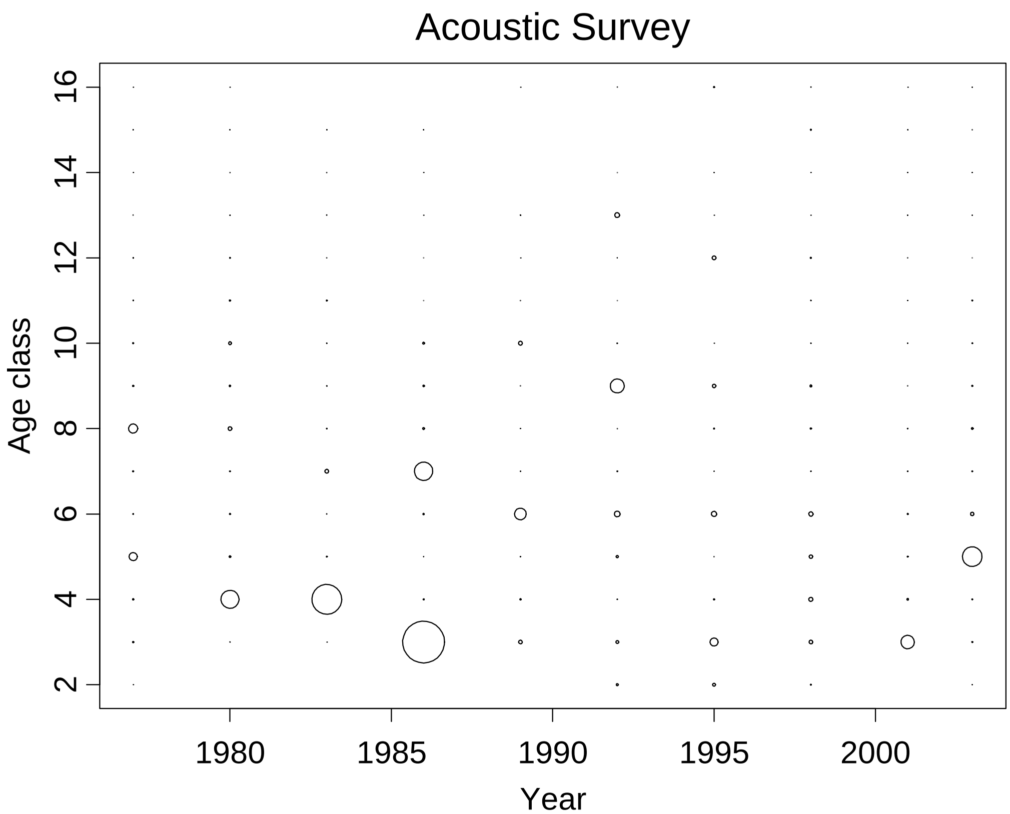


Figure 7 continued. Acoustic backscattering (SA) attributed to Pacific hake along transects off the U.S. and Canada west coast shelf and slope between Monterey, CA, and Newport, OR, during the 1998 and 2001 acoustic echo integration-trawl survey.



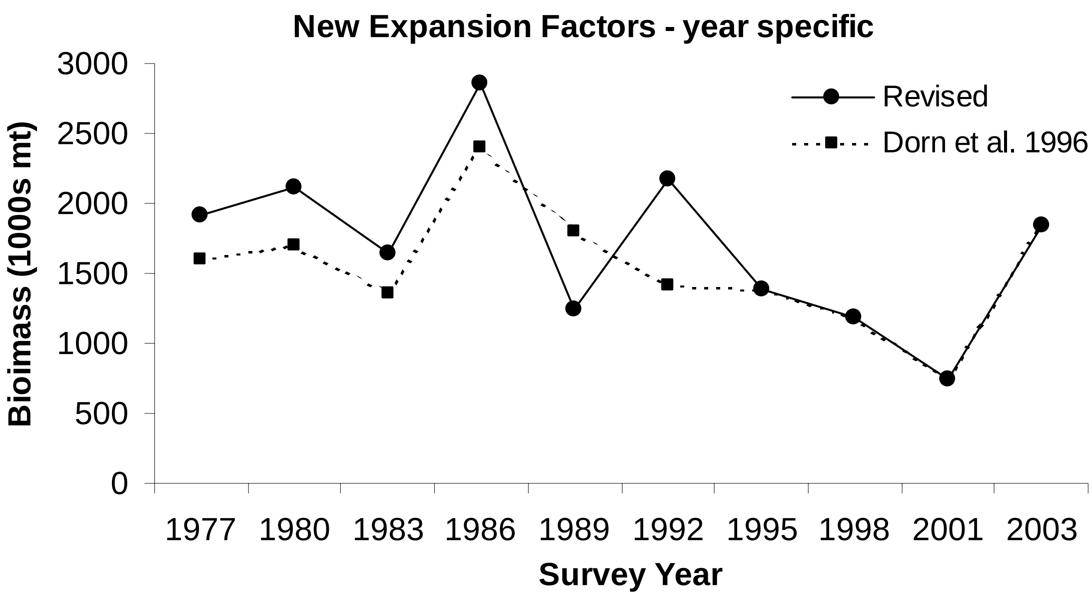


Figure 8. Top Panel) Trends in Pacific hake biomass in the acoustic survey based of revised deep water and northern expansion factors (See Helser et al. 2003). Bottom Panel) Catch at age of Pacific hake from the acoustic survey, 1977-2003. The diameter of the circle is proportional to the catch at age

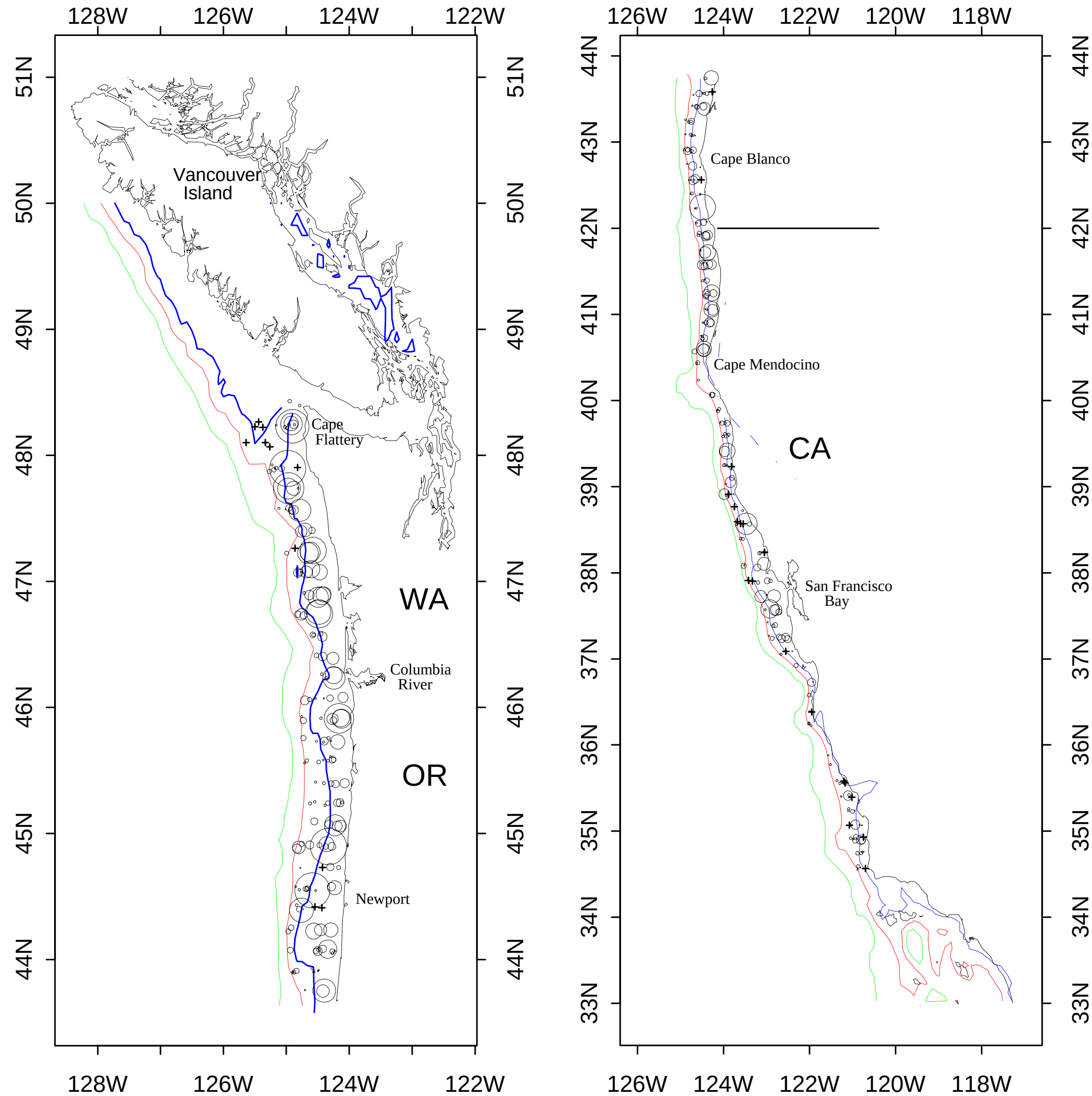


Figure 9. Spatial distribution of age 1+ Pacific hake in the NWFSC 2004 bottom trawl (Triennial) survey.

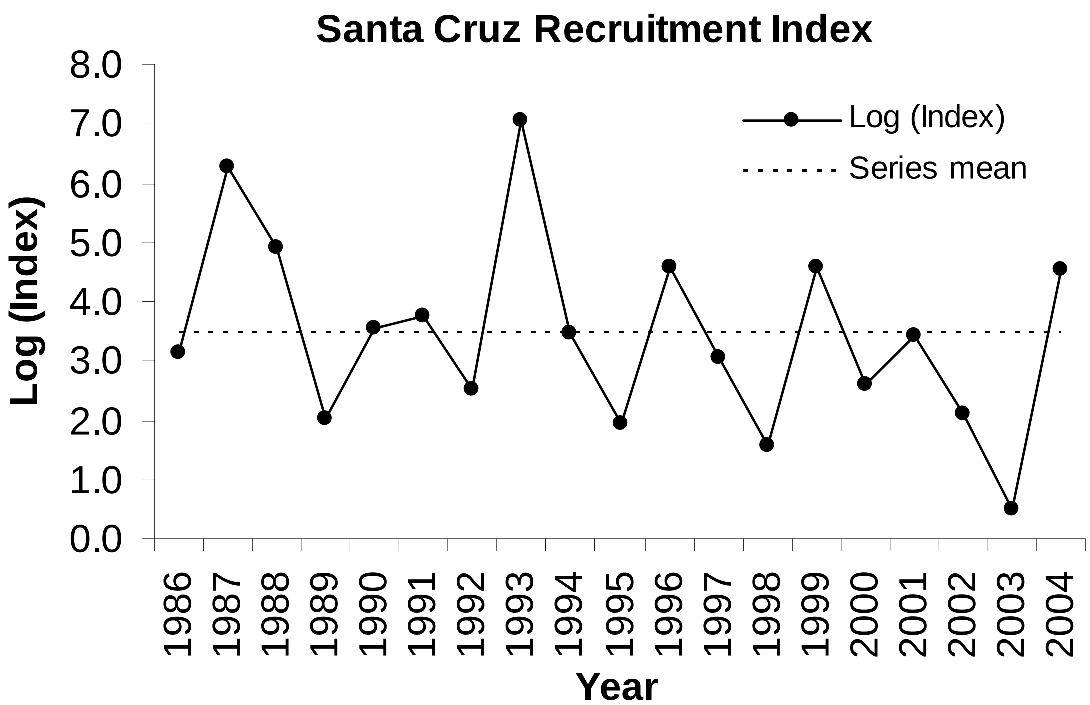


Figure 10. Santa Cruz Laboratory juvenile recruitment index (Monterey inside stratum only), 1986-2004. Index is obtained from a generalized linear model fit to the log-transformed CPUEs (Ralston et al. 1998). The juvenile index is projected two years in advance and is used as an index of age 2 hake recruitment, i.e., 1986 juvenile index represents age 2 hake recruitment in 1988.

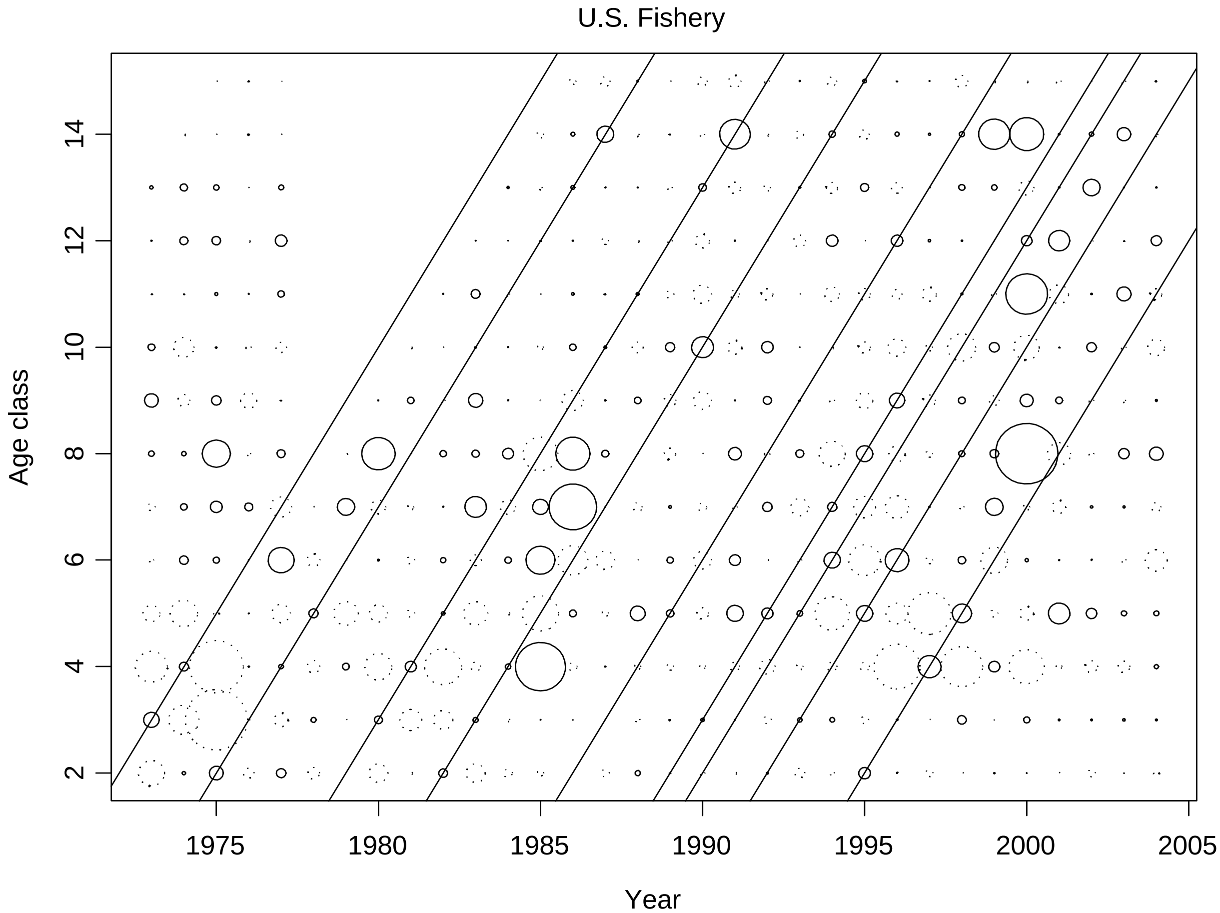


Figure 11. Pearson residuals from Models q=1.0 for the U.S. fishery age composition (q=0.6 are qualitatively similar and not shown). Circle areas are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is 3.7 for the age-2 fish in 1975. Diagonal lines show strong year classes (1970, 1973, 1977, 1980, 1984, 1988, 1990, and 1993).

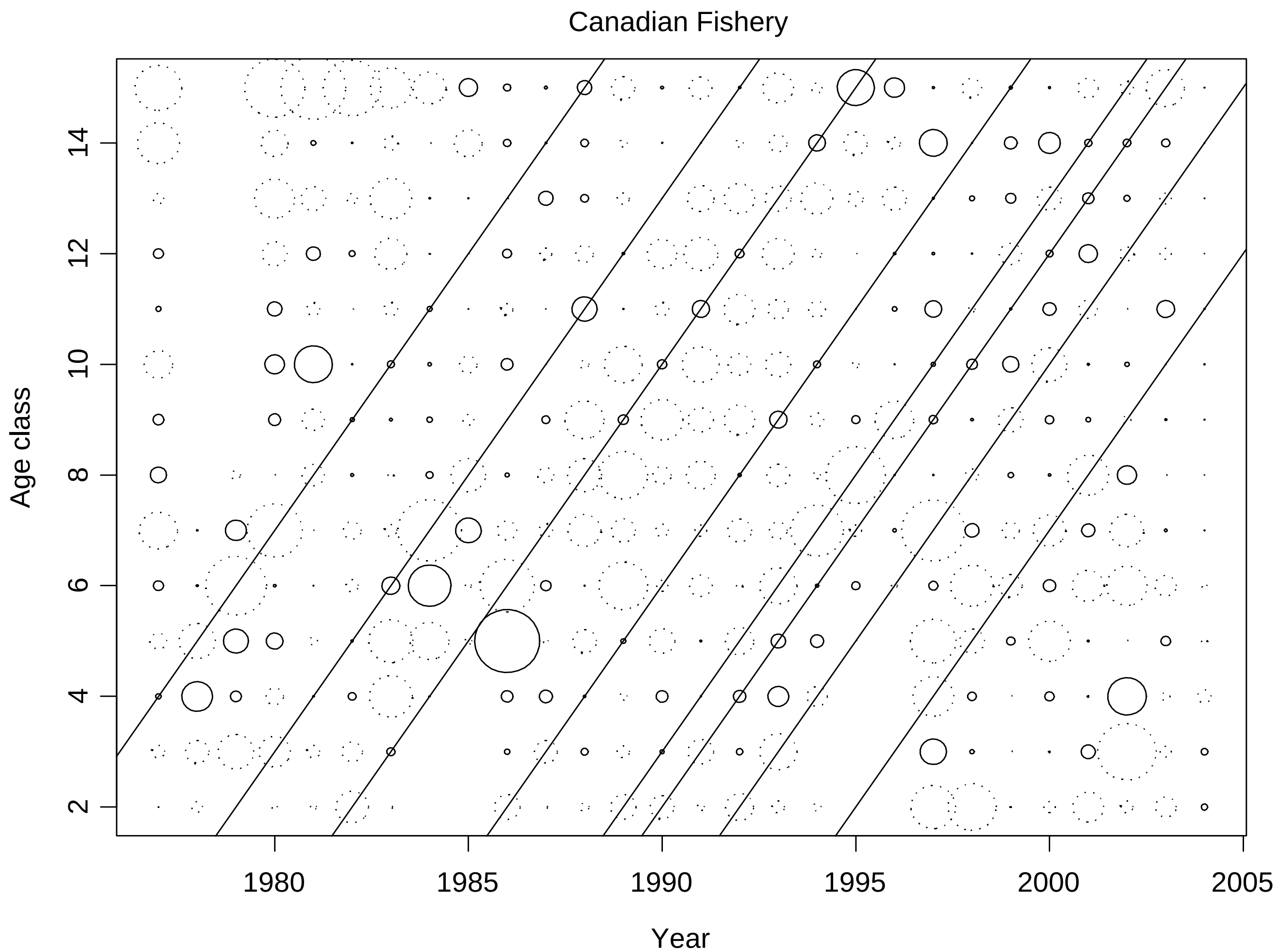


Figure 12. Pearson residuals from Models q=1.0 for the Canadian fishery age composition (q=0.6 are qualitatively similar and not shown). Circle areas are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is 5.1 for the age-5 fish in 1986. Diagonal lines show strong year classes (1973, 1977, 1980, 1984, 1987, 1988, 1990, and 1993).

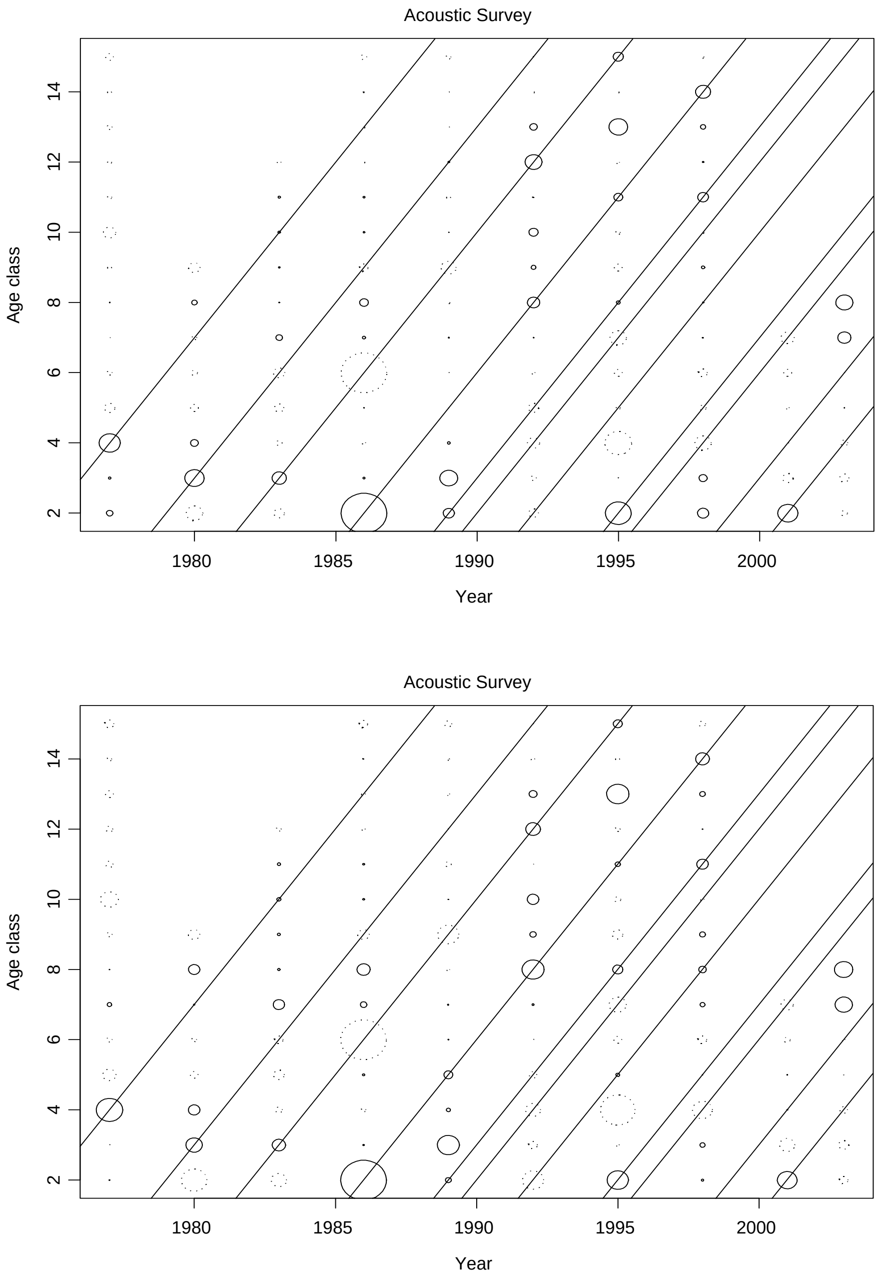


Figure 13. Pearson residuals from Models q=1.0 (top panel) and q=0.6 (bottom panel) for the acoustic survey age composition. Circle areas are proportional to the magnitude of the residual. Circles drawn with dotted lines indicate negative residuals. The largest residual in absolute value is -2.9 for the age-6 fish in 1986. Diagonal lines show strong year classes (1973, 1977, 1980, 1984, 1988, 1990, and 1993).

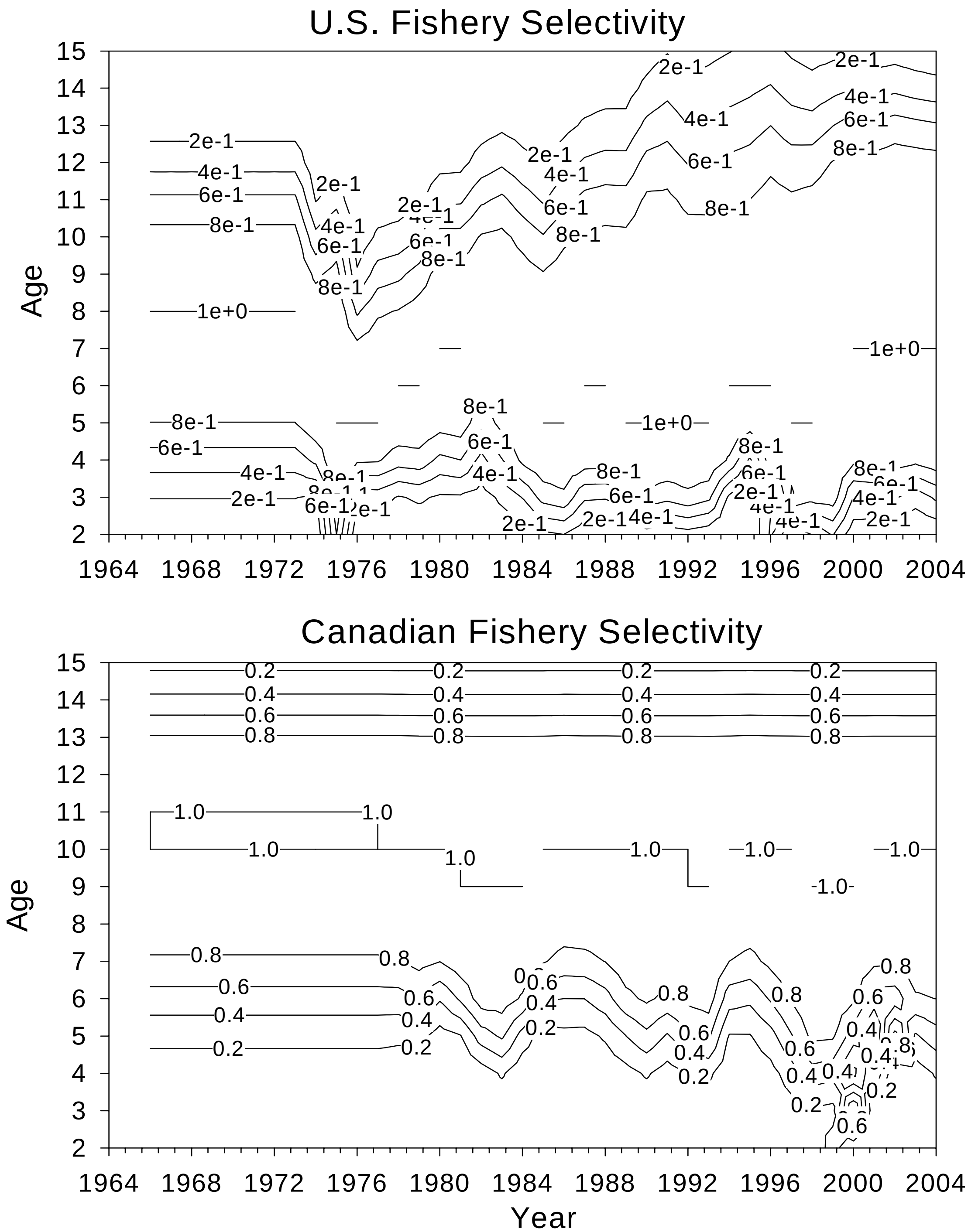
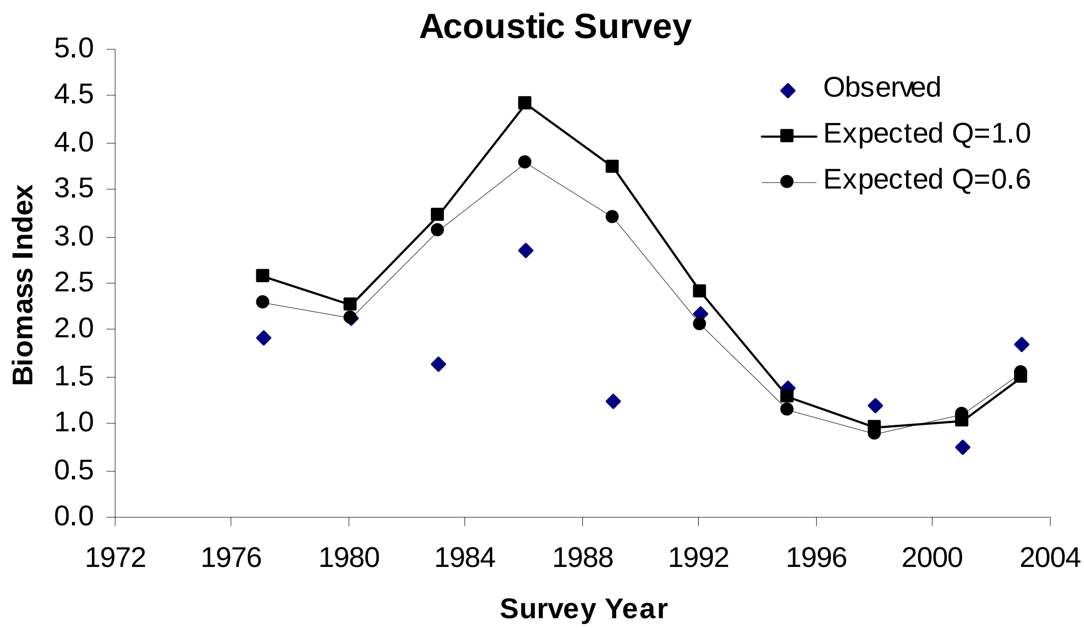


Figure 14. Contour plot showing annual changes in the U.S. and Canadian fishery selectivity at age estimated by Model q=1.0 (Fishery selectivity from model q=0.6 is qualitatively similar and not shown). Time varying selectivity was estimated using a random walk process error for parameters associated with both the ascending and ascending limb of the selectivity function in the U.S. fishery. In the Canadian fishery annual variation was assumed for only the ascending portion of the double logistic function.



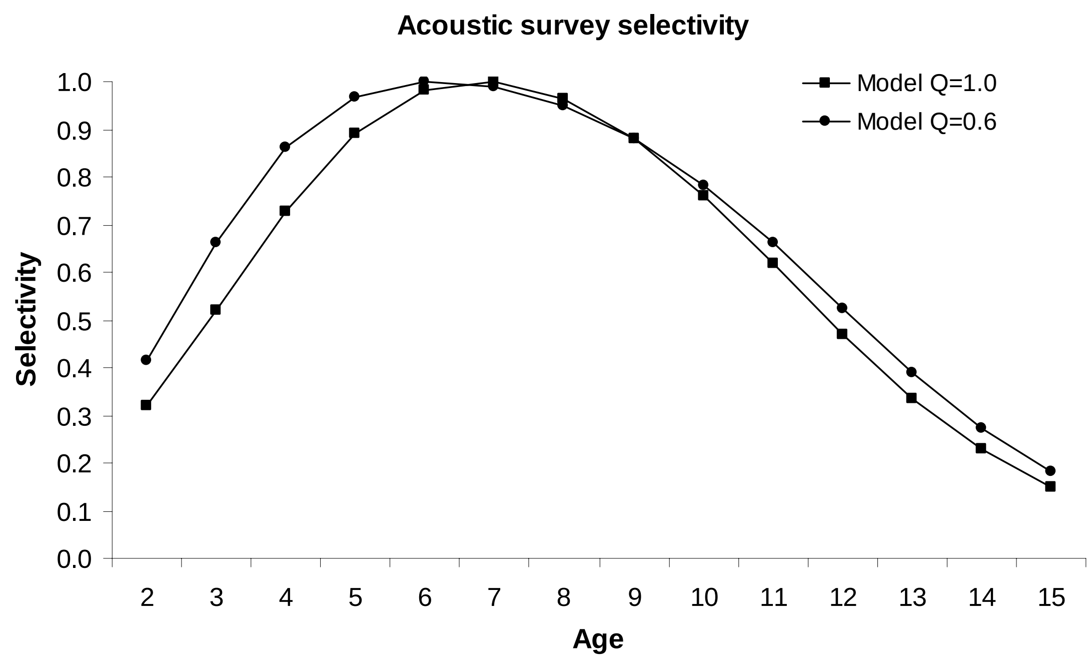


Figure 15. Fit of the expected to observed (revised 1977-1992 year-specific expansion factors) acoustic survey biomass and acoustic survey selectivity from models q=1.0 and q=0.6. See text for description of model configurations.

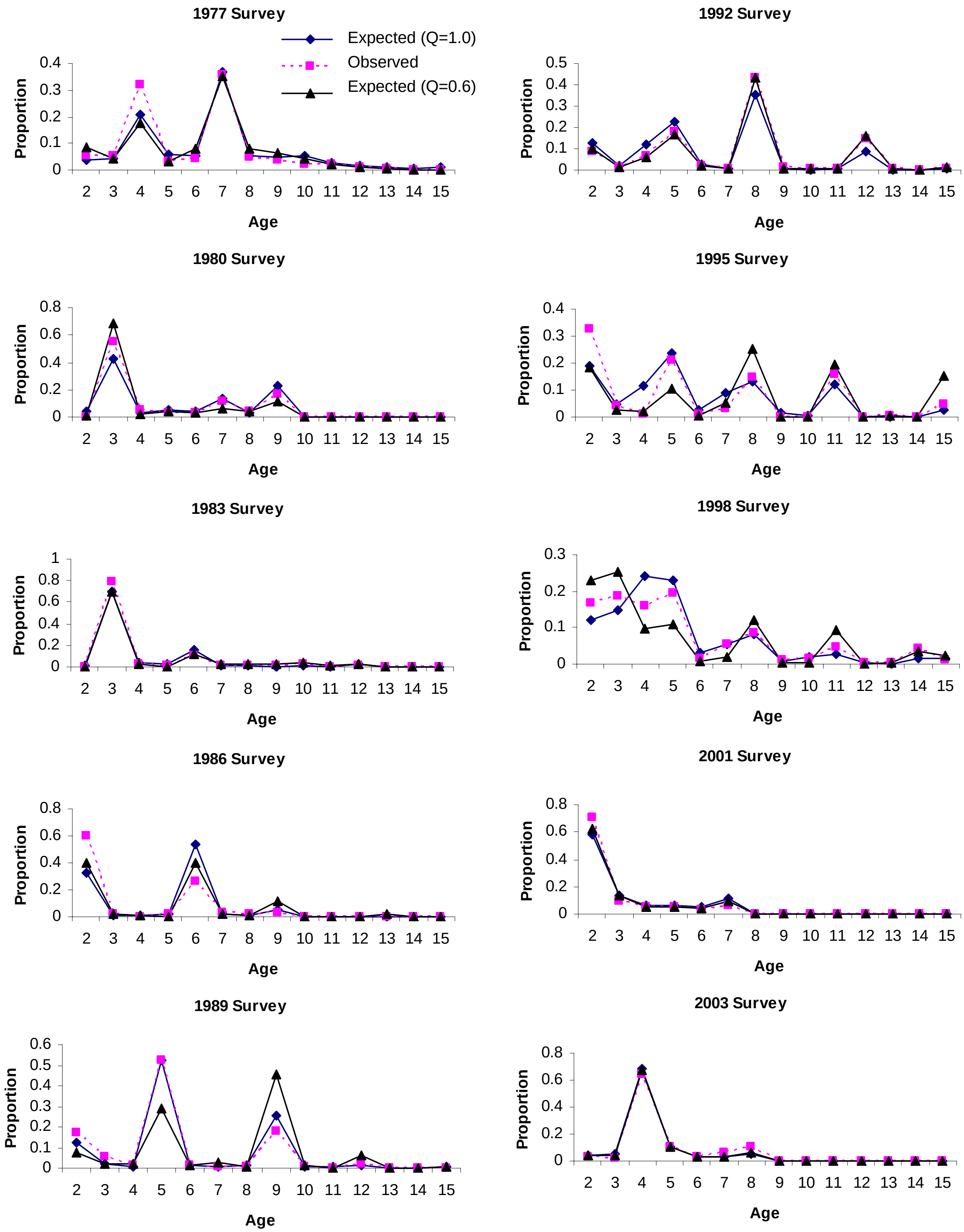
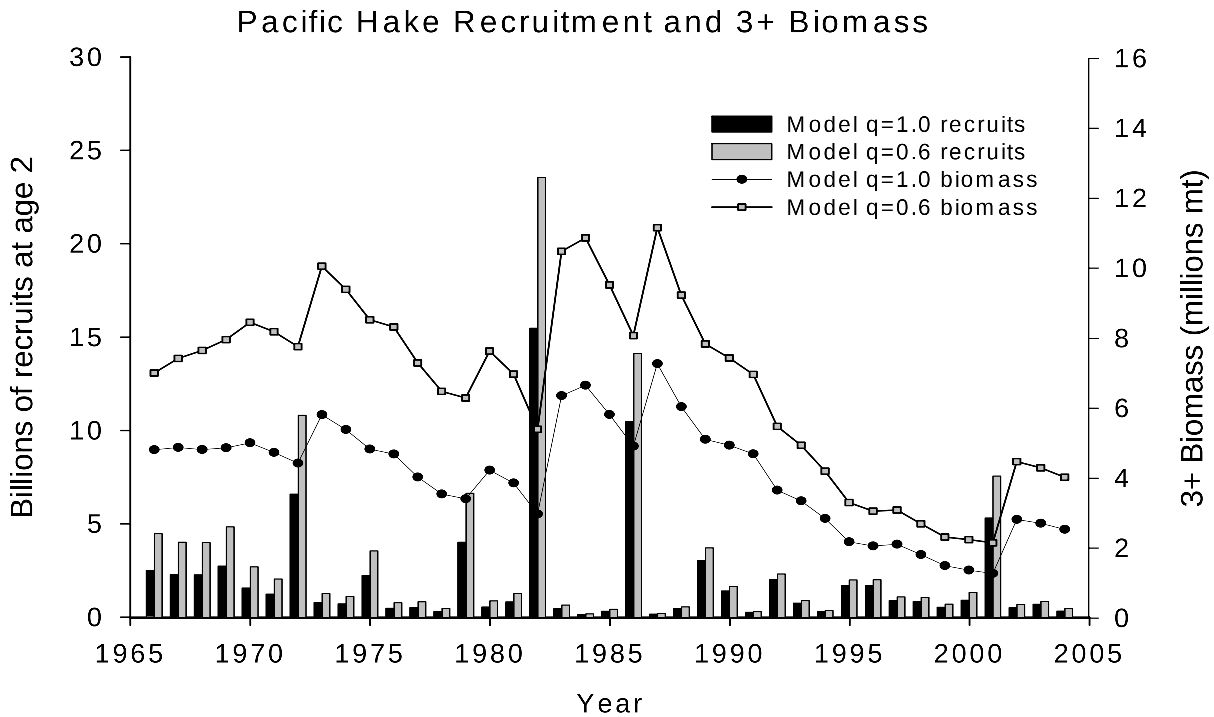


Figure 16. Fit of the expected to the observed acoustic survey age compositions, 1977-2003, for Models q=1.0 and q=0.6 (See text for description of model configuration).



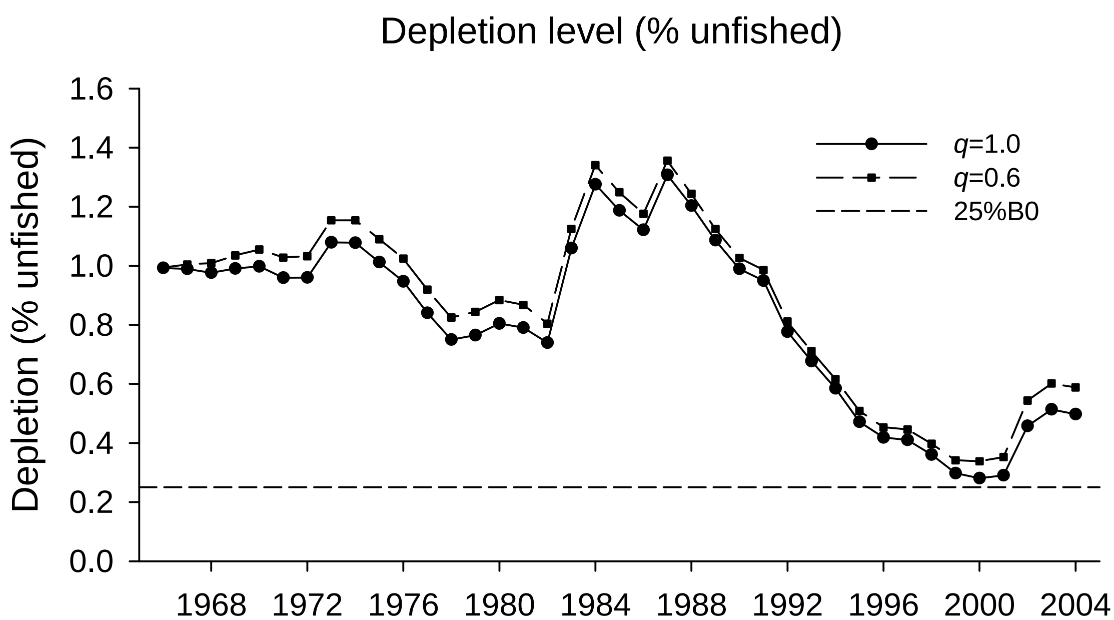
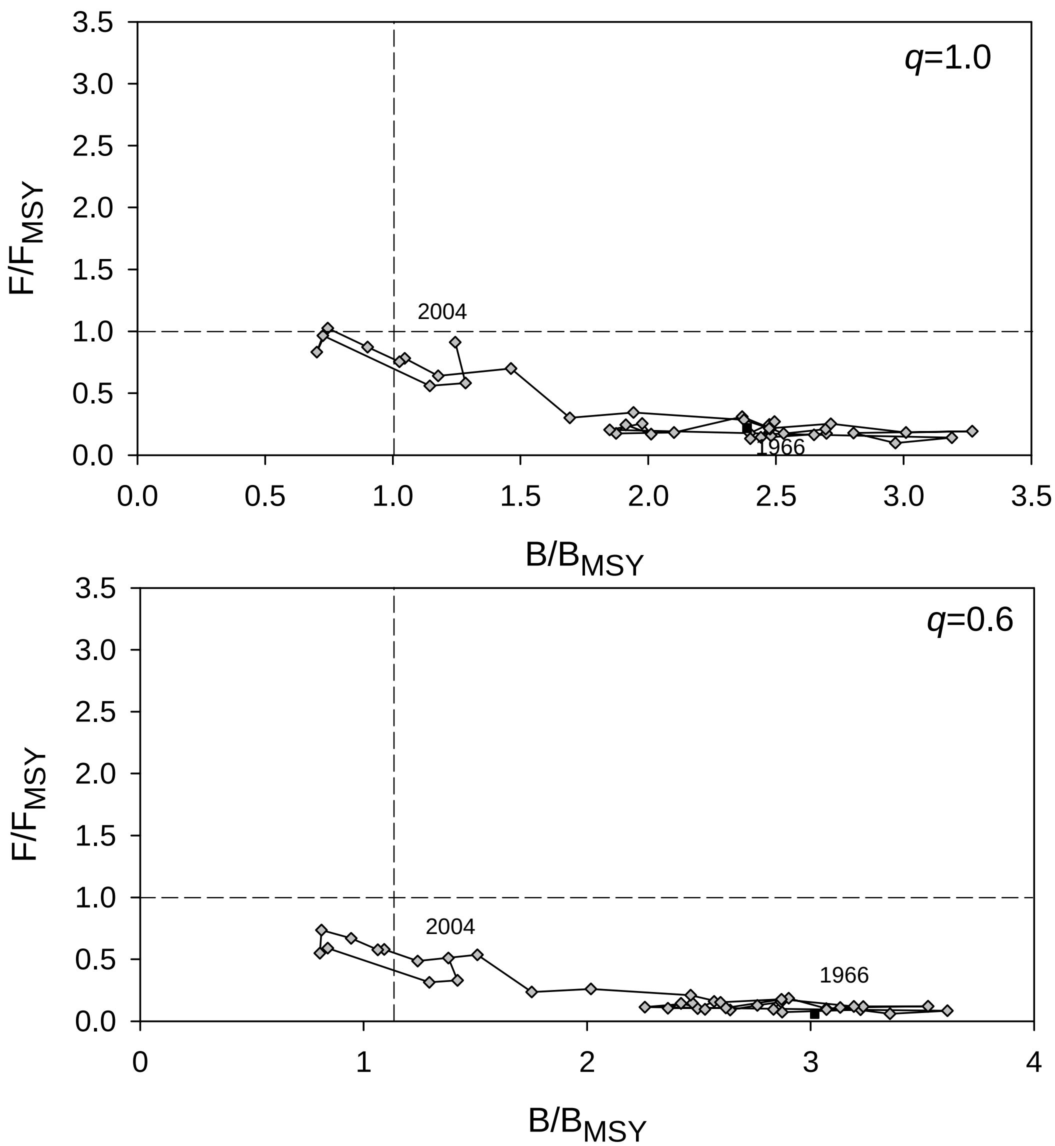


Figure 17. Estimated time series of Pacific hake age 3+ biomass (million mt) and age-2 recruitment (billions of fish) during 1966-2004 from Models *q*=1.0 and *q*=0.6. Lower panel shows trends in depletion levels relative to unfished biomass (See text for description of model configurations).

Figure 18. Historical levels of the instantaneous fishing mortality rate and biomass of Pacific hake relative to the F_{MSY} and B_{MSY} proxies, respectively.



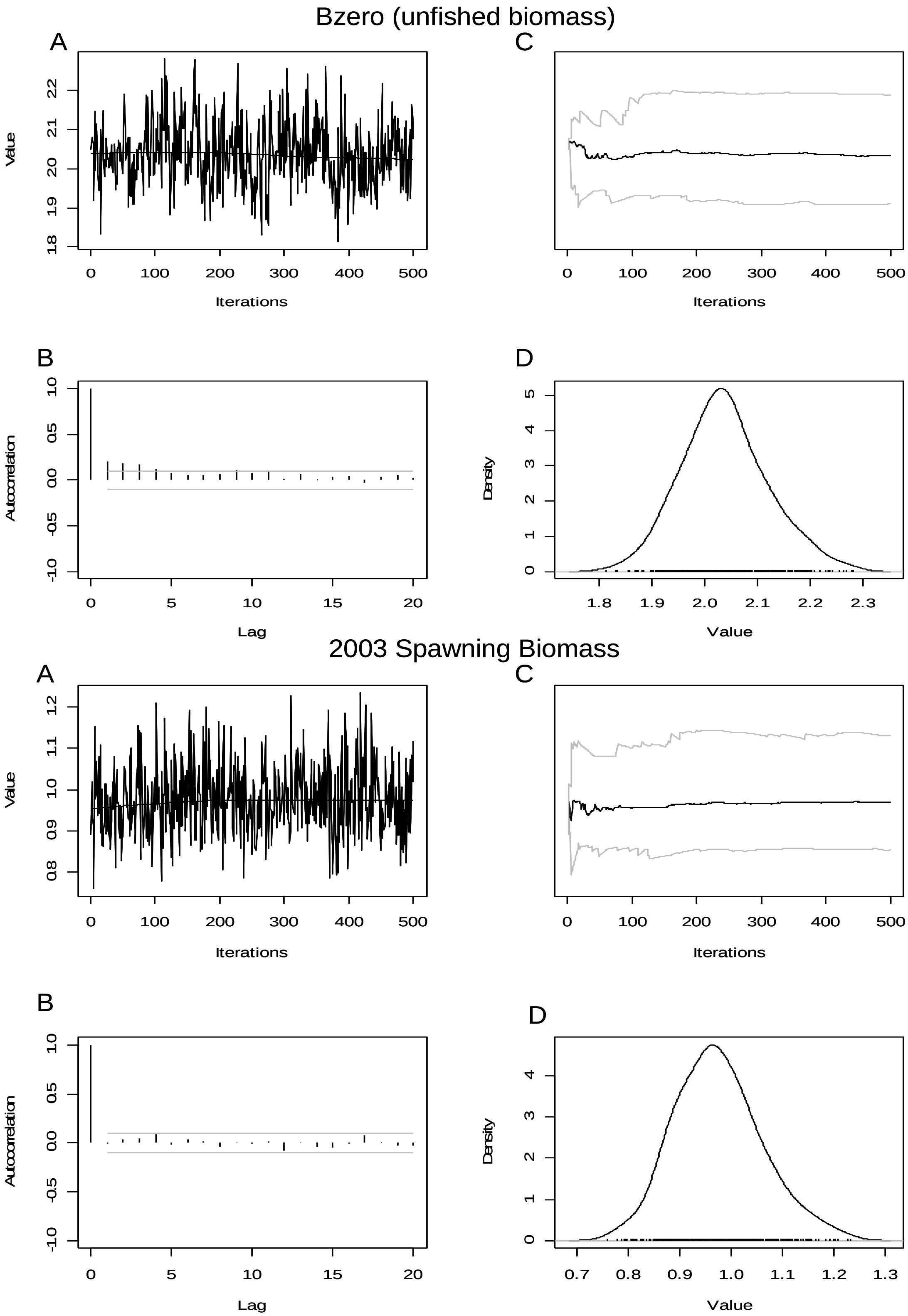


Figure 19. Results of Markov Chain Monte Carlo simulation diagnostics for selected parameters, Bzero (top) and spawning biomass (bottom), from Model q=1.0 showing: A) trace plots (with running average), B) chain sequence autocorrelation, C) 5%, 50% and 95% of the chain sequence, and D) kernel density. MCMC diagnostics were qualitatively similar for Model q=0.6 and are not shown.

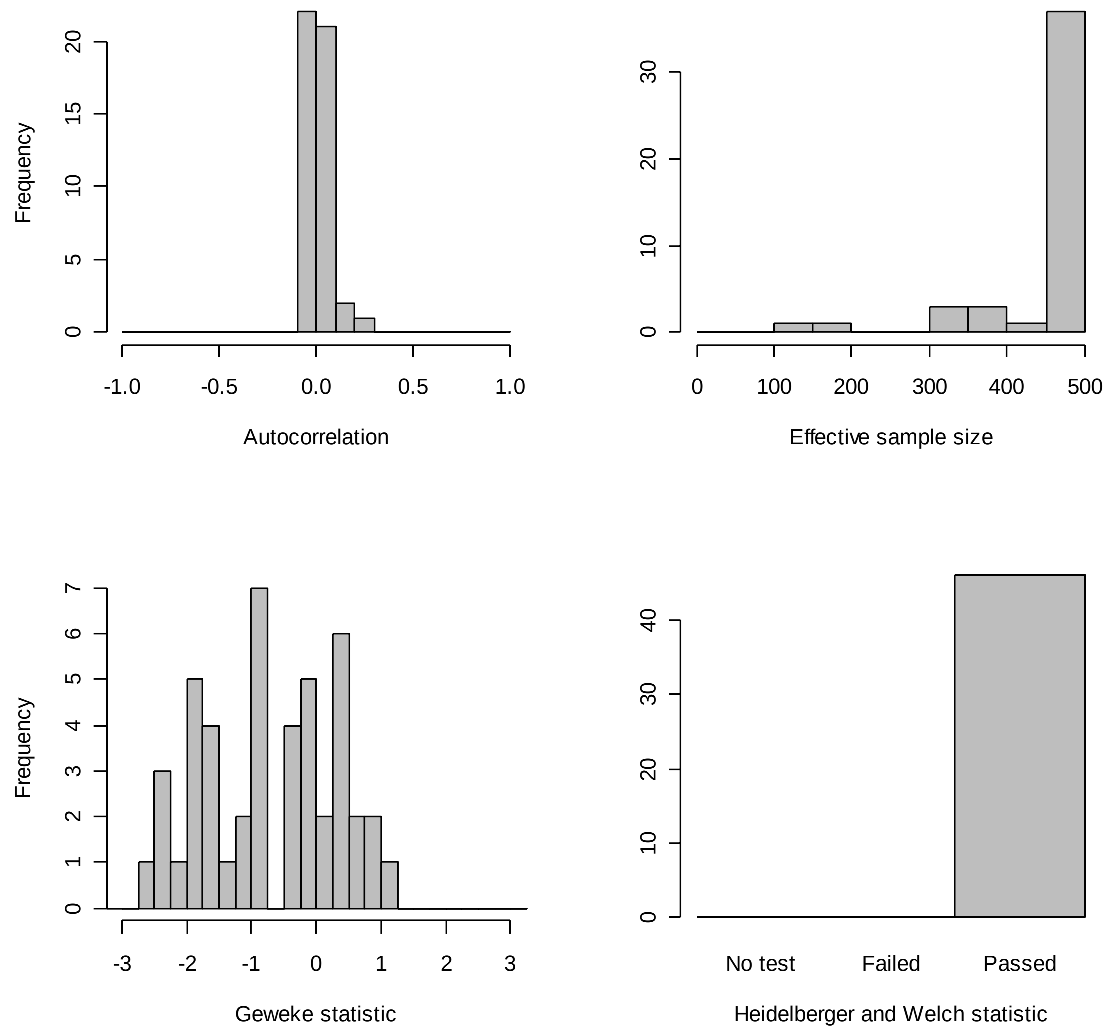


Figure 20. Summary diagnostics for 46 parameters from Model q=1.0 based on 1,000 draws (after discarding first 20% of samples and thinned at every 1000th sample) from the Markov Chain Monte Carlo simulation of the posterior distribution. Plots shown are autocorrelation, effective sample size (x10), Geweke statistics of convergence of the mean (should be < |2|), and Heidelberger and Welch statistic. MCMC diagnostics were qualitatively similar for Model q=0.6 and are not shown.

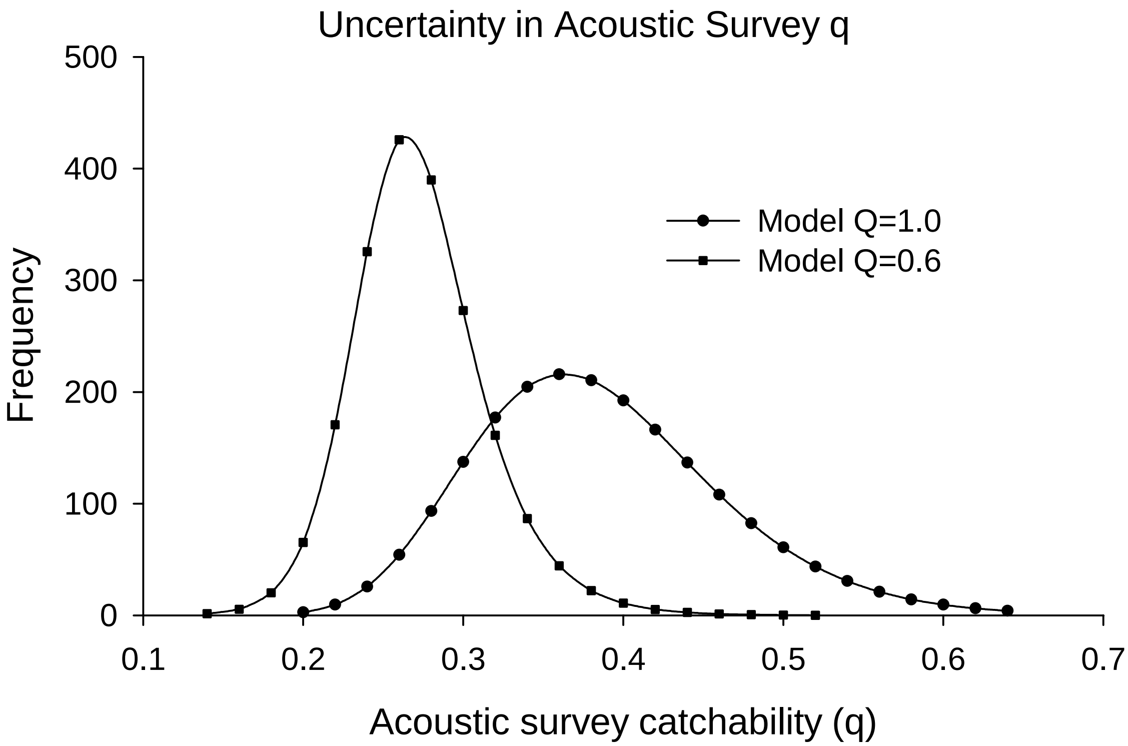


Figure 21. Uncertainty in acoustic survey catchability (q) for two models with different CVs associated with acoustic survey biomass time series. Marginal posterior distributions are based on 2,500,000 MCMC samples. Model q=1.0 (CV=0.2 1977-1989, CV = 0.1 1992-2003) and Model q=0.6 (CV=0.5 1977-1989, CV = 0.3 1992-2003).

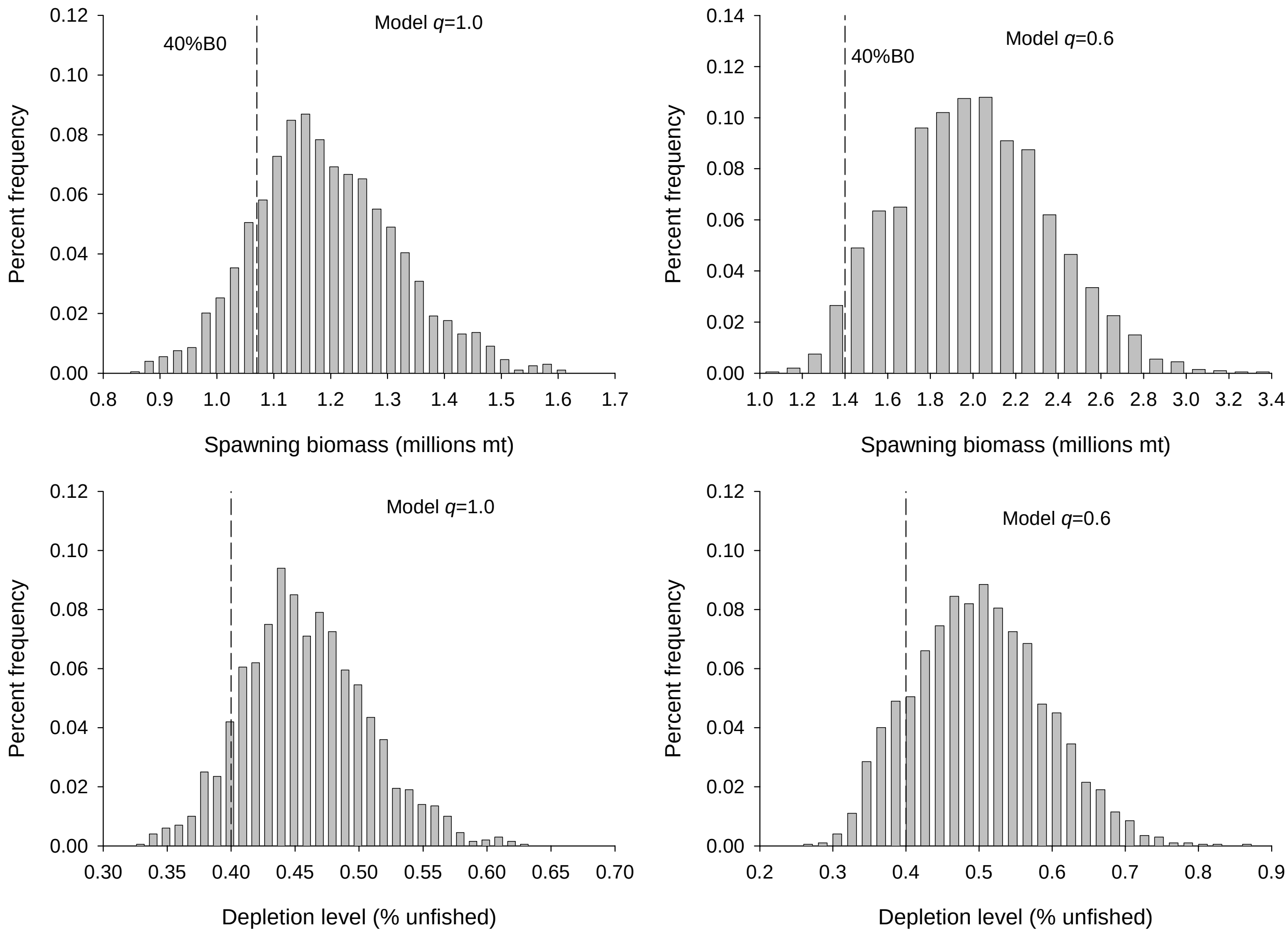


Figure 22. Uncertainty in the 2004 female spawning biomass and the corresponding depletion rate (% unfished biomass) for Models *q*=1.0 and *q*=0.6 as shown by marginal posterior distributions based on 2,500,000 Markov Chain Monte Carlo samples.

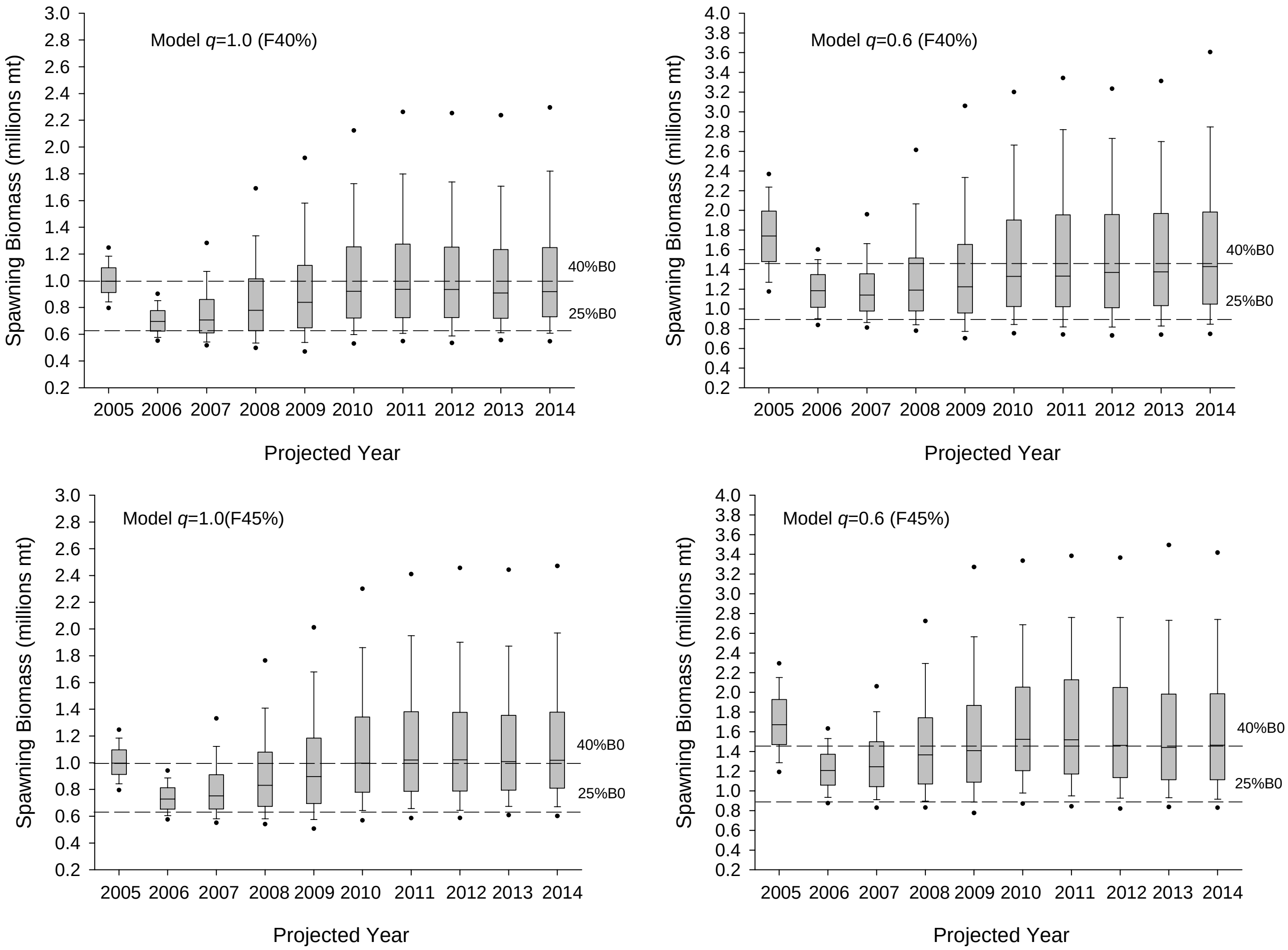


Figure 23. Uncertainty in projected 2005-2014 female spawning under the F40% (40-10) and F45% (40-10) harvest rate policy from models q=1.0 and q=0.6. Boxplots shown are based on 2,500,000 Markov Chain Monte Carlo samples.

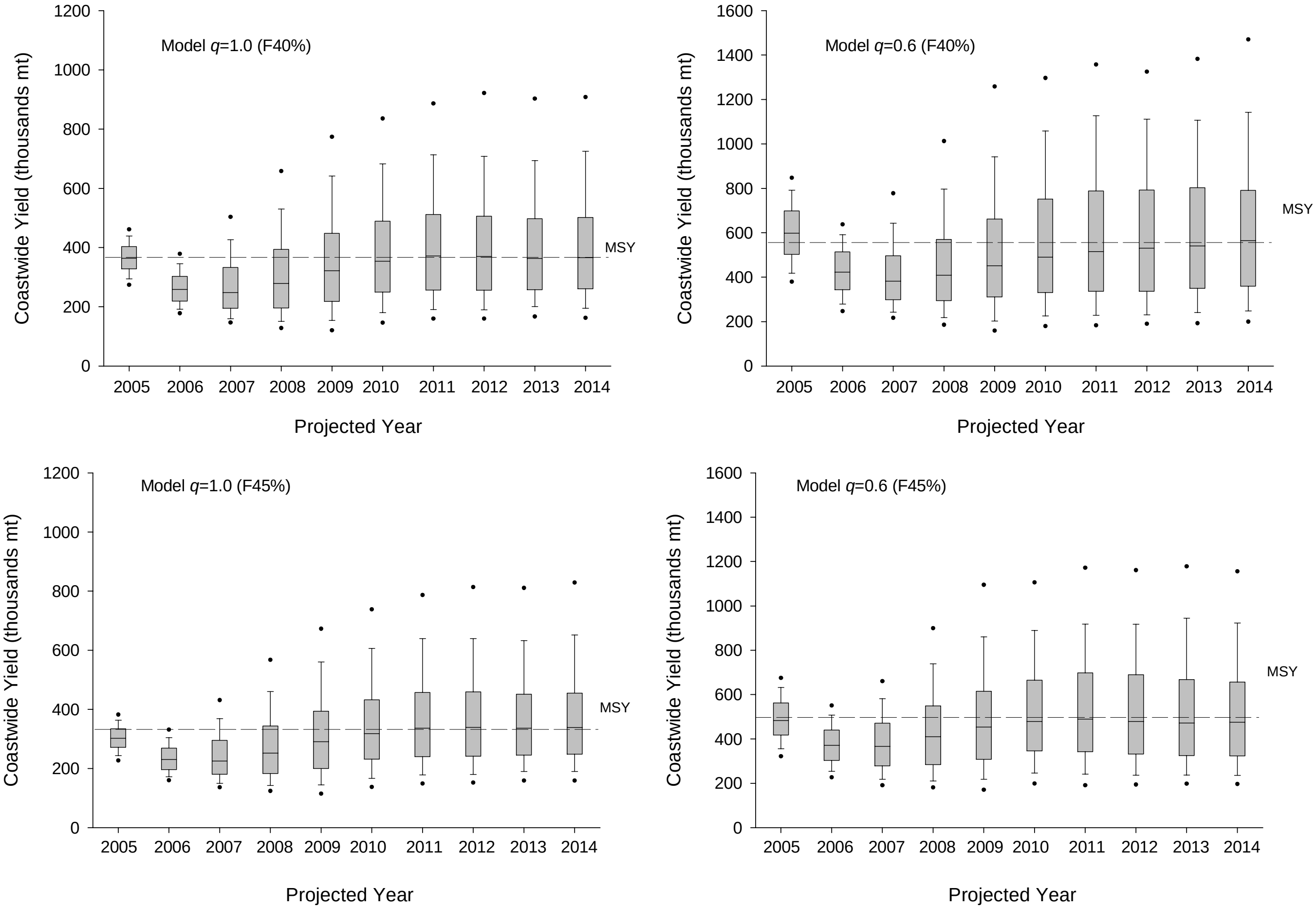


Figure 24. Uncertainty in projected 2005-2014 coastwide yield under the F40% (40-10) and F45% (40-10) harvest rate policy for Models *q*=1.0 and *q*=0.6. Boxplots shown are based on based on 2,500,000 Markov Chain Monte Carlo samples.

Appendix A

Summary

In the Helser et al. (2004) assessment of Pacific Hake, the STAR review panel identified seven possible model enhancements that may or may not reduce the uncertainty in parameter estimates, and ultimately improve information that is used in quota allocations. In this document, we investigate the interaction of the dome-shaped selectivity function with the fixed value of M and discuss the necessary requirements for estimating and age-specific M. We also examine if the current assessment model is over-parameterized by way of estimating deviations in parameters that describe size selectivity and determine if an oceanographic index could be used to aid in the estimation of variable selectivity. We explore the interaction between M and selectivity and the use of covariates for explaining changes in selectivity using simulation-estimation experiments. A reference model was constructed from the current statistical catch-at-age model structure to generate simulated relative abundance indices and age-composition information from surveys. We used the existing commercial catch observations and estimated recruitment from Helser et al. (2004) to generate time series data.

Results from the simulation-estimation experiments clearly demonstrated a confounding problem between M and the descending portion of the dome-shaped selectivity curve. Specifically, the age-independent natural mortality rate M was negatively correlated with the shape parameter (g_2) that describes how rapidly selectivity drops with older individuals. If a dome-shaped selectivity is the true reality for all fisheries harvest and survey sampling gears, then there is no real information in the age composition data to estimate age-specific M's, thus the model is over-parameterized. Results from the variable selectivity simulations suggests that data are not informative about deviations in selectivity parameters therefore and a reasonable variance for the prior distribution for deviations in random walk parameters is required. The use of an environmental correlate to describe variability in selectivity parameters greatly improves precision in estimated parameters and reduces bias in all estimated parameters including survey selectivity parameters (q's).

Contents

1 Introduction

The objective of this review of the assessment model is to examine 2 model enhancements identified by the STAR panel: 1) investigate the interaction of the dome-shaped selectivity function and the instantaneous natural mortality rate, and 2) investigate alternative methods to model annual variability in selectivity. To examine these issues we develop a reference model that generates simulated observations (relative abundance indices and age-composition information) using historical estimates of recruitment and fishing mortality as input data to the reference model. We then use the existing statistical catch-at-age model structure to evaluate estimation performance of M and changes in selectivity.

The STAR panel report identified the following enhancements to the assessment model:

1. Add in bias correction for log-normal distribution in appropriate likelihoods.

2. Recode the model so that projections are done as a post-MCMC procedure.

3. Develop an informed prior for the acoustic q. This prior should be used in the model when estimating the q parameter

4. Consider the development of a sex-structured model.

5. Investigate alternative methods to model annual variability in fishery selectivity. Identify the covariates that influence fishery selectivity.

6. Investigate the interaction of the dome-shaped selectivity functions with the fixed value of M. This investigation should include determining whether there is a trade-off between M and the declining limb of the selectivity function. Investigate the possibility of age-specific M.

7. Investigate alternatives to applying a single estimated acoustic selectivity based on trawl samples to the acoustic biomass indices.

Given the limited time constraints, we were not able to investigate all of these issues and we focused primarily on points 5 and 6. However, during the course of our analysis, we also estimate survey catchability coefficients q, and examine how well q is determined given alternative model assumptions.

The current assessment model suggests there must be many more large/older hake in the population under the assumption of an age/time-independent M, but these predictions are not supported by field observations (Helser et al. 2004). There are two alternative explanations to explain this discrepancy: a) larger/older fish are not as vulnerable to the sampling gear, and/or b) larger/older hake are fully vulnerable to the sampling gear but have a higher instantaneous natural mortality rate than younger individuals. An alternative modeling approach is to use age-specific natural mortality rate, but there is still some concern about the sampling process being representative of the true population age composition. Hake size segregate in the water column as well as over there range; larger hake are found in deeper in the water column and also migrate further to the north during the summer months (Sakuma and Ralston 1996; Dorn 1995; Helser et al. 2004). The commercial fisheries all use mid-water trawls and the acoustic survey uses both mid-water and bottom trawls to sample Pacific hake. Older hake are primarily sampled in the Canadian zone and older age-classes in the age-composition data from the acoustic trawl survey does not reflect the same proportions as those found in the commercial fisheries. In previous assessments the apparent non-representative sampling in the acoustic trawl survey data has been dealt with by using a strong dome-shape selectivity curve. It is possible that M is not independent of age and it may be more appropriate to use an age-specific M_a (e.g., Hampton 2000).

Pacific hake undergo seasonal migrations, and the extent of these migrations is probably influenced by oceanographic conditions and anomalous events such as el Niño and la Niña (Dorn 1992). Again, larger/older hake migrate further north in the summer months and evidence of this is reflected in the age-composition information between the US and CAN zones. Given the inter-annual variability in oceanographic conditions the vulnerability of each age-class to US and CAN fisheries also varies. Previous assessments have included additional time-dependent parameters to capture the changes in selectivity associated with variability in the distribution of the Pacific hake stock. Specifically, time varying selectivity was modeled as a random walk process where the ages at 50% vulnerability and shape parameters deviate around a mean on an annual basis (Helser et al. 2004). Is this model structure over-parameterized? Is it possible to incorporate oceanographic indices as a covariate for inter-annual changes in selectivity?

2 Methods

We conduct a series of simulation-estimation experiments using two models written in C++ using the AD Model Builder libraries (Otter Research 2001). Simulated observations are produced using a reference model, where the true parameter values and states are known. We then attempt to estimate these parameters using a statistical catch-at-age model based on the data generated by the reference model. To increase computational efficiency, we have re-written a condensed version of the original assessment model (essentially removed code associated with producing output files and projections), and because we were fitting this model to simulated data, we opted to omit much of the complex data massaging for dealing with suspect data. As a consequence of this decision, we have provided the source code (AD Model Builder template files) for both the reference model and the assessment model in the appendixes.

2.1 Statistical catch-at-age model

The assessment model is a statistical catch-at-age model, where numbers-at-age over time are based on the following equations:

$$\begin{aligned}
N_{i,2} &= R_i, \\
N_{i+1,j+i} &= N_{i,j}\exp(-Z_{i,j}) \quad \ldots \quad 2 < j < J, \\
N_{i+1,J} &= N_{i,j-1}\exp(-Z_{i,j-1}) + N_{i,J}\exp(-Z_{i,J}),
\end{aligned}$$

where the age-2 recruitment in year i (R_i) is an estimated parameter. Predicted catch-at-age in year i for fishery k was calculated using the Baranov catch equation,

$$\hat{c}_{i,j,k} = \frac{F_{i,j,k}}{Z_{i,j}}\left[1 - \exp(-Z_{i,j})\right] N_{i,j}$$

where $F_{i,j,k}$ is the fishing mortality rate in year i for age j in fishery k. Annual fishing mortality rates for each fishery ($f_{i,k}$) were treated as estimated parameters and age-year-specific fishing mortality rates are calculated as:

$$F_{i,j,k} = f_{i,k} v_{j,k}$$

where $v_{j,k}$ is the proportion of age j individuals that are vulnerable to fishery k. We adopted the same scaled-double-logistic selectivity function for calculating $v_{j,k}$ terms, i.e.,

$$\acute{v}_{j,k} = \left[(1 + e^{-g_1(j-lh_1)})(1 + e^{g_2(j-lh_2)})\right]^{-1}$$

$$v_{j,k} = \acute{v}_{j,k}/\max(\acute{v}_{j,k})$$

A set of 4 parameters (lh_1, lh_2, g_1 and g_2) were estimated for each fishery and each of the fishery independent surveys. Due to the rescaling of the $v_{j,k}$ terms we found it necessary to set a lower bound for the length at 50% vulnerability parameter (lh_2) to values greater than lh_1.

Vulnerable biomass in each year was calculated as the product of vulnerable numbers times the mean weight-at-age for year i:

$$B_{i,k} = \sum_j N_{i,j} v_{j,k} w_{i,j}.$$

It was necessary to calculate vulnerable biomass for each of the survey gears k in order to compare with relative abundance indices derived from different sampling gears.

2.1.1 Observation errors

Fisheries dependent observations consisted of total catch (tons) for each fishery (C_i), and catch-at-age proportions. Errors in reported catch were assumed to be log-normally distributed with a mean 0 and unknown σ_C. Unless otherwise stated, the standard deviation in σ_C was assumed constant over all years. Predicted total catch for each fishery in year i was calculated as:

$$C_{i,k} = \sum_j \hat{c}_{i,j,k} w_{i,j,k}$$

where $w_{i,j,k}$ is the observed mean weight-at-age in year i for fishery k. Predicted proportions-at-age were calculated as

$$\hat{p}_{i,j,k} = \hat{c}_{i,j,k} / \sum_j \hat{c}_{i,j,k}.$$

and observed proportions-at-age were assumed to be drawn at random from a mulitnomial distribution with probabilities $\hat{p}_{i,j,k}$. We also assumed aging is done without error. The combined negative log-likelihood for the observed total catch and age-proportions results in

$$\log L_{F,k} = \frac{1}{2\sigma_C^2} \sum_i \left(C_{i,k} - \hat{C}_{i,k} \right)^2 - \sum_i m_{i,k} \sum_j p_{i,j,k} \log \left(\frac{\hat{p}_{i,j,k}}{p_{i,j,k}} \right)$$

where $m_{i,k}$ is the multinomial sample size in fishery k.

Fisheries independent survey data consisted of a relative abundance index ($Y_{i,k}$), assumed to be proportional to biomass, and survey proportions-at-age. For simplification, it was assumed that each of the 3 surveys were independent and conducted just prior to the start of each fishing season. The predicted biomass index was calculated as

$$\hat{B}_{i,k} = q_k \sum_j N_{i,j} v_{j,k} w_{i,j}$$

where the catchability coefficient for each survey is unknown and estimated from the data. Predicted proportions-at-age in the survey samples were calculated from numbers-at-age and selectivity for survey k

$$\hat{\pi}_{i,j,k} = N_{i,j} v_{j,k} / \sum_j N_{i,j} v_{j,k}$$

The negative log-likelihood for the survey data is

$$\log L_{S,k} = \frac{1}{2\sigma^2_{Y,k}} \sum_i \left(Y_{i,k} - \hat{B}_{i,k} \right)^2 - \sum_i m_{i,k} \sum_j \pi_{i,j,k} \log \left(\frac{\hat{\pi}_{i,j,k}}{\pi_{i,j,k}} \right)$$

where $\pi_{i,j,k}$ is the observed proportion-at-age in the survey sample.

Unlike the Helser et al., (2004) assessment model, we did not consider the juvenile survey indices, as the additional information would not aid in the technical issues in this evaluation of model enhancements. Specifically, the juvenile survey index is only informative about estimates of age-2 recruits.

2.1.2 Process errors

There are 3 different process errors in this assessment model. Both annual estimates of recruitment and fishing mortality rates for each fishery are considered process error terms. The present Helser et al. (2004) assessment model does not use informative priors or constraints for these parameters. The only constrained process error term is on the deviations in the selectivity parameters. In this assessment model we also implement a constraint on the deviations in selectivity using a first differences in the δ_i terms

$$\log L_{p,l} = \sum \frac{(\delta_i - \delta_{i-1})^2}{2\sigma_\delta^2}$$

for each of l selectivity parameters in the commercial fisheries only. The details of this constraint is further discussed in section 2.2.2. The overall objective function to minimize is the sum of all negative log-likelihoods plus constraints

$$\log L = \sum_k \log L_{F,k} + \sum_k L_{S,k} + \sum_l \log L_{p,l}$$

2.2 Reference model

The reference model is the same age-structured model used in the statistical catch-at-age assessment model and is conditioned on the estimated historical recruitment and fishing mortality rates from the previous Pacific hake assessments. The reference model generates simulated age-composition data and total catches for each commercial fishery, relative abundance indices and age-composition data for each year that the surveys were conducted. We have set up this model such that data can be generated with zero measurement error in the abundance indices and age-proportions to determine if the assessment model is over-parameterized. To examine bias in parameter estimates coefficients of variation in the relative abundance indices and multinomial sample sizes for age-composition information are set to non-zero values. The code for the reference model ("simCAA.tpl") and the data file ("simCAA.dat") is presented in the appendixes. Note that this reference model creates the data file "CAA.dat" to be used in the statistical catch-at-age model: "CAA.tpl".

2.2.1 Bias M and other key parameters across a range of true and fit selectivity shapes

We did a broad range of simulations examining the direction and magnitude of the bias in M and other key parameters across a range of 'true' (simulated) and fit selectivity functions. The objective of this was to evaluate the performance of the model at estimating M and other key parameters. The key model parameters identified were the instantaneous natural mortality rate (M), initial selectivity parameters for the commercial fisheries, the survey selectivity parameters and the survey catchability coefficients q. We asked what the bias was in these key parameters in the following scenarios numbered 1-4:

1. data simulated with dome shaped vulnerability fit with dome vulnerability
2. data simulated with dome shaped vulnerability fit with aymptotic shaped vulnerability
3. data simulated with aymptotic shaped vulnerability fit with dome shaped vulnerability
4. data simulated with aymptotic shaped vulnerability fit with aymptotic shaped vulnerability

For each of these four scenarios we tested the model across of a range of slope g and lh parameters that is, we increased the steepness of the dome in the reference model and the age at 50 % selectivity for both the descending limb (lh_2) in the case of scenarios 1 and 2 or, the ascending limb (lh_1) in the case of scenarios 3 and 4. To do so we simultaneously increased the g_1 and g_2 parameter for all the surveys and both fisheries in increments of 0.25 starting with the first value listed in table 1. This made the dome progressively steeper with each increment. Note that the dome was made steeper for both fishery and the survey selectivity.

In a separate set of simulations we also tested the model across a range of lh_2 and lh_1 values. In scenarios 1 and 2 the initial lh_2 was increased in increments of 1 from the values listed in table 1. For scenarios 3 and 4 where data were generated with asymptotic vulnerabilities, lh_1 was increased in increments of 1 instead of lh_2. Starting values for this series are also listed in table 1.

The starting values of the g and lh parameters were chosen slightly below the existing maximum likelihood estimate for the parameters so that when the shape increment was 0.75 and the lh increment 3, the data were generated using vulnerability parameters that produced approximately the same mean vulnerabilities observed by Helser et al. (2004) in their scenario 1 c). Accordingly, the survey q's were set to 0.6 in the reference model and freely estimated in the assessment model. The survey CV for the US acoustic survey was set to 0.4 averaging between the 0.5 from years 1977-1989 and 0.3 for years 1992-2003 in this scenario.

For each scenario and shape or lh_2 increment we ran 100 simulations. We then made boxplots of the bias ratio calculated as $(Estimated - True)/True$ for M, the three survey q's, and the selectivity parameters of fisheries and surveys. We examined the biases in these parameters because they co-vary with estimates of the natural mortality in each simulation scenario. For clarity the proportional bias for those parameters not estimated (when asymptotic vulnerability shape is fit for example to data generated with dome shaped vulnerability) or not used in the reference model are not included. Starting parameter combinations used to simulate the data including the multinomial sample sizes and coefficients of variation for the survey and fishery catch at age sampling are list in table 1. To prevent errors due to starting parameter values being too far from true values, all parameter values in the stock assessment model were set to the same initial values listed in table 1.

Table 1: Reference model starting parameter values for increasing dome steepness (g) and lh

Parameters common to all scenarios

Survey Q's CV's	US (A)	US trawl	Can (A)
Mulitinomial sample size	60	60	60
CV in indices	0.4	0.3	0.3
catchability coefficients	0.6	0.6	0.6

Fishery Sample and CV's	*US*	*Canada*
CV in total catches	0.3	0.3
Mulitinomial sample size	300	130

Natural Morality	
M	0.23

	Varying Dome Steepness			**Varying lh2**		
Survey selectivity	*US (A)*	*US trawl*	*Can (A)*	*US (A)*	*US trawl*	*Can (A)*
lh1	3	3	3	3	3	3
shp1	1	1.85	1	1	1.85	1
lh2	12	13.3	12	11	12.3	11
shp2	0.2	0.48	0.2	0.7	0.98	0.7
Fishery selectivity	*US*	*Canada*		*US*	*Canada*	
lh1	3	4.65		3	4.65	
shp1	1.85	1.15		1.85	1.15	
lh2	13.3	13.45		11.3	11.45	
shp2	0.5	0.8		0.98	1.37	

2.2.2 Variability in fishery selectivity

We investigate if the use of a random walk for the selectivity parameters is over-parameterized, meaning that all model parameters cannot be uniquely determined from the data, and if it is possible to use oceanographic indices as a covariate for inter annual changes in fisheries selectivity. The use of prior distributions or constraints is common practice in mixed-error models because there is usually no independent information or measures of observation errors or process errors. In the hake assessment model, the inter annual variability in size selectivity is treated as a process error, and the use of the first difference acts as a prior (in a Bayesian sense) or a constraint (in a maximum likelihood sense) in the estimation process. Here we use a set of simulation-estimation experiments to examine the following questions:

- In the absence of measurement errors, are the data alone sufficient enough to allow for the estimation of the δ_i terms without the use of any constraint in the model?

- Is the first difference constraint required for the estimation of δ_i terms when there are measurement errors?

- Is it possible to use oceanographic data to model systematic changes in selectivity?

The 2004 assessment model implements a "pseudo random walk model" for simulating changes in selectivity over time as:

$$\gamma_i = \bar{\gamma} + \delta_i$$

where $\bar{\gamma}$ represents a mean value of a specific parameter in the selectivity function and δ_i is a random variable with a mean 0 and σ_δ. We term this a "pseudo random walk model" because the objective function minimizes the first differences in the δ_i terms

$$\sum \frac{(\delta_i - \delta_{i-1})^2}{2\sigma_\delta^2},$$

which implies an autocorrelated series in the δ_i terms and σ_δ^2 limits the changes in γ_i around an overall mean. This is not the same as a continuous random walk model in which γ_i is updated according to

$$\gamma_i = \gamma_{i-1} + \delta_i.$$

The main difference between the two approaches is that the "pseudo random walk" constrains all values of γ_i around a mean $\bar{\gamma}$ and the "continuous random walk" only constrains the rate at which γ_i can change from year to year. Data sets from the reference model were generated using the continuous random walk model and the continuous random walk model was also implemented in the assessment model.

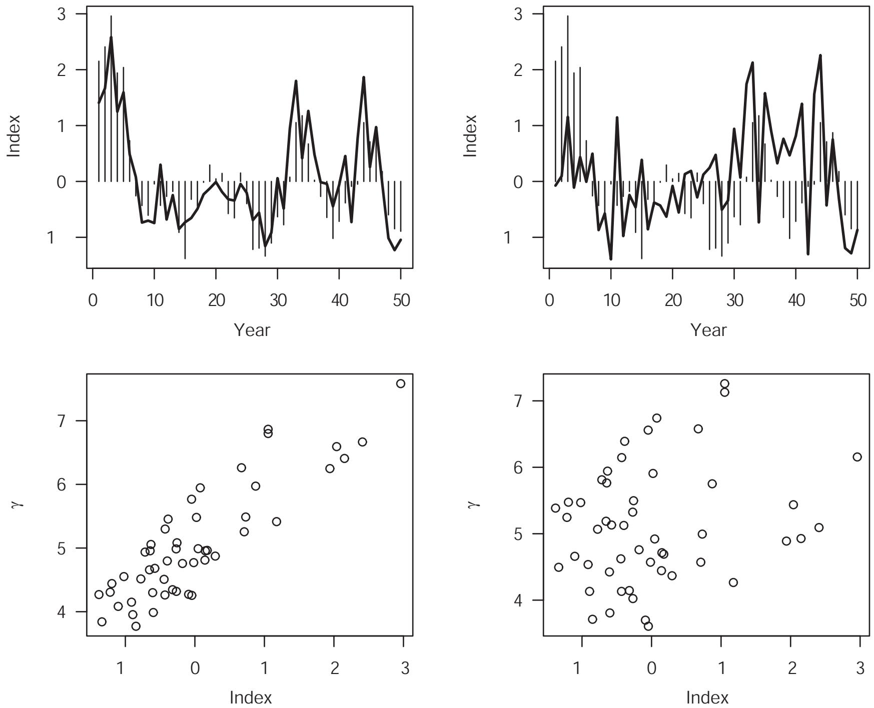


Figure 1: Two contrasting examples with strong (a-b) and weak (c-d) correlation between γ and the oceanographic index x. As the ratio of $\varrho : \sigma_\epsilon$ approaches 1, changes in γ perfectly track the index (as shown by the solid line in panel a), and as this correlation breaks down (d) the index x explains less of the variation in γ (c).

Due to time constraints we did not search for correlations between environmental or oceanographic indexes and changes in size selectivity in the commercial fisheries. Alternatively, we assume for the time being that there is a single index that is well correlated with the latitudinal distribution of the stock during the fishing season and investigate whether such an index could be used to estimate systematic changes in fisheries selectivity. Oceanographic indexes were generated from a random uniform distribution with an autocorrelation coefficient = 0.8 (e.g., Figure 1). The simulated oceanographic index x_i is standardized to have a mean = 0 and σ_x=1 by subtracting $\bar{x}$ from x_i and dividing by standard deviation in x_i. Time varying changes in selectivity parameters were treated as:

$$\gamma_i = \bar{\gamma} + \varrho x_i + \sigma_\epsilon \epsilon_i$$

where ϱ is the rate at which $\bar{\gamma}$ changes relative to the index x (assuming a linear relationship between x and γ) and ϵ_i is the residual error or additional variation in γ_i not explained by x. This approach markedly reduces the number of estimated parameters but assumes a constant relationship between x and γ. It is identical to the "pseudo random walk" approach defined earlier, but the estimated δ_i terms are replaced with the oceanographic index terms x_i and only ϱ and the mean selectivity parameter $\bar{\gamma}$ are treated as unknowns. The key question is how well correlated must x be with γ, or the ratio of ϱ to σ_ϵ, to consider using such an index to model changes in selectivity?

To address the question about if it is possible to use an index of some sort to model changes in size selectivity, we generated simulated data over a range correlation coefficients between the index and changes in selectivity parameters.

3 Results

3.1 Bias M and other key parameters across a range of true and fit selectivity shapes

The model performed reasonably well at producing estimates of M in all scenarios where dome steepness was increased except scenario 2 (Fig. 2). For scenario 1, the mean bias in M tended to be positive with a maximum mean bias of approximately 30 %. In addition, the variance about these estimates tended to be very large, and increasing with dome steepness. The worse bias in M occurred in scenario 2 when the data were generated with dome shaped vulnerability but fit with asymptotic vulnerability. In this case the model attributed the absence of older fish to increased natural mortality because it did not have the capacity to attribute it to decreased vulnerability of older fish. The bias in M was small in scenario 3 when data were generated with asymptotic selectivity yet fit with a dome shaped function (row 3 Fig. 2). In this case the mean bias was small, a maximum of 0.05 and there was a small increase this bias with the steepness of the ascending

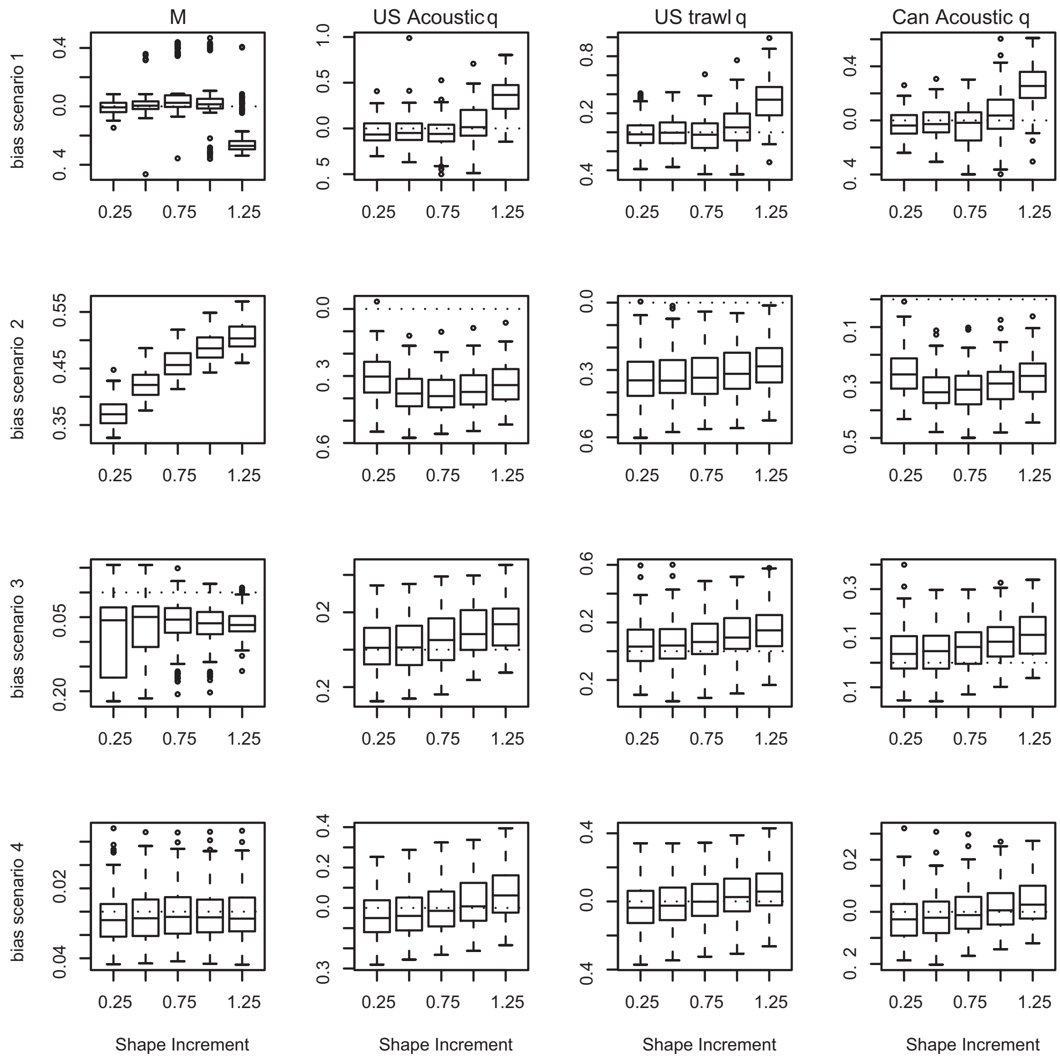


Figure 2: Box plots of parameter bias ratio's for 100 realized data sets for M and survey q's for U.S. acoustic, U.S. trawl ,Canadian acoustic across a range of dome steepness

limb. When data were generated with asymptotic vulnerability and fit with asymptotic vulnerability in scenario 4 (row 4 Fig. 2), the bias in M was on average slightly negative (0.02) and essentially invariant to the shape of the vulnerability function.

The bias in the estimated survey q's followed the inverse pattern to the bias in M across all scenarios (Fig. 2). In scenario 1 (row 1 Fig. 2), as the bias in M grew more positive at intermediate dome steepness the bias in all three survey q's became more negative, eventually approaching a mean 0 bias as the mean bias in M approached 0. For scenario 2 the bias in all three survey q's was unbiased at low dome steepness but then consistently unbiased at higher dome steepness (row 2 Fig. 2). The pattern observed in scenario 1 was also observed for scenarios 3 and 4, where increasingly positive bias in M. In this case the mean bias was relatively small for scenario 3 where the maximum bias ratio was approximately 10% at the maximum steepness values of the ascending limb. For scenario 4 the bias in q tended to be larger with a maximum bias ratio of approximately 40%.

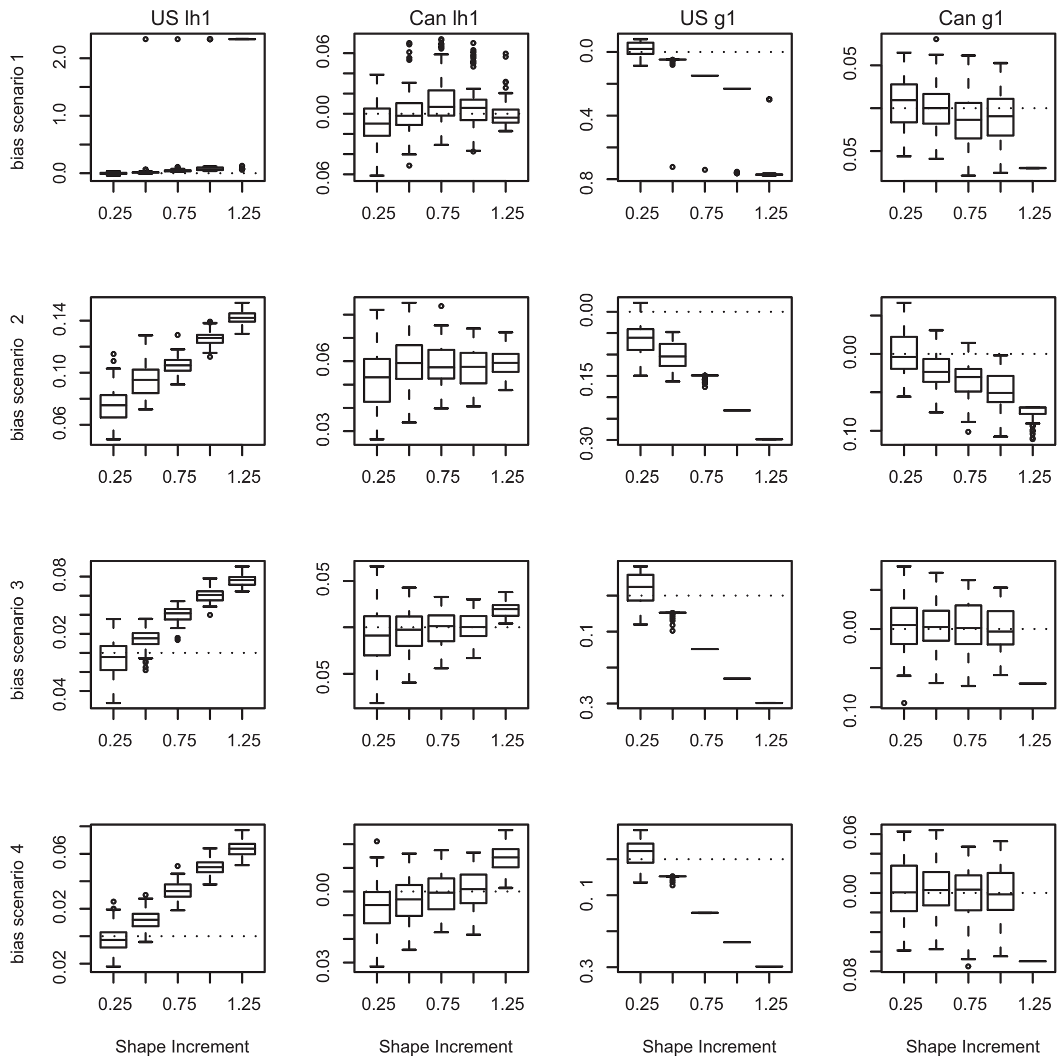


Figure 3: Box plots of parameter bias ratio's for 100 realized data sets for fishery selectivities lh_1 and $g1$ across a range of dome steepness

The fishery selectivity parameters describing the ascending limb of the selectivity were precisely estimated across almost all scenarios (Fig. 3) but parameter estimates were biased for the U.S. g_1 parameter at high steepness. Again the largest bias was observed under the conditions of fitting an asymptotic model to dome-shaped data (scenario 2). Even in this case however, the maximum bias observed in the U.S. lh_1 parameter was 12% at the maximum dome steepness. The bias in the Canadian lh_1 increased with dome steepness but only marginally ($\approx 5\%$). Values of the simulated U.S. g_1 were poorly defined for any scenario where the dome (or ascending limb in the case of scenarios 3 and 4) steepness increment was greater than 0.75. Similar results were also observed for selectivity parameter in the research surveys.

3.2 Key parameter bias with increasing age at 50% vulnerability (lh)

In the scenarios where the age at 50 % vulnerability (lh_2 or lh_1) was increased estimates of natural mortality M were essentially unbiased for all scenarios except scenario 2 (Fig. 4). As in section 3.1 above, M was over estimated for scenario 2, accounting for those fish not captured due to the 'real' dome shaped selectivity with increased natural mortality. Scenarios 3 and 4 had only very slight biases in M except when the lh_1 increment was very high in scenario 3 where the dome shaped vulnerability function had a difficult time fitting simulated data with a high lh_1 values.

The survey q's were well determined and unbiased except in scenarios 2 and 4, where asymptotic selectivity was fit (Fig. 4). For scenarios 1 and 3 estimates of q were on average unbiased, but with maximum bias of 0.10 in scenario three at the maximum lh_1 increment. For scenarios 2 and 4, the bias in survey q followed a pattern similar to that observed in section 3.1 that is as bias in M became negative, the bias in q became more positive. Here the maximum positive bias observed was in scenario 4 (row 4 of Fig. 4) where for the simulated acoustic q it was in the order of 0.5.

The fisheries selectivity parameters describing the ascending limb of the vulnerablity function were estimated fairly precisely with little bias for all scenarios except in scenario

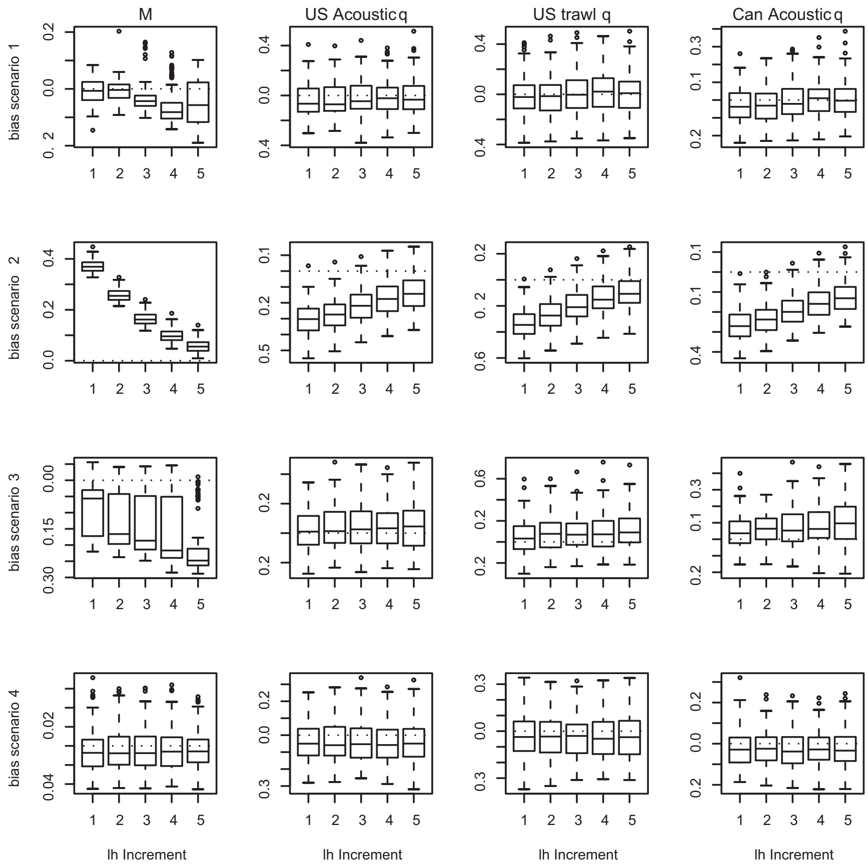


Figure 4: Proportional bias in estimates of M and survey q's for U.S. acoustic, U.S. trawl, Canadian acoustic over a range of increasing lh values

2 (Fig. 5). Here the maximum bias in the U.S. and Canadian lh_1, which like M decreased as lh_2 increased, was in the order of 6.5%. Otherwise the model performed very well across scenarios and lh increments.

The survey selectivity lh_1 for the Canadian acoustic surveys and both the lh_1 and g_1 parameters for U.S. trawl and were well determined for all scenarios (not shown). Unfortunately, the Canadian acoustic lh_1, g_1, and the U.S. g_1 were poorly determined for scenarios 2 and 4. In this case, the Canadian lh_1 parameter was over-estimated by nearly a factor of 2 in scenario 2 and was very poorly determined for scenario 4. This was expected for scenario 2, but is somewhat surprising for scenario 4, where data were generated with an asymptotic selectivity function and fit to a model that assumes asymptotic selectivity. The Canadian and U.S. g_1 parameters were negatively biased for

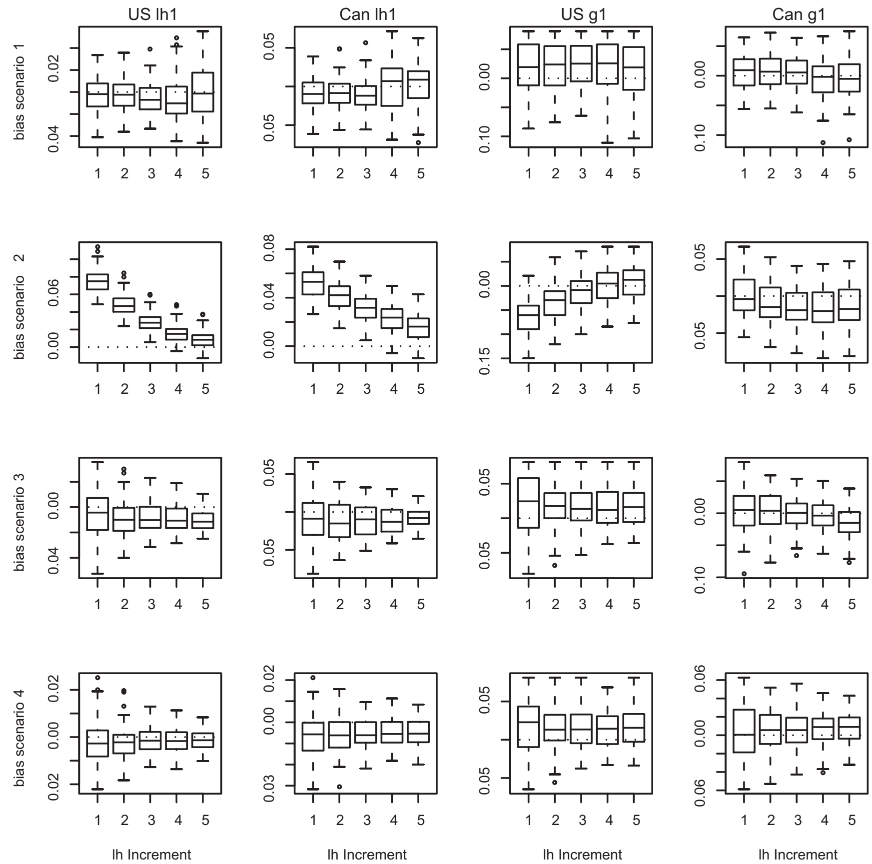


Figure 5: Proportional bias in estimates of lh_1 and g_1 for the U.S. and Canadian fisheries with varying simulated lh values

scenario 2, with mean biases of -50% and in scenario 4 a maximum bias of 0.8 which decreased at higher lh increments.

3.3 Variation in fisheries selectivity

To determine if the statistical catch-at-age model with time varying changes in the selectivity parameters is over-parameterized, 100 realized data sets were generated with no measurement errors to determine if the data alone are sufficient for estimating key model parameters. Input parameters used to generate simulated observations were constant and only the random number sequences used to generate process and observation errors differed. The key model parameters were identified as the instantaneous natural mortality rate, initial selectivity parameters for commercial fisheries and the survey catchability coefficients. For this example, we assumed that *survey* selectivity was time invariant and each realized data set contains a different sequence of random numbers for the variability in fisheries selectivity. No constraints were used for the deviations in selectivity parameters to determine if the data alone are sufficient for estimating the true parameter values.

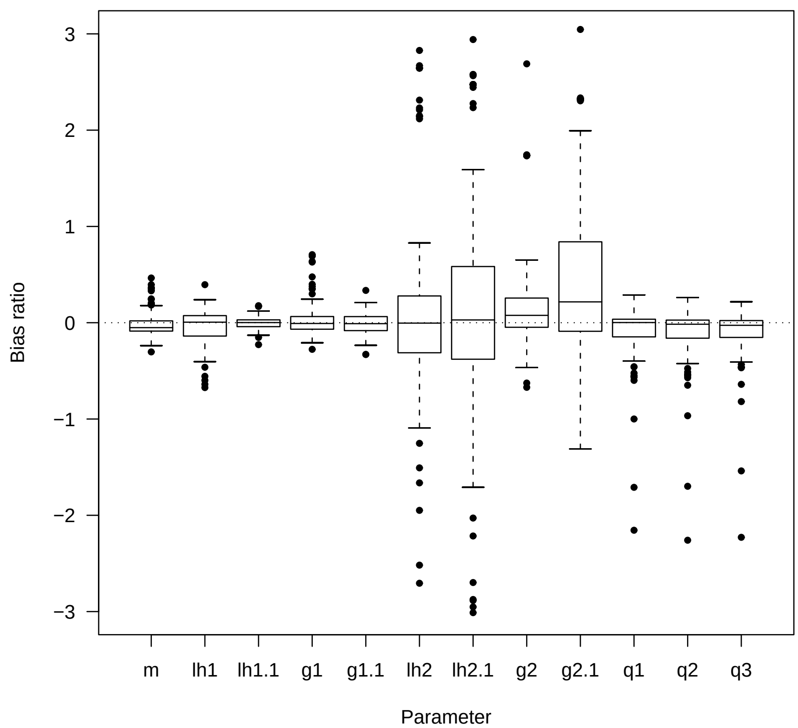


Figure 6: Box plots of parameter bias ratio's for 100 realized data sets with no measurement errors. Bias ratio's are represented on a $\log_2$ scale where a bias ratio value of 1 indicates over-estimation of the true parameter value by a factor of 2.

Resulting parameter estimates from 100 realized data sets (with no measurement errors) are shown in Figure 6. For each simulation-estimation experiment, a total of 445 parameters were estimated. The natural mortality rate M, survey catchabilities and the parameters for the ascending limb of the fisheries selectivity are well determined in the absence of measurement errors. Parameters for the descending limb of the selectivity function were less well determined and survey catchabilities are slightly biased downwards.

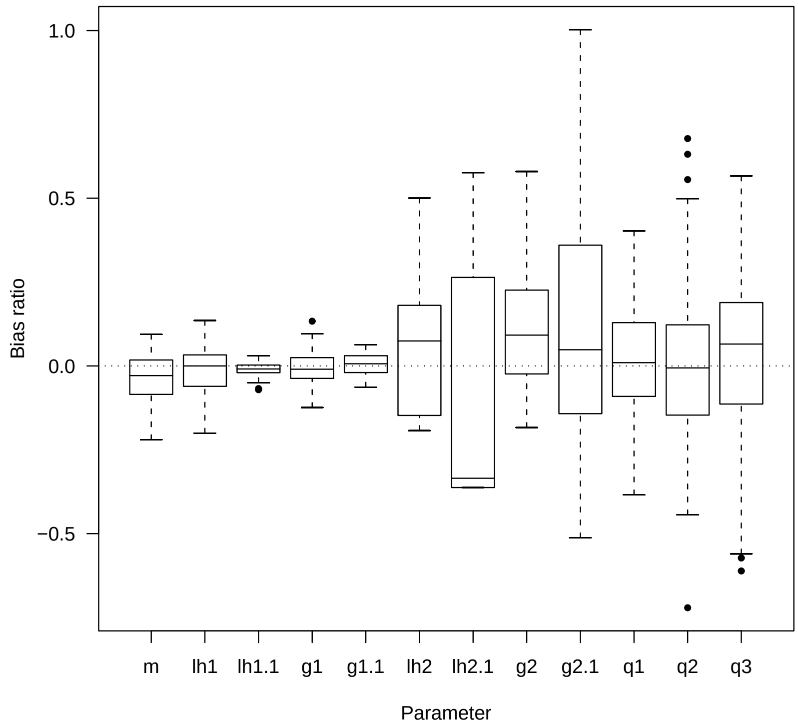


Figure 7: Box plots of parameter bias ratio's for 100 realized data sets with measurement errors and constant size selectivity.

As expected, uncertainty in estimates for M and q's increases when measurement errors are included into the simulated data sets (Figure 7). The results in Figure 7 were generated with time invariant selectivity functions for commercial fisheries and surveys in both the reference and assessment models. The largest uncertainty was observed in parameters that describe the descending limb of the selectivity curves for each fishery, particularly for the simulated Canadian fishery where larger/older fish are more vulnerable to the fishing gear. There is a tendency for the for lh_2 parameters to hit there lower bound in the Canadian fishery, and when estimated with no bounding constraints $lh_2 < lh_1$ for many of the simulated data sets. Survey catchability coefficients tend to be unbiased and the range of parameter estimates is within 50% of the true value.

Table 2: Correlations between natural mortality and bounded US and CAN selectivity parameters among the 100 simulated data sets with no inter annual variability in selectivity.

US fishery

	M	lh_1	g_1	lh_2	g_2
M	1.00	0.38	0.23	-0.28	-0.65
lh_1	0.38	1.00	-0.60	-0.90	-0.76
g_1	0.23	-0.60	1.00	0.38	0.10
lh_2	-0.28	-0.90	0.38	1.00	0.83
g_2	-0.65	-0.76	0.10	0.83	1.00

CAN fishery

	M	lh_1	g_1	lh_2	g_2
M	1.00	0.11	0.32	-0.13	-0.48
lh_1	0.11	1.00	-0.59	-0.68	-0.61
g_1	0.32	-0.59	1.00	0.02	-0.15
lh_2	-0.13	-0.68	0.02	1.00	0.88
g_2	-0.48	-0.61	-0.15	0.88	1.00

Estimates of natural mortality are slightly biased downward (Figure 7) and are negatively correlated with the shape parameter (g_2) of the descending limb of the selectivity curves (Table 2). Note that the correlations in Table 2 are biased due to the bounding constraints for the shape parameter lh_2, as shown in Figure 8. There is additional confounding among the selectivity parameters themselves. For parameters that describe the ascending portion of the selectivity curve, there is a tradeoff between the age at 50% vulnerable and how steep the selectivity curve is. For the descending portion of the selectivity curve there is a positive correlation in the shape parameter and the age at 50% vulnerable. The strongest negative correlation exist between the inflection points between the ascending portion and descending portions of the selectivity curves (lh_1 and lh_2). This strong negative correlation, as well as, the frequent occurrence of estimating $lh_2 < lh_1$ arises due to the renormalization of the selectivity curve to a maximum of 1.

Figure 8 demonstrates the confounding between estimates of M and the shape parameters for the descending portion of the selectivity curve for the US fishery assuming constant selectivity over time. There appears to be little correlation between the age at

50% selectivity on the descending limb (lh_2) and natural mortality as well as parameters for the ascending limb of the selectivity function (lh_1 and γ_1). Similar correlation patterns in parameter estimates were observed in simulated data sets with time-varying changes in size selectivity.

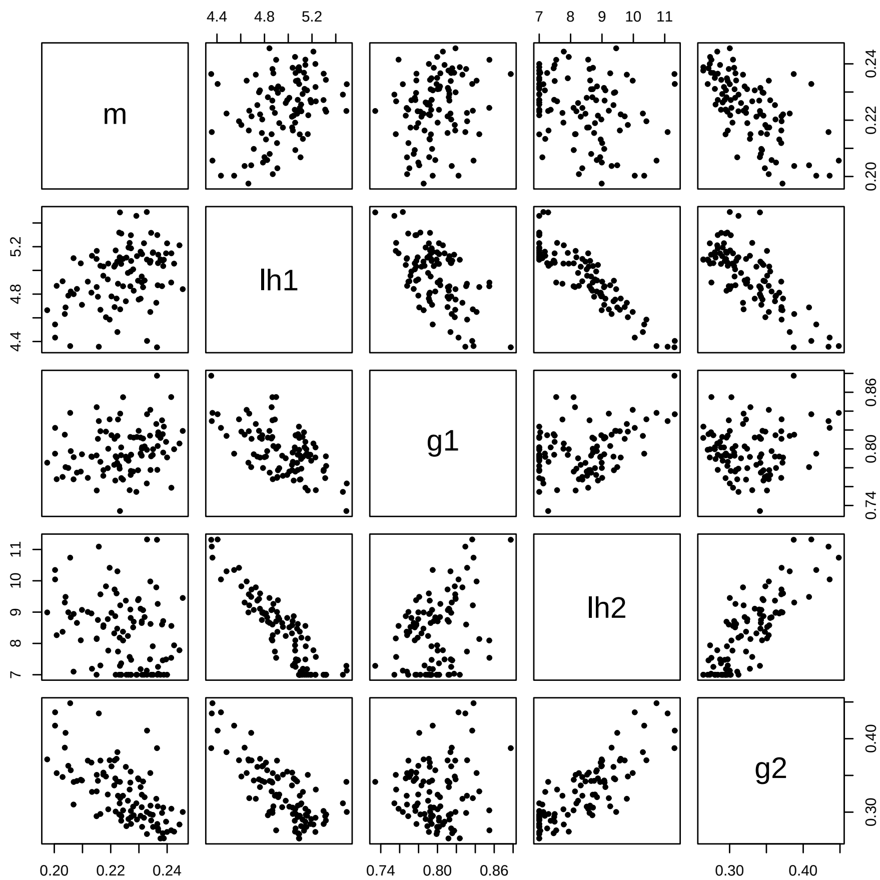


Figure 8: Coplot of parameter estimates for 100 simulated data sets comparing estimates of natural mortality and selectivity parameters with constant size selectivity.

Uncertainty in selectivity and survey catchability parameters increases substantially under conditions of time-varying changes in commercial fishery selectivity (Figure 9). Natural mortality and selectivity parameters for the ascending limb are fairly well defined and unbiased. There is a slight downward bias in the estimates of survey catchability (note that no priors were assumed for the survey q parameters). Overall, the full estimation method is able to capture trends in abundance but fails to estimate the absolute abundance much of the time.

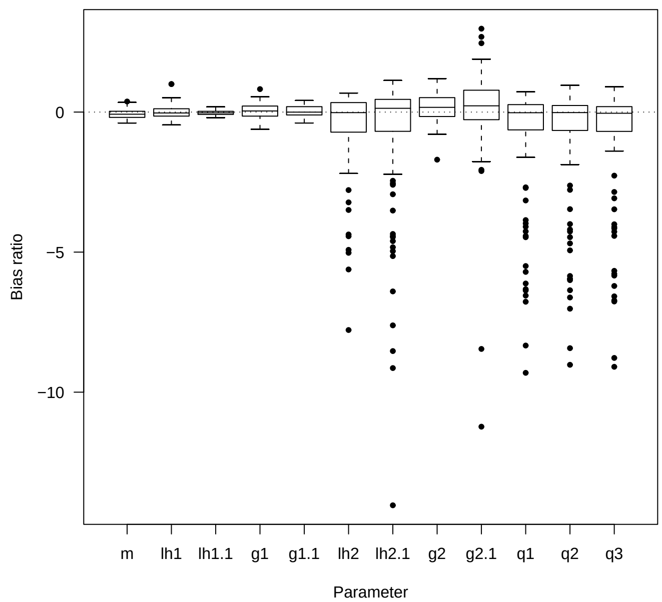


Figure 9: Box plots of parameter bias ratio's for 100 realized data sets with measurement errors and time-varying size selectivity in the commercial fisheries.

Estimates of the deviation parameters in the random walk model δ_i appear to be unbiased provided that the proper σ_δ is specified in the penalty or prior distribution (Figure 10a). If an over-dispersed or no prior is used, the variance of estimated δ terms increases (Figure 10b). Uncertainty in other key model parameters (selectivity and survey catchability coefficients) increases dramatically without the use of constraints on the δ_i terms. There is a slight tendency to underestimate the survey catchability coefficients, although the median of the 100 simulated data sets appears to be unbiased.

3.3.1 Incorporating oceanographic indices in selectivity

If the oceanographic index explains 100% of the variation in selectivity parameters, estimated parameters are unbiased (Fig. 12 and the range in estimates is much less than that of estimating annual deviations in selectivity parameters (compare Fig. 12 with Fig. 9). Overall, the range of uncertainty decreases for all estimated parameters, however, on

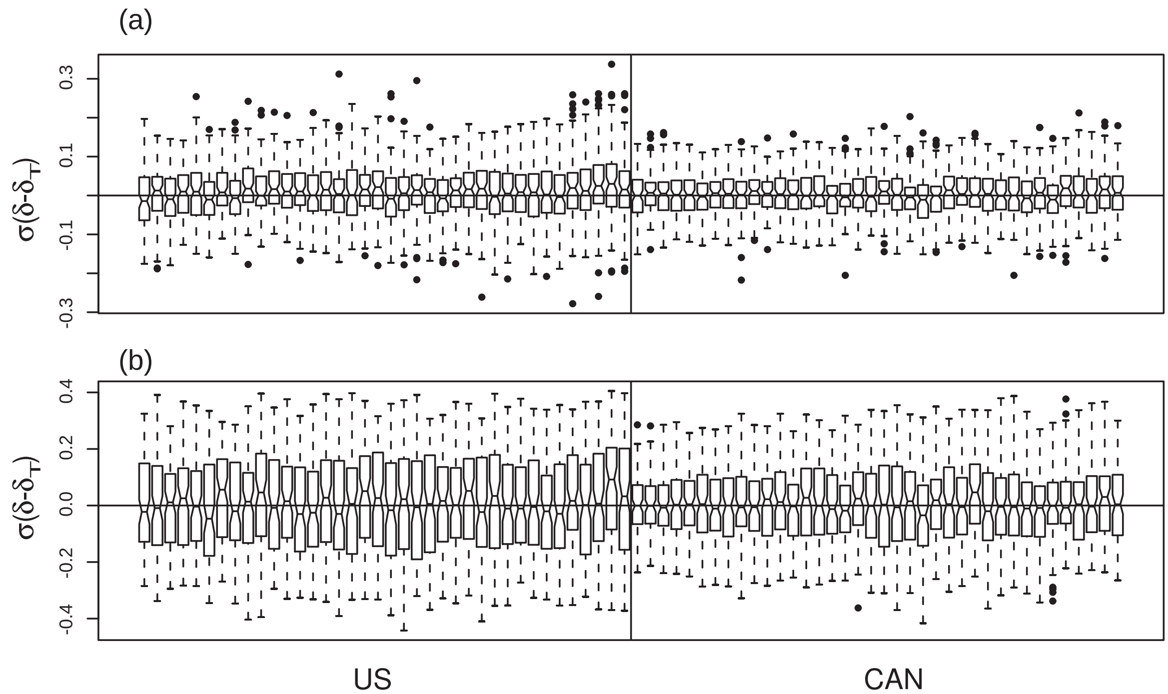


Figure 10: Distribution of differences between in estimated and true δ_i parameters from 100 simulated data sets for the random walk in lh_1 for the commercial US and Canadian selectivity. The true $\sigma = 0.25$ was used in the first differences constraint (a), and no constraint in (b).

a few occasions the estimation routine was not able to estimate all model parameters, leading to some extreme values. This was largely a result of the different oceanographic indices used for each simulation.

There is a substantial improvement in parameter estimates, especially M and selectivity parameters that describe the ascending limb, if the index explains only a small fraction of the variation in selectivity (Fig. 13b). The bias in selectivity and survey catchability parameters is greatly reduced, and the uncertainty in these estimates is further reduced as correlation between the index and γ increases. The oceanographic index needs to explain greater than 50% of the variation in selectivity in order to improve estimates of the selectivity parameters that describe the descending limb.

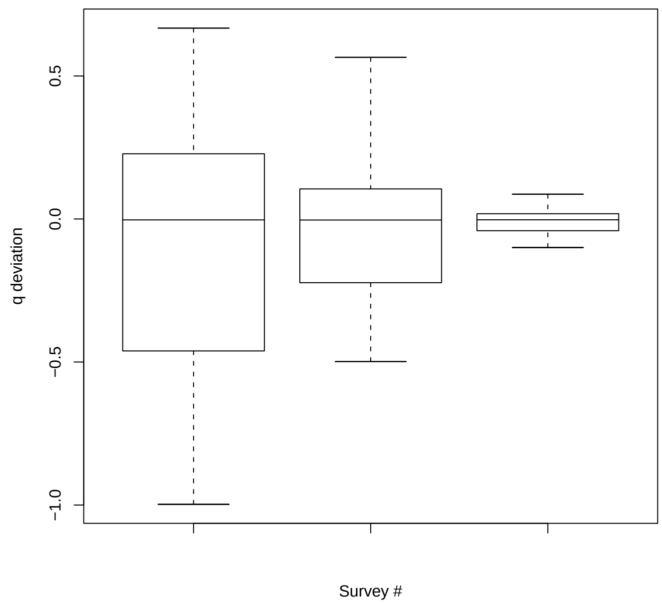


Figure 11: Deviations in the estimate of the survey catchability coefficients. True survey q's from left to right are 1.0, 0.5, and 0.1.

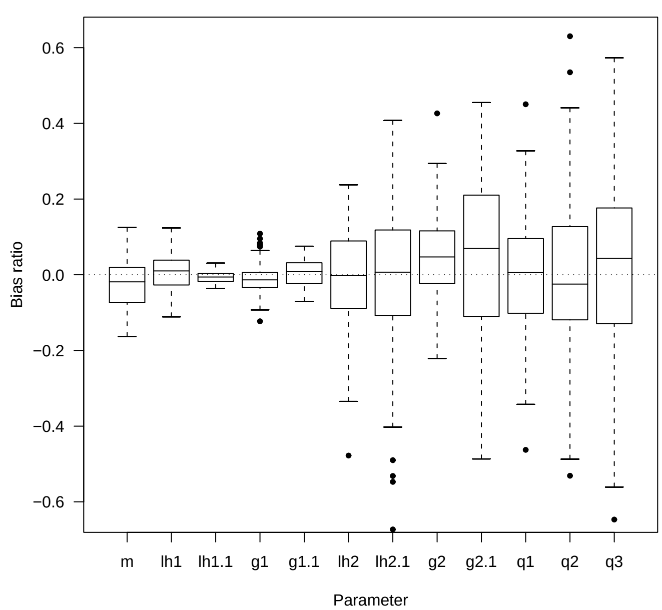


Figure 12: Box plots of parameter bias for 100 realized data sets with measurement errors and variability in size selectivity parameters are 100% explained by the oceanographic index x. Note that a different index x was used in each of the simulations.

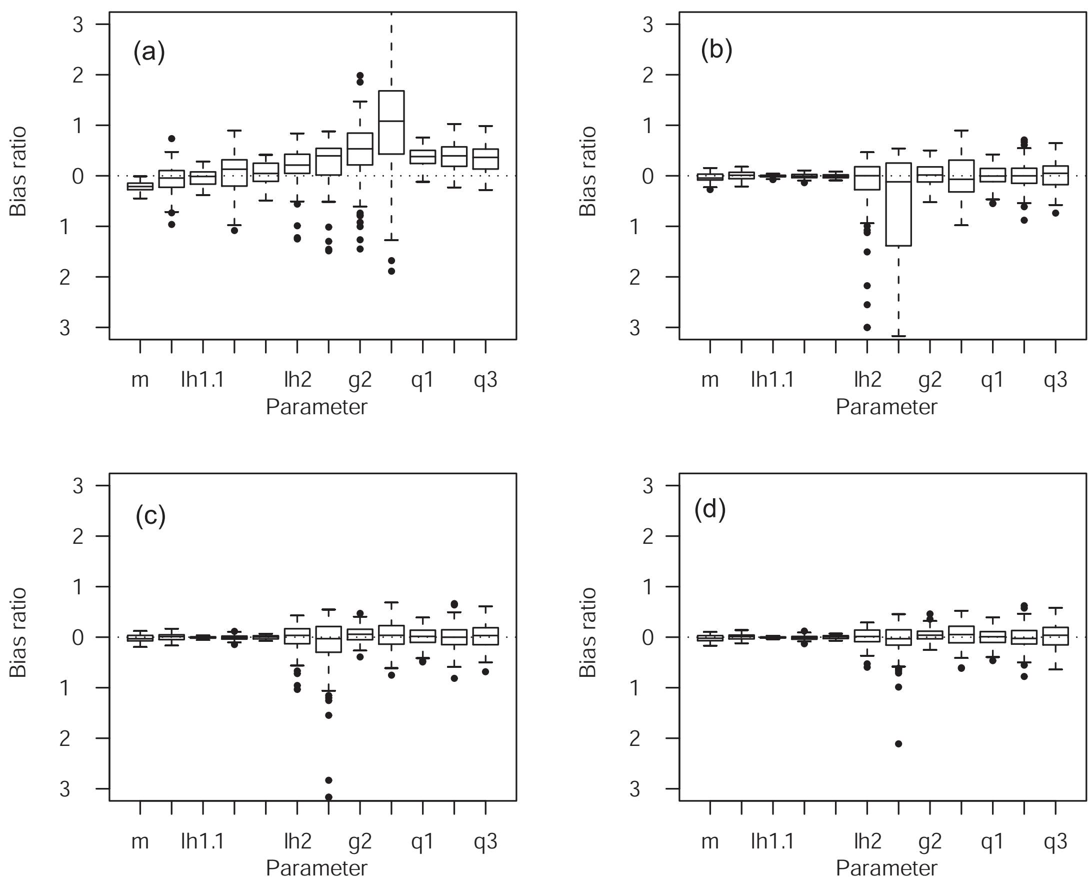


Figure 13: Comparison of parameter estimates from 100 realizations where (a) there is no relationship between the environmental index x and selectivity parameters, (b) correlation between the index x and $\gamma = 0.25$, (c) correlation = 0.5, and (d) correlation = 0.75. Note that all figures are plotted on the same y-axis scale.

4 Discussion

The statistical catch-at-age model precisely estimates natural mortality M and all other model parameters when under circumstances of no measurement error (i.e., perfect information). This was not the case when estimating parameters to describe temporal variation in selectivity. This suggests that the random walk model for changes in fishery selectivity is over-parameterized. It was still possible to obtain reasonable parameter estimates, with minimal bias, when introducing the previously assumed observation errors; however, the use of constraints were necessary to prevent unreasonable estimates of certain parameters, primarily the selectivity parameters for the descending portion of the selectivity curve. Furthermore, in nearly all of the results from simulation-estimation experiments the greatest uncertainty was observed in the selectivity parameters that describe the descending portion of the selectivity curve. We did not explore the relative influence of recruitment survey data on the over-all estimation performance; however, we do not feel such an index would contribute much information on changes in selectivity for older age animals.

4.1 Natural mortality

Results from the simulation-estimation experiments involving changes in the selectivity parameters have clearly defined that trade-offs exist between estimate of an age-independent M and parameters for a dome-shaped selectivity curve. Previous assessments have indicated that the assessment model suggest that there should be a large number of older-aged fish in the population; however, this contradicts the observations from the acoustic trawl survey age-proportions (Helser et al. 2004). Age independent natural mortality appears to trade-off negatively with the decline rate of the descending portion of the selectivity curve, and the use of an age-independent M would increase this confounding even further. One potential way to reduce this confounding of parameters is to assume a sigmoid selectivity curve and reduce the plus group-age to an age that is fully vulnerable to all sampling gears. This is nearly equivalent to scenario 2 (where data were generated with a dome-shaped selectivity curve and estimated with a sigmoid curve) and increased bias was observed for many of the parameters, especially the natural mortality rates.

Examples of assessment models that estimate age-specific M's all share 2 common elements: 1) the oldest age-class is fully vulnerable to at least one of the fisheries or sampling gears, and 2) a constraint or prior is used on relative changes in age-specific M's to discern between real changes in M and errors in age/size composition sampling (see e.g., Hampton 2000; 2002). It may be possible to estimate age-specific M's, or parameters for a function that describe changes in M as a function of age, but one would have to assume that the research trawl survey data or acoustic surveys are fully sampling the oldest age classes.

One of the key findings in the simulation experiments was that M is negatively correlated with the shape parameters (g), and the real danger is over-estimating M (this leads over-optimistic estimates of biomass). All of the scenarios involving fitting an asymptotic or sigmoid selectivity function to data that were sampled from a dome-shaped selectivity function (Scenario 3) lead to an under-estimate of M. This results in a conservative estimate of biomass and the survey catchability coefficient will be biased upwards. In contrast, fitting a dome-shaped model to data that were sampled from a sigmoid selectivity function (i.e., scenario 2), tends to over-estimate M, which tends to over-estimate biomass and the survey q's are biased downward. In recent assessments of Pacific hake when q is allowed to be estimated freely there is a strong tendency for q to be much less than 1 (i.e., Helser et al. 2004). This is thought to be biased downward and fixed $q = 1$ and $q = 0.6$ options have been used for presenting projections to decision makers. Although we have not ruled out other potential sources of bias in q, it could be that the fisheries selectivities (at least in the Canadian zone) are actually sigmoid.

4.2 Estimating selectivity

It appears that it is possible to estimate annual deviations in selectivity parameters given independent information on natural mortality and some prior information about variability in selectivity parameters. In cases where selectivity varies from year-to-year, we observed that estimates for the length at 50% vulnerability for the descending limb were often less than that of the ascending limb. Thinking about this further, we noticed that the scaled double logistic function (which re-calculates the age-specific selectivities) would still produce a reasonable dome-shaped curve when $lh_2 << lh_1$. There are very few older-age individuals in the catch-at-age proportions relative to younger individuals and therefore much of the information to estimate parameters for the dome-shaped selectivity curve comes from the few strong cohorts that survive to an older age. Furthermore, there is strong confounding between the shape parameter for the descending portion of the selectivity curve and the natural mortality rate. This negative relationship between M and g_2 implies that the data just as likely to have come from a population with a high natural mortality rate and a nearly asymptotic selectivity curve or a low natural mortality rate and a more dome-shaped selectivity curve. At this moment, we cannot think of a reasonable way to resolve this confounding issue other than to use constraints or priors for M or g_2 or simply assume a sigmoid selectivity function. Since it is not possible to estimate all model parameters using simulated data with no observation errors the present statistical catch-at-age model with the random walk in selectivity parameters is over-parameterized. In contrast to the real data, the simulated data sets were much more informative (lower CV's, and relative abundance indices are proportional to B_t), and it was still difficult to estimate time-varying selectivity parameters.

It should also be noted that the manner in which we dealt with changes in selectivity parameters differed slightly from the previous hake assessment models. We used a continuous random walk model to model changes in selectivity parameters, whereas, Helser et al. (2004) used a constrained random walk model. We did not conduct any simulation experiments to examine the difference, but note that the constrained random walk model will tend to allow selectivity parameters to wander around a mean, and the continuous model permits systematic changes in selectivity. Other than estimating one less parameter, we suspect the differences are very minor.

Previous work on the migration of hake populations, catch-age observations from the commercial fisheries, the distribution of hake during the triennial acoustic surveys and variation in hake diets, clearly demonstrates inter annual variability in the distribution of the hake stock (Dorn 1991; 1992; 1995; Buckley and Livingston 1997). There appears to be a relationship between mean January-February sea level height and the proportion of the hake stock that migrates into the Canadian zone (Mark Saunders, Pers. Comm.), as well as a relationship between temperature (Dorn 1995). These dynamic changes in distribution obviously affect the availability of certain age-classes to US and Canadian fishing fleets, and hence the need to develop a method to capture these dynamic changes in selectivity. The results from including an oceanographic index to model changes in selectivity parameters were quite surprising. Including an oceanographic index, even one that was only slightly correlated ($r^2 = 0.25$), greatly improved estimation precision for all parameters, including survey q's and selectivity parameters for the descending limb. Dorn (1995) found significant correlations ($r^2 \geq 0.8$) between an estimated migration coefficient and sea-temperature anomalies at 100m depth; however, this strong correlation has broken down recently. Adding to the difficulty of finding an appropriate index will be the uncertainty in estimated changes selectivity. By comparison, the contour plots for changes in selectivity between this years assessment and the previous year differ slightly as a result of the new catch-at-age data for 2004 fishing season.

4.3 Explicit representation of hake movement

The present assessment model (Helser et al. 2004) implicitly represents the spatial variation in the hake distribution through the use of a series of dome-shaped selectivity curves that vary over time. An alternative approach is to explicitly represent the spatial variation in hake distribution relative to the Canadian zone through the use of an age-specific movement model, where in each year the fraction of each age-class in the Canadian zone is calculated or estimated. A similar model was constructed by Dorn (1995) to estimate what fraction of the stock was in the Canadian zone for years in which surveys were not conducted. Dorn (1995) documented a high positive correlation exists between the mean sea-water temperature at 100m depth between 30º–42ºN and a migration coefficient ($p_{3,i}$) implying that intensified poleward flowing currents (as index by temperature-at-depth) results in a higher fraction of the hake stock in the Canadian zone.

It may be possible to eliminate the use of dome-shaped selectivity curves in the commercial fisheries if the assessment model includes explicit terms for the fraction of the total stock that is in the US and Canadian zones. This involves a simple modification to the catch equations, namely:

$$\hat{c}_{i,j,k} = \frac{F_{i,j,k}}{Z_{i,j}} \left[1 - \exp(-Z_{i,j})\right] p_{i,j,k} N_{i,j},$$

and

$$F_{i,j,k} = \frac{f_{i,k}}{1 + e^{-g_k(j - lh_k)}},$$

where $p_{i,j,k}$ is the fraction of the total $N_{i,j}$ that is in zone k. Dorn (1995) suggested a simple logistic curve to calculate the proportion-at-age in the Canadian zone:

$$p_{i,j,k} = \frac{\gamma_{1,i}}{1 + e^{-\gamma_2(j - \gamma_3)}}$$

and the proportion in the US zone is $1 - p_{i,j,k}$. Note the vector $\gamma_{1,i}$ implies inter-annual variation in the fraction of hake in the Canadian zone, and it is this term that is positively correlated with mean sea water temperature. The shape parameter γ_2 is roughly proportional to the size-specific swimming speeds, that is, it reflects the between cohort differences in annual migration distances. There is a serious limitation in this model, in that the constant γ_3 parameter implies that the center of the hake distribution is fixed over time. For example, if $\gamma_3 = 5$ and $\gamma_1 = 1$, then a maximum of 50% of age-5 individuals could ever enter the Canadian zone. This is inconsistent with 1998 observations, where hake were spawning in the Canadian zone. An alternative model that is more consistent with recent observations would be to estimate a vector of $\gamma_{1,i}$ and $\gamma_{3,i}$ parameters, which implies both variation in the northward extent of the migration as well as variation in the center of the hake distribution.

4.4 Alternatives to priors on q

The greatest source of uncertainty, or conflict, is trying to scale the biomass to the acoustic survey data, or q. In the present assessment model, there appears to be sufficient information to estimate q, however, the estimates are believed to be seriously biased downward. One of the model enhancements recommended by the STAR review panel was to develop an informed prior on q. What basis should this prior be built upon? As we noted in the above simulation-estimation experiments, the information in q was confounded with parameters such as natural mortality rates and selectivity parameters. An alternative to developing priors for q would be to re-parameterize the model to reduce confounding (i.e., reduced the number of estimated nuisance parameters) or build in a production function, such as a stock-recruitment relationship, where we do have information to construct priors (e.g., Myers and Barrowman 1996; Myers et al. 1999).

References

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

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

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

Dorn, M. W. . U. D. C. (1991). Spatial and temporal patterns in the catch of pacific whiting in the u.s. management zone during 1978-88. *NOAA Tech. Memo. NMFS-F/NWC-205,*, page 68.

Hampton, J. (2000). Natural mortality rates in tropical tunas: size really does matter. *Can. J. Fish. Aquat. Sci.*, 57:1002–1010.

Hampton, J. (2002). Stock assessment of skipjack tuna in the western and central pacific ocean. *In 15th Meeting of the Standing Committee on Tuna and Billfish. Working paper SKJ–1, Ocean Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia (http:www.spc.org.nc/Oceanfish).*

Helser, T. E., Methot, R. D., and Fleischer, G. W. (2004). Stock assessment of pacific hake (whiting) in u.s. and canadian waters in 2003. *Northwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration 2725 Montlake Blvd., East Seattle, WA 98112, USA.*

Myers, R. A. and Barrowman, N. J. (1996). Is fish recruitment related to spawner abundance? *Fish. Bull.*, 94:707–724.

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

Otter Research (2001). An introduction to ad model builder version 6.0.2 for using in nonlinear modeling and statistics. *Otter Research Ltd, Box 2040, Sidney B.C., V8L 3S3*, 2001.

Sakuma, K. M. and Ralston, S. (1996). Vertical and horizontal distribution of juvenile pacific whiting *(Merluccius productus)* in relation to hydrography of california. *Calif. Coop. Oceanic Fish. Invest. Rep.*, 38(137-146).

5 ADMB code for reference model

```
//****************************************************
//  Programmer: Steve Martell
//  Project Name: simCAA.tpl
//  Date:   Dec 16, 2004
//  Version:1.0
//  Comments: A reference model for Pacific Hake stocks
//
//****************************************************/
DATA_SECTION
    //Error distribution parameters

    init_number cv_catch;
    init_vector cv_yt(1,3);
    init_ivector fsh_multn(1,2);    //multinomial fisheries
    init_ivector sur_multn(1,3);    //multinomial survey

    //standard deviations for fisheries selectivity parameters
    init_vector sel_rwlk_std(1,2);

    //scaler for oceanographic index
    init_vector varrho(1,2);

    //random number seed comes from a file.
    int seed;
    !!ifstream ifs("seedno.txt");
    !!ifs>>seed;

    init_int syr;                           //starting year
    init_int nyr;                           //ending year
    init_int rcrage;                        //recruitment age
    init_int trmage;                        //+group age
    vector age(rcrage,trmage);
    !!age.fill_seqadd(rcrage,1);
    init_number m;                          //instantaneous natural mortality

    init_vector mat(rcrage,trmage)      // Proportion mature
    init_vector femmult(rcrage,trmage)  // Multiplier to get spawning biomass


    //Selectivity parameters for fisheries.
    init_vector lh1(1,2);
    init_vector shp1(1,2);
    init_vector lh2(1,2);
    init_vector shp2(1,2);


    //Selectivity parameters for surveys.
    init_int nsurveys;
    init_vector sur_q(1,nsurveys);
    init_vector sur_lh1(1,nsurveys);
    init_vector sur_shp1(1,nsurveys);
    init_vector sur_lh2(1,nsurveys);
```

```
    init_vector sur_shp2(1,nsurveys);

    //survey number and year
    //number of survey years
    init_ivector nsurv_year(1,nsurveys);
    init_imatrix surv_years(1,nsurveys,1,nsurv_year);//actual survey years


    //Driving variables for reference model
    init_vector recruits(syr,nyr);
    init_matrix f(1,2,syr,nyr);

    init_3darray fsh_wt(1,2,syr,nyr,rcrage,trmage);

    init_matrix wt_pop(syr,nyr,rcrage,trmage)// Population weight at age
    //++++++++++++++++++++++END OF DATA INPUT+++++++++++++++++++++++++


    vector bio(syr,nyr);                        //total pop biomass
    vector x(syr,nyr);                      //Oceanographic index

    matrix z(syr,nyr,rcrage,trmage);            //instantaneous total mortality
    matrix n(syr,nyr,rcrage,trmage);            //numbers-at-age matrix
    matrix sur_yt(1,nsurveys,1,nsurv_year);//survey indicies
    matrix tot_catch(1,2,syr,nyr);          //total catch by fishery
    matrix nu(1,2,syr,nyr);                     //random variables for catch error
    matrix delta(1,nsurveys,1,nsurv_year);  //Random variable for survey errors
    matrix shp1_dev(1,2,syr,nyr);           //random walk variables for shp1
    matrix lh1_dev(1,2,syr,nyr);            //random walk variables for lh1
    matrix shp2_dev(1,2,syr,nyr);           //random walk variables for shp2
    matrix lh2_dev(1,2,syr,nyr);            //random walk variables for lh2


    3darray fsh_c(1,2,syr,nyr,rcrage,trmage);       //catch-at-age matrix
    3darray fsh_p(1,2,syr,nyr,rcrage,trmage);       //catch-at-age proportions matrix
    3darray fsh_sel(1,2,syr,nyr,rcrage,trmage);     //selectivity for commercial fisheries
    3darray sur_sel(1,nsurveys,1,nsurv_year,rcrage,trmage); //selectivity for the surveys.
    3darray sur_p(1,nsurveys,1,nsurv_year,rcrage,trmage);   //proportions-at-age for the surveys.


PARAMETER_SECTION

    objective_function_value func;
    LOC_CALCS
        cout<<"________SIMULATING DATA_________"<<endl;
        generate_error_dists();
        get_selectivities();
        get_mortality();
        numbers_at_age();
        get_catch_at_age();
        survey_data();
        write_data_file();

        cout<<"RANDOM SEED NO. = "<<seed<<endl;
```

```
        cout<<"********DONE SIMULATION********"<<endl;
        exit(1);
    END_CALCS

PROCEDURE_SECTION


FUNCTION generate_error_dists
    random_number_generator rng(seed);

    nu.fill_randn(rng);     //errors in total catch
    delta.fill_randn(rng);
    x.fill_randu(rng);      //uniform oceanographic index
    for(int i=syr;i<nyr;i++)x[i+1]=0.8*x[i]+0.2*x[i+1]; //autocorrelated
    x=(x-mean(x))/sqrt(var(x));


    //selectivity deviations
    shp1_dev.fill_randn(rng);
    lh1_dev.fill_randn(rng);
    shp2_dev.fill_randn(rng);
    lh2_dev.fill_randn(rng);
    for(int j=1;j<=2;j++)
    {
        shp1_dev(j)*= 0.25*sel_rwlk_std[j];
        lh1_dev(j)*= sel_rwlk_std[j];
        shp2_dev(j)*= 0.25*sel_rwlk_std[j];
        lh2_dev(j)*= sel_rwlk_std[j];
    }




FUNCTION get_selectivities
    int i,j;
    double g1, g2, h1, h2;
    //This is the fisheries selectivities only.
    for(j=1;j<=2;j++)
    {
        //initialize random walks for selectivity parameters in fishery j
        g1=shp1[j];
        g2=shp2[j];
        h1=lh1[j];
        h2=lh2[j];

        for(i=syr;i<=nyr;i++)
        {
            if(i>syr&&varrho(j)==0)
            {//update random walk parameters for year i
                g1+=shp1_dev(j,i);
                h1+=lh1_dev(j,i);
                g2+=shp2_dev(j,i);
                h2+=lh2_dev(j,i);
            }
```

```
            if(varrho(j)>0)
            {   //NEED TO IMPLEMENT OCEANOGRAPHIC INDEX
                g1=shp1[j]+varrho[j]*x[i]+(1.-varrho[j])*shp1_dev(j,i);
                h1=lh1[j]+varrho[j]*x[i]+(1.-varrho[j])*lh1_dev(j,i);
                g2=shp2[j]+varrho[j]*x[i]+(1.-varrho[j])*shp2_dev(j,i);
                h2=lh2[j]+varrho[j]*x[i]+(1.-varrho[j])*lh2_dev(j,i);

            }
            fsh_sel(j)(i)=selectivity(g1,h1,g2,h2,age);
        }
    }
    //cout<<fsh_sel<<endl;

FUNCTION get_mortality
    int i;

    for(i=syr;i<=nyr;i++)
    {
        z(i)=m+(f(1,i)*fsh_sel(1)(i))+(f(2,i)*fsh_sel(2)(i));
    }
    //cout<<z<<endl;


FUNCTION numbers_at_age
    int i;

    //initialize recruitment vector
    n.colfill(rcrage,recruits);

    //initialize numbers at age
    n(syr)=recruits(syr)*pow(exp(-m),age-1.);
    n(syr,trmage)/=(1-exp(-m));

    for(i=syr;i<nyr;i++)
    {
        //numbers at age in year i
        n(i+1)(rcrage+1,trmage)=++elem_prod(n(i)(rcrage,trmage-1),
                                        exp(-z(i)(rcrage,trmage-1)));
        n(i+1,trmage)+=n(i,trmage)*exp(-z(i,trmage));

        //total biomass
        bio(i)=sum(elem_prod(n(i),wt_pop(i)));
        if(i==nyr-1)bio(nyr)=sum(elem_prod(n(nyr),wt_pop(nyr)));
    }


FUNCTION get_catch_at_age
//get catch-at-age then p at age from multinomial sample
    int i,j;
    fsh_p.initialize();
    dvector pdf(rcrage,trmage);

    for(i=syr;i<=nyr;i++)
    {
```

```
        for(j=1;j<=2;j++)   //loop over fisheries
        {
            //catch-at-age in numbers (millions)
            fsh_c(j)(i)=elem_prod(n(i),elem_prod(
                            elem_div(f(j,i)*fsh_sel(j)(i),z(i)),1.-exp(-z(i))));

            //get total catch for each fishery
            tot_catch(j,i)=sum(elem_prod(fsh_c(j)(i),fsh_wt(j)(i)));
            tot_catch(j,i)*=exp(nu(j,i)*cv_catch);

            pdf=fsh_c(j)(i);    //make a shallow copy for multinomial sample.
            fsh_p(j)(i)=multinomial(fsh_multn(j),seed+2*i+j,pdf);
            fsh_p(j)(i)/=sum(fsh_p(j)(i));  //turn into proportions
            if(fsh_multn(j)==1) //no multinomial sampling sampling error.
                fsh_p(j)(i)=pdf/sum(pdf);
        }
    }


FUNCTION survey_data
    //simulate survey data
    //Acoustic units are in biomass

    int i,j,k;
    double vul_bio;
    dvector pdf(rcrage,trmage);
    for(j=1;j<=nsurveys;j++)
        {
        for(k=1;k<=nsurv_year(j);k++)
        {
            i=surv_years(j,k);

            //survey selectivity
            sur_sel(j)(k)=selectivity(sur_shp1[j],sur_lh1[j],
                                sur_shp2[j],sur_lh2[j],age);


             //biomass vulnerable to survey gear.
            vul_bio=sum(elem_prod(elem_prod(n(i),
                            wt_pop(i)),sur_sel(j)(k)));
            sur_yt(j,k)=sur_q(j)*vul_bio;
            sur_yt(j,k)*=mfexp(delta(j,k)*cv_yt(j));

            //survey catch at age data
            pdf=elem_prod(n(i),sur_sel(j)(k));
            sur_p(j)(k)=multinomial(sur_multn(j),seed+j+i,pdf);
            sur_p(j)(k)/=sum(sur_p(j)(k));
            if(sur_multn(j)==1)
                sur_p(j)(k)=pdf/sum(pdf);  //use for exact data.
        }
    }
    //cout<<sur_q<<endl;

FUNCTION write_data_file
```

```
    ofstream ofs("CAA.dat");

    ofs<<"#Simulation years"<<endl;
    ofs<<syr<<" "<<nyr<<endl;
    ofs<<"#Ages"<<endl;
    ofs<<rcrage<<"  "<<trmage<<endl;
    ofs<<"#Maturity"<<endl<<mat<<endl;
    ofs<<"#Female multiplier"<<endl<<femmult<<endl;
    ofs<<"#sel_rwlk_std"<<endl<<sel_rwlk_std<<endl;
    ofs<<"#CV in total catch"<<endl<<cv_catch<<endl;
    ofs<<"#total catch (tons)(US)"<<endl;
    ofs<<1000000*tot_catch(1)<<endl;
    ofs<<"#total catch (tons)(CAN)"<<endl;
    ofs<<1000000*tot_catch(2)<<endl;
    ofs<<"#multinomial sample sizes for commercial fisheies"<<endl;
    ofs<<fsh_multn<<endl;
    ofs<<"#US catch-at-age proportions"<<endl;
    ofs<<fsh_p(1)<<endl;
    ofs<<"#CAN catch-at-age proportions"<<endl;
    ofs<<fsh_p(2)<<endl;
    ofs<<"#US weight-at-age proportions"<<endl;
    ofs<<fsh_wt(1)<<endl;
    ofs<<"#CAN weight-at-age proportions"<<endl;
    ofs<<fsh_wt(2)<<endl;

    ofs<<"#***************SURVEY DATA***************"<<endl;
    ofs<<"#nsurveys"<<endl<<nsurveys<<endl;
    ofs<<"#CV in surveys"<<endl<<cv_yt<<endl;
    ofs<<"#multinomial sample sizes for surveys"<<endl;
    ofs<<sur_multn<<endl;
    ofs<<"#nsurv_year"<<endl<<nsurv_year<<endl;
    ofs<<"# years for survey 1"<<endl;
    ofs<<surv_years<<endl;
    ofs<<"#survey indices"<<endl;
    ofs<<sur_yt<<endl;
    ofs<<"#Mean population weight at age"<<endl<<wt_pop<<endl;

    for(int i=1;i<=nsurveys;i++)
    {
        ofs<<"#Age proportions in survey "<<i<<endl;
        ofs<<sur_p(i)<<endl;
    }
    ofs<<"#Oceanographic index"<<endl<<x<<endl;

    //True states
    ofs<<"#lh1_dev"<<endl<<lh1_dev<<endl;

//************************CALLED FUNCTIONS*************************
//Return Selectivity curve______________________________________________________
FUNCTION dvector selectivity(double g, double h, double g2, double
h2,dvector x)
    //Dome shaped selectivity option when g2>0
    {
        dvector sel;
```

```
        if(g2!=0){

            sel = pow(elem_prod(1.+exp(-g*(x-h)),1.+exp(g2*(x-h2))),-1);
        }else{
            sel=1./(1.+exp(-g*(x-h)));
        }
        sel/=max(sel);
        return sel;
    }


//_______________________________________________________________________________
FUNCTION dvector multinomial(long nobs, int seed, dvector& PDF)
    /**__Returns a vector of sampled frequencies from a PDF distribution__**/
    {
        //Convert PDF to cummulative distribution
        PDF/=sum(PDF);                      //normalize to sum=1.
        int ni=PDF.indexmin();
        int nb=PDF.indexmax();
        double xx;
        dvar_vector dist(ni-1,nb);
        dist.initialize();
        for(int i=ni;i<=nb;i++)
        {
            dist(i)=sum(PDF(ni,i));
            //cout<<i<<"    "<<dist(i)<<endl;
        }
        //Now Sample from the distribution and bin Frequencies
        random_number_generator rng(seed);
        dvector freq(ni,nb);
        freq.initialize();
        //cout<<dist.fill_multinomial(rng,dist)<<endl;
        for(int j=1;j<=nobs;j++)
        {
            xx=randu(rng);
            i=ni-1;
            do
            {
                i++;
                if(dist(i)>xx) freq(i)++;
            } while(dist(i)<=xx && i<nb);
        }

        return(freq);
    }
//=========================================================================
```

6 ADMB code for assessment model

```
//****************************************************
//  Programmer: Steve Martell
//  Project Name: simCAA.tpl
//  Date:   Dec 16, 2004
//  Version:1.0
//  Comments: A reference model for Pacific Hake stocks
//
// To Do List: add time-varying changes to selectivities
//                  catch-at-age data
//
//****************************************************/
DATA_SECTION
    !!system("simCAA.exe");


    init_int syr;                           //starting year
    init_int nyr;                           //ending year
    init_int rcrage;                        //recruitment age
    init_int trmage;                        //+group age
    vector age(rcrage,trmage);
    vector yrs(syr,nyr);

    !!age.fill_seqadd(rcrage,1);
    !!yrs.fill_seqadd(syr,1);

    init_vector mat(rcrage,trmage)      // Proportion mature
    init_vector femmult(rcrage,trmage)  // Multiplier to get spawning biomass

    init_vector sel_rwlk_std(1,2);      //std in selectivity parameter deviations

    init_number cv_catch;
    init_matrix tot_catch(1,2,syr,nyr); //total catch by fishery

    init_vector fsh_multn(1,2);

    init_3darray fsh_p(1,2,syr,nyr,rcrage,trmage);  //catch-at-age proportions matrix
    init_3darray fsh_wt(1,2,syr,nyr,rcrage,trmage);
    //Read in survey information
    init_int nsurveys;
    init_vector cv_yt(1,nsurveys);
    init_ivector sur_multn(1,nsurveys);
    init_ivector nsurv_year(1,nsurveys);
    init_imatrix surv_years(1,nsurveys,1,nsurv_year);   //survey years
    init_matrix sur_yt(1,nsurveys,1,nsurv_year);            //survey indicies
    init_matrix wt_pop(syr,nyr,rcrage,trmage);          //weight at age

    //proportions-at-age from the surveys.
    init_3darray sur_p(1,nsurveys,1,nsurv_year,rcrage,trmage);

    //oceanographic index
    init_vector x(syr,nyr);
```

```
    //input true states
    init_matrix true_lh1_dev(1,2,syr+1,nyr);
    //+++++++++++++++++++++++END OF DATA INPUT+++++++++++++++++++++++++++++


PARAMETER_SECTION
    init_bounded_number m(0.1,0.8,2);   //instantaneous natural mortality

    init_bounded_vector varrho(1,2,0.,1.,1);

    //Selectivity parameters for fisheries.
    init_bounded_vector lh1(1,2,0,10,2);
    init_bounded_vector shp1(1,2,0,2,2);
    init_bounded_vector lh2(1,2,1.,99.,2);
    init_bounded_vector shp2(1,2,0,2,2);


    //Selectivity parameters for surveys.
    init_vector sur_q(1,nsurveys,1);
    init_bounded_vector sur_lh1(1,nsurveys,0,10,2);
    init_bounded_vector sur_shp1(1,nsurveys,0,2,2);
    init_bounded_vector sur_lh2(1,nsurveys,1.,99.,2);
    init_bounded_vector sur_shp2(1,nsurveys,0,2,2);


    //population recruits
    init_vector log_recruits(syr,nyr);


    //fishing mortality
    init_bounded_matrix f(1,2,syr,nyr,0.,0.5);


    //Random walk parameters for fisheries selectivities
    !!int phz=3;
    !!if(sel_rwlk_std(1)==0)phz=-3;
    !!if(active(varrho))phz=-3;
    init_bounded_matrix lh1_dev(1,2,syr+1,nyr,-1,1,phz);
    init_bounded_matrix shp1_dev(1,2,syr+1,nyr,-1,1,phz);
    init_bounded_matrix lh2_dev(1,2,syr+1,nyr,-1,1,phz);
    init_bounded_matrix shp2_dev(1,2,syr+1,nyr,-1,1,phz);

    //Objective function variable
    objective_function_value func;

    vector loglik(1,15);
    vector bio(syr,nyr);                    //total pop biomass

    matrix z(syr,nyr,rcrage,trmage);    //instantaneous total mortality
    matrix n(syr,nyr,rcrage,trmage);    //numbers-at-age matrix
    matrix pred_sur_yt(1,nsurveys,1,nsurv_year);
    matrix pred_tot_catch(1,2,syr,nyr);

    3darray fsh_c(1,2,syr,nyr,rcrage,trmage);   //catch-at-age matrix
```

```
    3darray pred_fsh_p(1,2,syr,nyr,rcrage,trmage);  //predicted proportions at age in catch
    3darray fsh_sel(1,2,syr,nyr,rcrage,trmage);     //selectivity for commercial fisheries

    //selectivity for the surveys.
    3darray sur_sel(1,nsurveys,1,nsurv_year,rcrage,trmage);

    // predicted catch-at-age for survey
    3darray pred_sur_p(1,nsurveys,1,nsurv_year,rcrage,trmage);


PROCEDURE_SECTION
    //_________MAIN_________

        get_selectivities();
        get_mortality();
        numbers_at_age();
        get_catch_at_age();
        survey_data();
        calc_objective_func();

    //**********************


FUNCTION get_selectivities
    int i,j;
    dvariable g1, g2, h1, h2;
    //This is the fisheries selectivities only.
    for(j=1;j<=2;j++)
    {
        //initialize random walks for selectivity parameters in fishery j
        g1=shp1[j];
        g2=shp2[j];
        h1=lh1[j];
        h2=lh2[j];

        for(i=syr;i<=nyr;i++)
        {
            if(i>syr && active(lh1_dev))
            {//update random walk parameters for year i
                g1+=shp1_dev(j,i);
                h1+=lh1_dev(j,i);
                g2+=shp2_dev(j,i);
                h2+=lh2_dev(j,i);
            }
            //
            if(active(varrho))
            {
                g1=shp1[j]+varrho[j]*x[i];
                h1=lh1[j]+varrho[j]*x[i];
                g2=shp2[j]+varrho[j]*x[i];
                h2=lh2[j]+varrho[j]*x[i];
            }
            fsh_sel(j)(i)=selectivity(g1,h1,g2,h2,age);
        }
```

```
    }
    //cout<<fsh_sel<<endl;

FUNCTION get_mortality
    int i;

    for(i=syr;i<=nyr;i++)
    {
        z(i)=m+(f(1,i)*fsh_sel(1)(i))+(f(2,i)*fsh_sel(2)(i));
    }
    //cout<<z<<endl;


FUNCTION numbers_at_age
    int i;

    //initialize recruitment vector
    n.colfill(rcrage,mfexp(log_recruits));

    //initialize numbers at age
    n(syr)=mfexp(log_recruits(syr))*pow(exp(-m),age-1.);
    n(syr,trmage)/=(1-exp(-m));

    for(i=syr;i<nyr;i++)
    {
        n(i+1)(rcrage+1,trmage)=++elem_prod(n(i)(rcrage,trmage-1),
                                    exp(-z(i)(rcrage,trmage-1)));
        n(i+1,trmage)+=n(i,trmage)*exp(-z(i,trmage));

        //total biomass
        bio(i)=sum(elem_prod(n(i),wt_pop(i)));
        if(i==nyr-1)bio(nyr)=sum(elem_prod(n(nyr),wt_pop(nyr)));
    }

    //cout<<bio<<endl;

FUNCTION get_catch_at_age
//get catch-at-age then p at age from multinomial sample
    int i,j;
    //fsh_p.initialize();
    //dvector pdf(rcrage,trmage);

    for(i=syr;i<=nyr;i++)
    {
        for(j=1;j<=2;j++)   //loop over fisheries
        {
            //catch-at-age in numbers (millions)
            fsh_c(j)(i)=elem_prod(n(i),elem_prod(elem_div
                            (f(j,i)*fsh_sel(j)(i),z(i)),1.-exp(-z(i))));
            pred_fsh_p(j)(i)=fsh_c(j)(i)/sum(fsh_c(j)(i));



            //get total catch for each fishery
```

```
            pred_tot_catch(j,i)=1000000*sum(elem_prod(fsh_c(j)(i),fsh_wt(j)(i)));

        }
    }

FUNCTION survey_data
    //simulate survey data
    //Acoustic units are in biomass

    int i,j,k;
    dvariable vul_bio;
    //dvector pdf(rcrage,trmage);
    for(j=1;j<=nsurveys;j++)
        {
        for(k=1;k<=nsurv_year(j);k++)
        {
            i=surv_years(j,k);

            //survey selectivity
            sur_sel(j)(k)=selectivity(sur_shp1[j],sur_lh1[j],
                                    sur_shp2[j],sur_lh2[j],age);


             //biomass vulnerable to survey gear.
            vul_bio=sum(elem_prod(elem_prod(n(i),wt_pop(i)),sur_sel(j)(k)));
            pred_sur_yt(j,k)=sur_q(j)*vul_bio;


            //get predicted survey age proportions
            pred_sur_p(j)(k)=elem_prod(n(i),sur_sel(j)(k));
            pred_sur_p(j)(k)/=sum(pred_sur_p(j)(k));

        }
    }
    //cout<<sur_yt<<endl;

FUNCTION calc_objective_func
    int j,k;
    double o=1.e-10;
    dvar_vector prior(1,2);

    loglik.initialize();
    prior.initialize();
    dvariable std;

    //Likelihoods for total catches
    if(cv_catch==0)std=1; else std=cv_catch;
    for(j=1;j<=2;j++)
    {
        loglik[j]=0.5*norm2((log(tot_catch(j)+o)-log(pred_tot_catch(j)+o))/std);
    }

    //Likelihoods for the fishery catch at data
    //NB set multinomial sample size to 1 when using error free data.
```

```
    for(j=1;j<=2;j++)
    {
        loglik[j+2]=-sum(elem_prod(fsh_multn(j)*(fsh_p(j)+o),
                        log(elem_div(pred_fsh_p(j)+o,fsh_p(j)+o))));
    }

    //Likelihoods for relative abundance data.
    for(j=1;j<=nsurveys;j++)
    {
        if(cv_yt(j)==0)std=1;else std=cv_yt(j);
        loglik[j+4]=0.5*norm2((log(sur_yt(j)+o)-log(pred_sur_yt(j)+o))/std);
        loglik[nsurveys+j+4]=-sum(elem_prod(sur_multn(j)*(sur_p(j)+o),
                                log(elem_div(pred_sur_p(j)+o,sur_p(j)+o))));
    }

    //Priors on deviations in selectivity parameters
    for(j=1;j<=2;j++)
    {
        if(sel_rwlk_std[j]!=0)prior[j]=0.5*
                    norm2(first_difference(lh1_dev(j))/sel_rwlk_std[j]);
        if(sel_rwlk_std[j]!=0)prior[j]+=0.5*
                    norm2(first_difference(shp1_dev(j))/0.25*sel_rwlk_std[j]);
    }

    func=sum(loglik)+sum(prior);
    cout<<sum(prior)<<endl;

//****************************CALLED FUNCTIONS***************************
//Return Selectivity curve_____________________________________________________
FUNCTION dvar_vector selectivity(dvariable g, dvariable h, dvariable
g2, dvariable h2,dvector x)
    //Dome shaped selectivity option when g2>0
    {
        dvar_vector sel;
        if(g2!=0){
            sel = pow(elem_prod(1.+exp(-g*(x-h)),1.+exp(g2*(x-h2))),-1);
        }else{
            sel=1./(1.+exp(-g*(x-h)));
        }
        sel/=max(sel);
        return sel;
    }

//_______________________________________________________________________
FUNCTION dvector pearson_residuals(long m, dvector obs_p, dvector
pred_p)
    {
        obs_p/=sum(obs_p);
        pred_p/=sum(pred_p);

        dvector var=elem_prod(pred_p,(1.-pred_p))/m;
        dvector r=elem_div(obs_p-pred_p,sqrt(var));
        return(r);
    }
```

```
//==============================================================================

RUNTIME_SECTION
  convergence_criteria 1.e-4 1.e-9 1.e-15 1.e-15
  maximum_function_evaluations 500 1000 2000 2000


REPORT_SECTION
    report<<"#Years"<<endl<<yrs<<endl;
    report<<"#Age"<<endl<<age<<endl;
    report<<"#Fish_sel"<<endl<<fsh_sel<<endl;
    report<<"#Pearson residuals"<<endl;
    for(int j=1;j<=2;j++){
        for(int i=syr;i<=nyr;i++){
            report<<pearson_residuals(long(fsh_multn(j)),
                    value(fsh_p(j)(i)),value(pred_fsh_p(j)(i)))<<endl;
        }}

    report<<"Age-2 recruits"<<endl<<exp(log_recruits)<<endl;
    report<<"F"<<endl<<f<<endl;
    report<<"Negative Log Likelihoods"<<endl<<loglik<<endl;
    report<<"Predicted survey indices"<<endl<<pred_sur_yt<<endl;


    if(last_phase()) write_par_rep();


FUNCTION write_par_rep
    //append selected parameters for repeated simulations
    ofstream rep("ParDevs.rep",ios::app);
    rep<<m<<lh1<<shp1<<lh2<<shp2<<sur_q<<endl;


    ofstream rep2("lh1dev.rep",ios::app);
    rep2<<(lh1_dev(1)-true_lh1_dev(1))<<"   "
        <<(lh1_dev(2)-true_lh1_dev(2))<<endl;
```