Agenda Item E.3.a
Attachment 1
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Assessment and Management advice for Pacific hake in U.S. and Canadian waters in 2010

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- Corrections sent in on January 26, 2010
-STAR Panel Feb 8-10, travel on Feb 7
-Revise document and produce projections and decision table for SSC, Feb 11, 2010
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Contents

Executive summary

Stock

This assessment reports the status of the coastal Pacific hake (or Pacific whiting, *Merluccius productus*) resource off the west coast of the United States and Canada. Smaller populations of hake occur in the major inlets of the northeast Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California. However, the coastal stock is distinguished from the inshore populations by larger body size and seasonal migratory behavior. The coastal population is modeled as a single stock, and the landings data from the United States and Canadian fishing fleets are combined.

Catches

Combined US and Canadian Catches for Pacific hake have averaged 221.7 thousand metric tons (mt) from 1966 to 2008. Recent coast wide landings have been above the long-term average with 297mt and 322mt taken in the 2007 and 2008 fisheries. The Optimal Yield for the 2009 fishery was 184,000 mt and the total U.S. and Canadian combined landings was 176,671 mt; this is roughly 96% of the 2009 OY (Table c).

Data and assessment

This assessment uses a model known as TINSS, which is an age-structured assessment model that directly estimates management variables C^* (the maximum sustainable yield) and F^* (the fishing mortality rate that produces C^*). The model was implemented in the AD Model Builder software and is based on the methods in Martell et al. (2008). The structural assumptions are similar to that of Stock Synthesis (SS) model that is used by the National Marine Fisheries Service: a Beverton-Holt stock recruitment relationship is assumed, it is assumed that the population was at an unfished state in 1966, and the model is conditioned on historical catch information. The data for TINSS was extracted from the input files use for Stock Synthesis and the catch and catch-age information from U.S. and Canadian fisheries are aggregated into a single fishery. The selectivity curve for this aggregate fishery is assumed to be asymptotic and follows a logistic distribution. I also assume logistic selectivity curve for the fisheries independent acoustic trawl survey where the age-at-50% vulnerability is fixed at 2.0 years and the standard deviation is 0.45 years. In contrast to previous assessments, this assessment attempts to reduce the amount of prior information on key population parameters and subjective weighting of data that ultimately defines the catch advice. Model parameters were estimated using both maximum likelihood methods and Bayesian methods. Catch advice is based on a Bayesian view of the model parameters, where the joint posterior distribution was constructed using the Metropolis Hastings algorithm that is built into the ADMB software (version 9.0 downloaded from `http://admb-project.org/downloads`).

There was a substantial change in the likelihood kernel used for the age-composition data between the assessments Martell (2008) and Martell (2009). In the Martell (2008) assessment, a robust normal approximation to the multinomial distribution was used as the likelihood for the age composition data. This is the same likelihood function that is used in Multifan CL (see Fournier et al., 1990; Martell et al., 2008). In the Martell (2009) assessment I adopted a less subjective

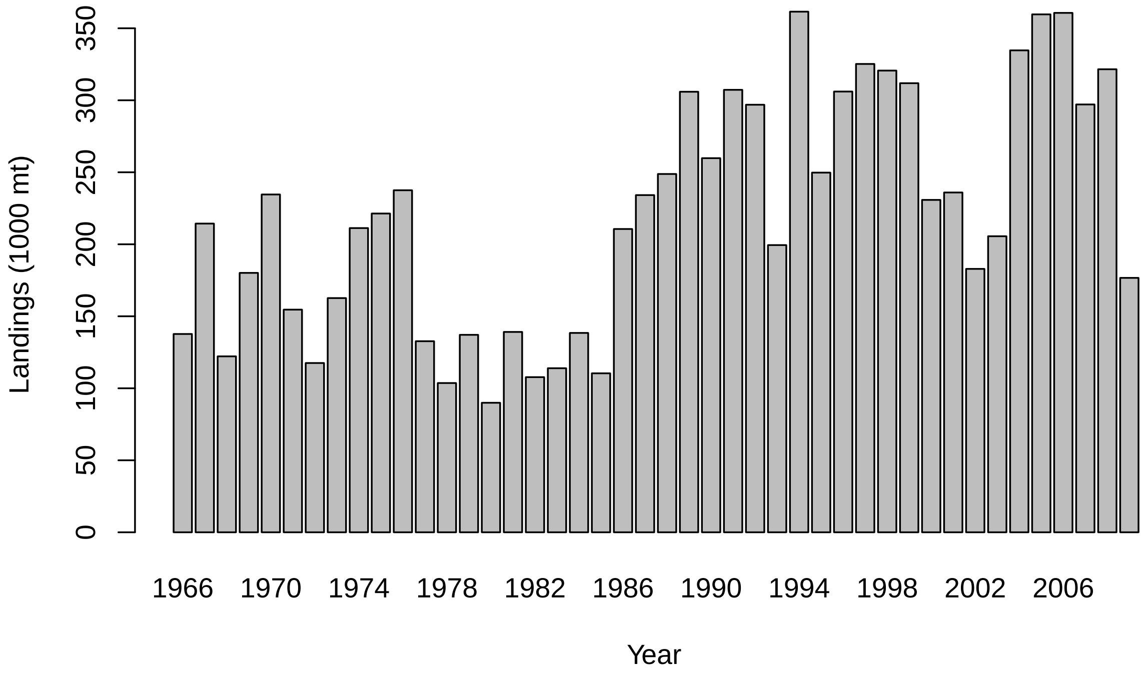

Figure a: Total combined US and Canadian Pacific hake landings between 1966 and 2009 used in the stock assessment model.

approach and used the multivariate logistic kernel (see Richards and Schnute, 1998) where the conditional maximum likelihood estimate of the variance was used to weight the age-composition data in the commercial fishery samples. The age composition data from the acoustic survey samples were given zero weight based on recommendations from the 2010 STAR panel.

Catch advice for the 2010 fishery is extremely sensitive to the 2009 acoustic biomass survey data point. Removing the 2009 survey data point from the assessment lowers the 2010 ABC estimate by almost 50%. The 2009 acoustic biomass survey is highly suspect due to the large abundance of humboldt squid present during the course of the survey; as such the STAR panel felt that this survey may have a different Q based on post processing of the data. For this years assessment the STAR panel recommended that the 2009 survey biomass estimate be omitted from the statistical fitting criterion.

Reference points

Three different reference points are provided in this assessment: reference points based on maximum sustainable yield calculations, reference points based on reducing spawning stock biomass to 40% of its unfished state, and reference points based on reducing the spawning potential ratio to 40%. The median unexploited equilibrium female spawning stock biomass SB_o is estimated at 1.931 million mt, with a 95% credible interval of 1.411-2.88 million mt. The median estimate of total biomass between the ages of 1 and 15+ years is 4.868 million mt with a 95% credible interval of 3.456-7.496 million mt. The median estimate of unfished age-1 recruits is 3.145 billion (95% credible interval of 1.84-5.779 billion).

MSY based reference levels

Management reference points based on maximum sustainable yield (MSY based reference points) result in a median estimate of female spawning stock biomass SB_{msy} of 773,000 mt with a long term equilibrium yield of 301,000 mt (Table h). The resulting spawning potential ratio is 0.53 , which is considerably higher than the normal proxy level of 0.4. Also, the exploitation fraction, which is defined as the catch divided by the age-3+ biomass, is 0.267 .

$\text{SB}_{40\%}$ proxy

Using 40% of the unfished spawning stock biomass as a management target results in similar reference point estimates as the MSY reference levels. The target spawning stock biomass is 773,000 mt, and the corresponding spawning potential ratio is 0.54 . The long-term equilibrium yield and exploitation fractions are estimated at 300,000 mt and 0.265 , respectively (Tbale h).

$\text{SPR}_{40\%}$ proxy

Management targets based on reducing the spawning potential ratio to 40% of its unfished state are much more aggressive in comparison to the estimated MSY and $\text{SB}_{40\%}$ policies (see comparison in Figure b). In this case the median estimate of target spawning stock biomass is 412,000 mt when the spawning potential ratio is reduced to 0.4. In order to achieve such a reduction the exploitation fraction is 0.498 and the corresponding yield is 266,000 mt. In short, the estimated

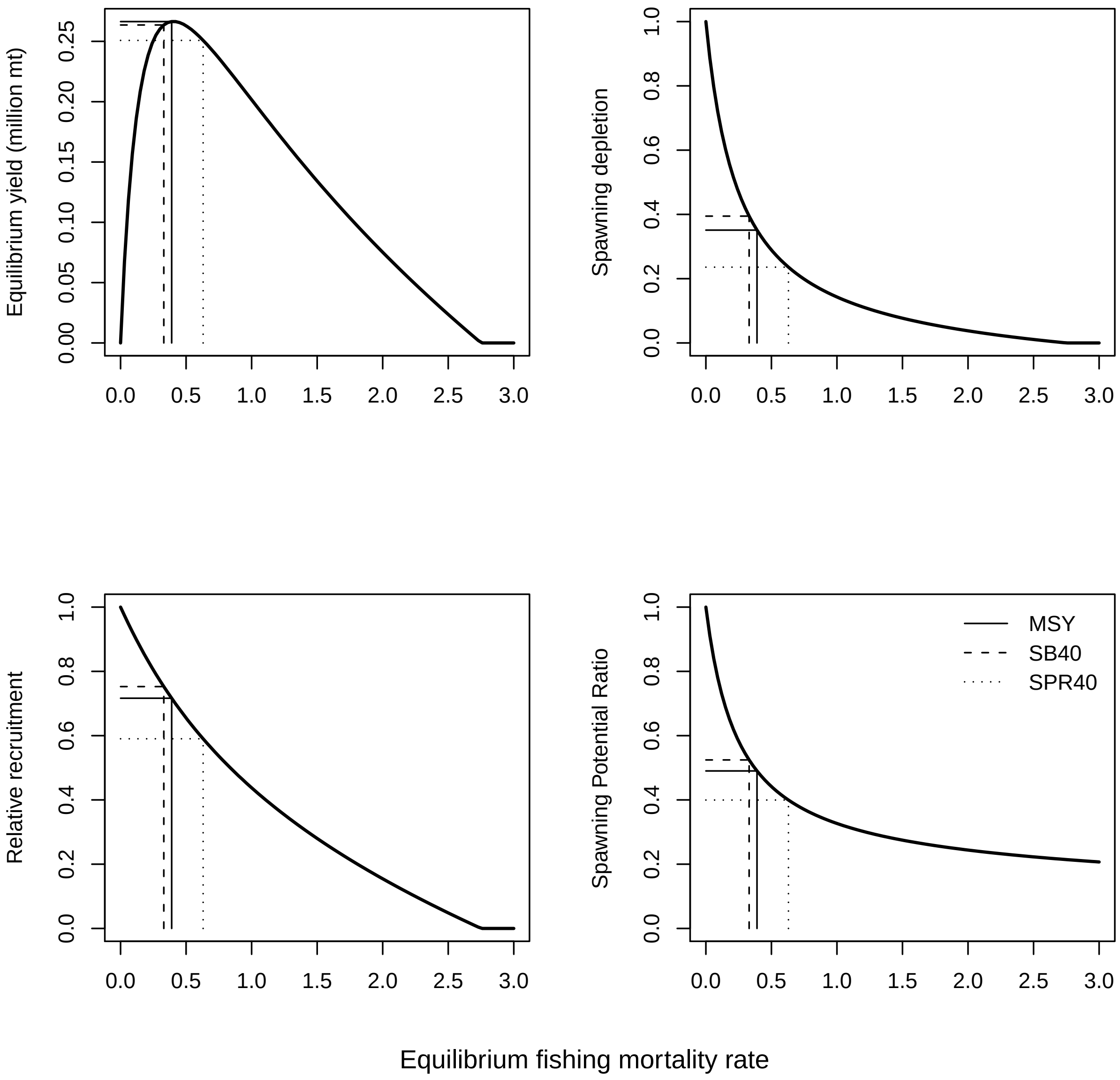

Figure b: Relationship between equilibrium fishing mortality rate and yield, recruitment, spawning biomass depletion and spawning potential ratio for Pacific hake based on maximum likelihood estimates of model parameters. Vertical and horizontal lines correspond to reference points based on MSY, SB_{40} and SPR_{40} management targets.

selectivity curve is such that a large fraction of age-2 to age-4 fish have a chance to spawn before the recruit to the fishing gear; therefore, very high fishing mortality rates are required to reduce the spawning potential ratio to 0.4.

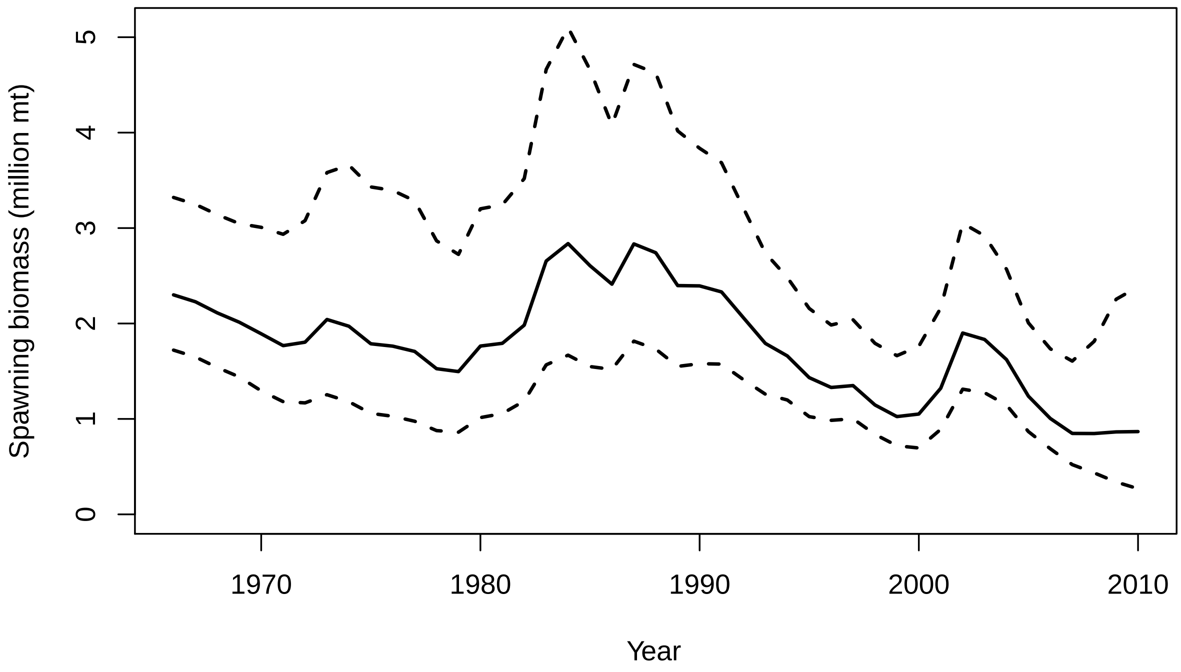

Figure c: Median estimates of female spawning stock biomass with 95% credible intervals.

Stock biomass

Median estimates of spawning stock biomass were relatively stable between 1966 and 1980, followed by and increase in the mid 1980s that was associated with the strong 1980 and 1984 year classes. Since the late 1980s, trends in spawning stock biomass declined to a low in 2000, then rapidly increased as the strong 1999 cohort became sexually mature (Figure c). By 2002, the estimated median spawning stock biomass rebuilt to near unfished levels (Table a). Current estimates of depletion for the beginning of the 2010 fishery is 38% and the 95% credible interval ranges between 17% and 73%.

Recruitment

Median estimate of historical age-1 recruits for Pacific hake indicate very large cohorts for the 1977, 1980, 1984, and 1999 year classes. In addition to the extremely large cohorts, above average age-1 recruitment events also occurred in 1971, 1974, 1987, and 1991. With the exception of the 1999 year class recruitment in the last 10 years has been below the long-term mean and recruitment in 2008 and 2009 is estimated to be below the long-term median (Figure e). The strongest cohort since 2000 appears to the the 2005 year class, and in the 2009 survey this year

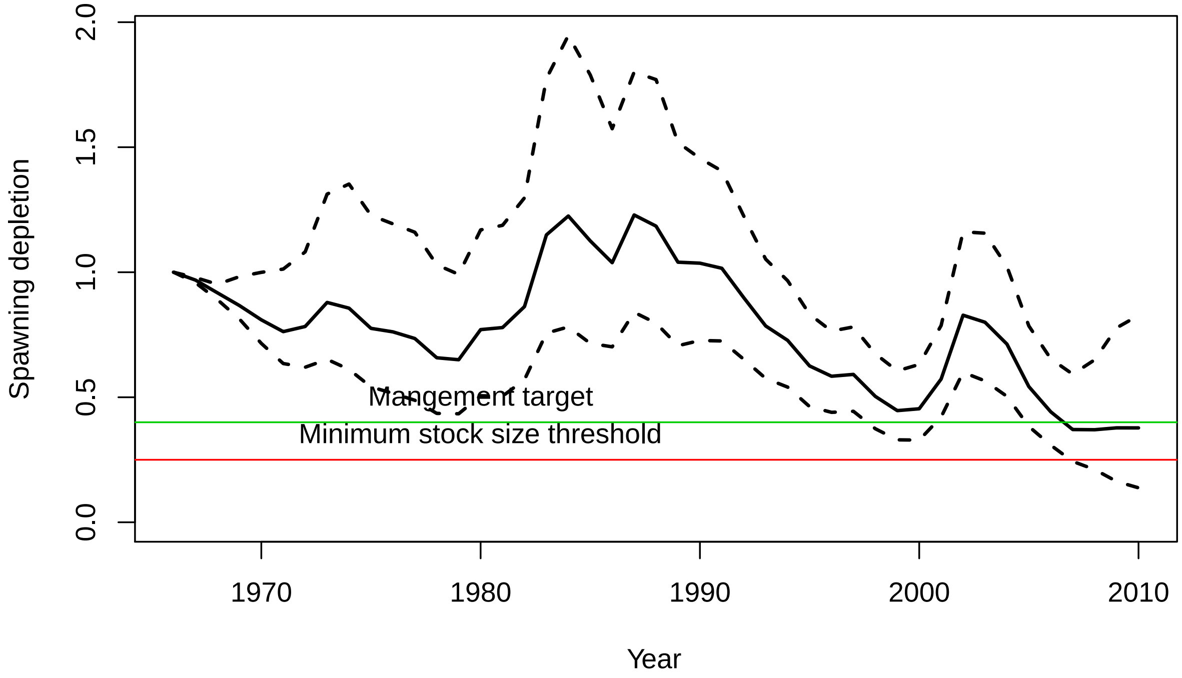

Figure d: Median estimates of spawning stock depletion with 95% credible intervals. Management target and minimum stock size thresholds are defined as 40% and 25% of the unfished spawning stock biomass.

Table a: Recent trends in estimated female spawning stock biomass (million mt) and depletion level based on 5000 systematic samples from the joint posterior distribution.

	Female biomass			**Depletion**		
Year	median	5%	95%	median	5%	95%
2001	1.31	0.95	1.98	0.57	0.44	0.75
2002	1.89	1.39	2.83	0.83	0.63	1.10
2003	1.83	1.34	2.71	0.80	0.59	1.09
2004	1.62	1.21	2.40	0.71	0.53	0.97
2005	1.24	0.92	1.86	0.54	0.41	0.74
2006	1.00	0.72	1.59	0.44	0.33	0.61
2007	0.85	0.56	1.45	0.37	0.26	0.55
2008	0.85	0.48	1.61	0.37	0.23	0.59
2009	0.87	0.39	1.89	0.38	0.19	0.70
2010	0.87	0.34	1.99	0.38	0.17	0.73

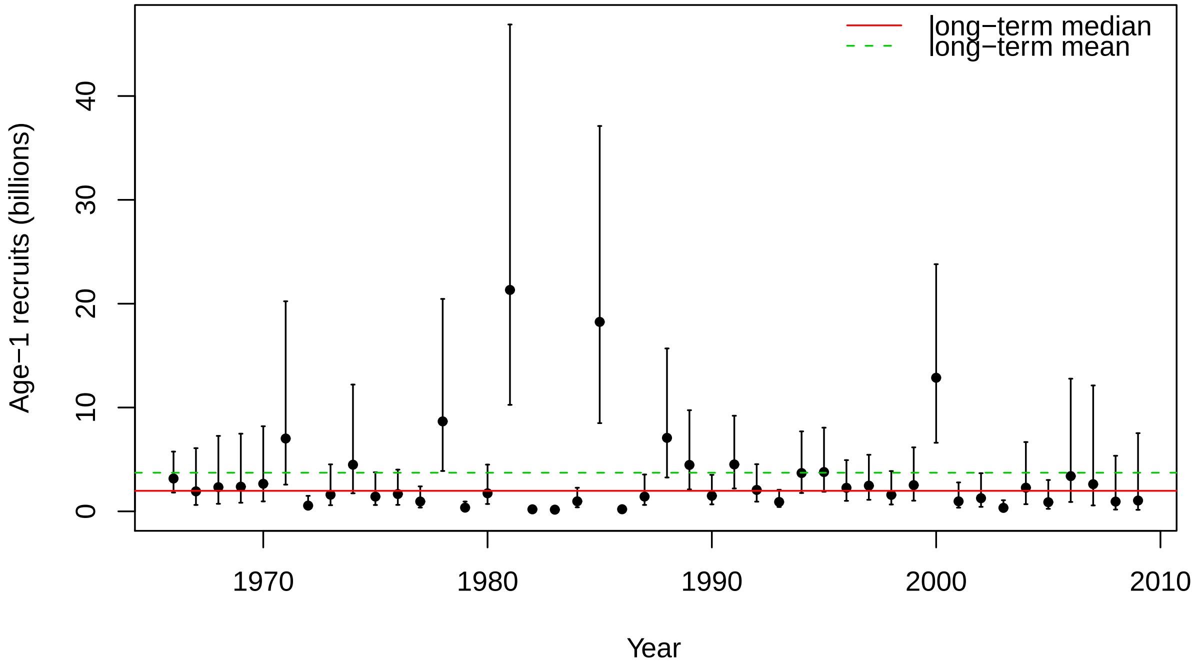

Figure e: Median estimates of age-1 recruits and associated 2.5% and 97.5% quantiles (vertical bars) based on 5000 systematic samples from the joint posterior distribution. Long-term average and median recruitments are shown by the horizontal lines.

class made up roughly 45% of individuals ages-2 to age 15+, followed by 31% of the 2006 year class. The 1999 year class, now age-10, is a mere 7.85% of the total numbers-at-age in the acoustic survey data. The median estimate of unfished age-1 recruits is 3.145 billion , and in the last 10 years median estimates have ranged between 0.34 billion in 2003 to 12.87 billion in 2000 (Table b).

Exploitation status

Trends in the spawning potential ration has been well below the target SPR (based on MSY reference points where SPR$_{MSY}$ = 0.53 , Figure f). Since 2003 exploitation rates have increases and in the 2008 fishery were estimated to be above the target SPR exploitation rate. Large reductions for the 2009 OY appears to have changed the increasing trend in exploitation and is estimated to be slightly below the target value. There is a great deal of uncertainty in the estimate of absolute exploitation rates due to the large uncertainty in the over all population scale.

Another measure that has been previously used to measure exploitation status in the Pacific hake fishery is the exploitation fraction, which is defined here as the catch divided by the 3+

Table b: Recent estimated trends in age-1 recruits for Pacific hake. Quantiles are based on 5000 systematic samples from the joint posterior distribution.

	Age-1 recruits (billions)		
Year	median	2.5%	97.5%
2000	12.87	6.61	23.80
2001	0.97	0.36	2.79
2002	1.27	0.44	3.68
2003	0.34	0.11	1.07
2004	2.28	0.69	6.67
2005	0.88	0.24	3.02
2006	3.39	0.91	12.78
2007	2.62	0.57	12.12
2008	0.94	0.17	5.35
2009	1.04	0.15	7.53

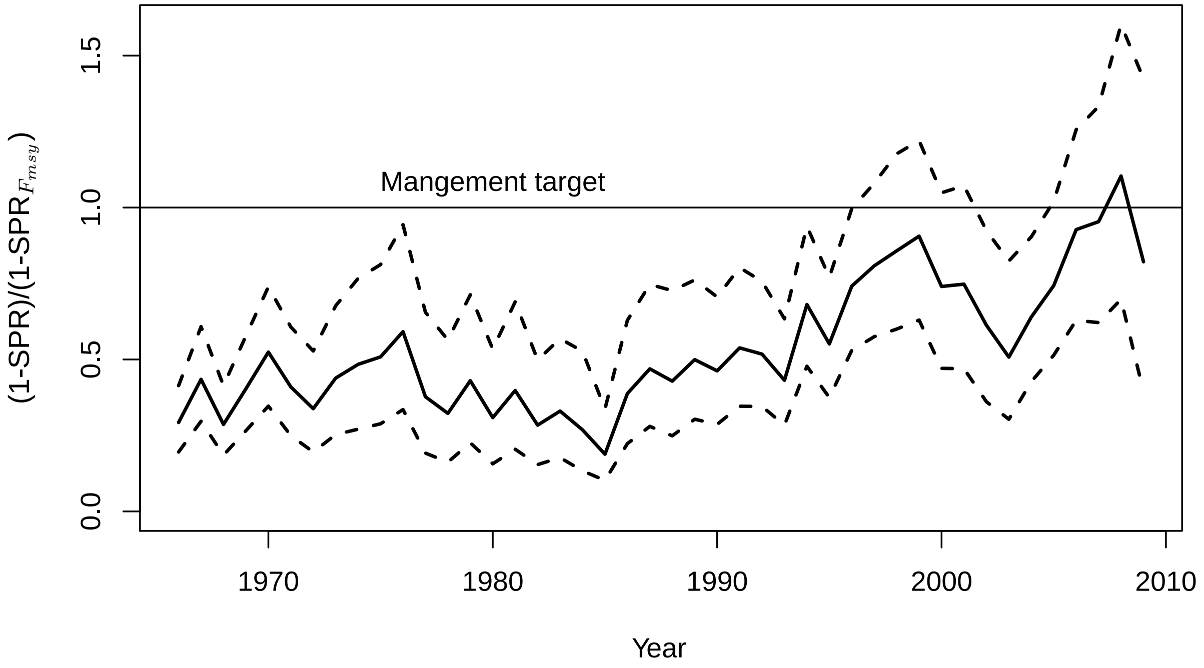

Figure f: Recent trends in median spawning potential ratio (solid line) relative to SPR at F^* and 95% credible intervals (dotted line). Note that the maximum likelihood estimate of SPR$_{MSY}$ = 0.53 .

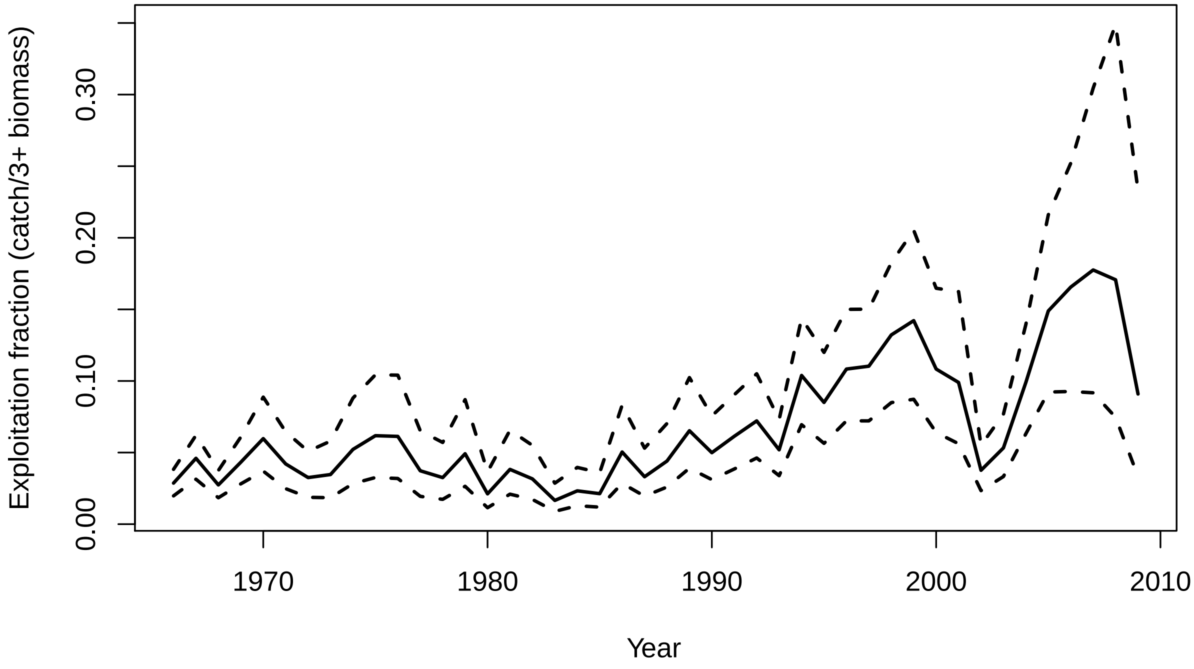

Figure g: Recent trends in the median exploitation fraction (catch divided by age 3+ biomass, solid line) with 95% credible intervals (dotted line).

biomass. Trends in the exploitation fraction (Figure g) mirror that of the SPR based mortality rates (Figure f).

The full history of fishing mortality relative to the fishing mortality based on F$_{msy}$ and trends in spawning stock biomass relative to SB$_{msy}$ is shown in Figure h. Median estimates of fishing mortality and spawning stock biomass are very near optimal levels based on MSY reference points. However, there is considerable uncertainty in the current status of the stock as shown by the contours in Figure h. The area of the “fried egg” in each quadrant is roughly proportional to the probability that the stock is below $\mathrm{SB}_{\mathrm{MSY}}$ ($<$ 0.5 probabliity) and that fishing mortality exceeds F^* ($<$0.5 probability).

Management performance

A treaty between the United States and Canada has been in place since 2003, but is not fully implemented, establishes that U.S. and Canadian shares of the coast-wide allowable biological catch ABC) at 73.88% and 26.12%, respectively. Since the late 1970s annual quotas have been the primary management tool in place to limit catch of Pacific hake by foreign and domestic fisheries. In the past 10 years catches have been below the coast-wide ABC (Table c) and only in

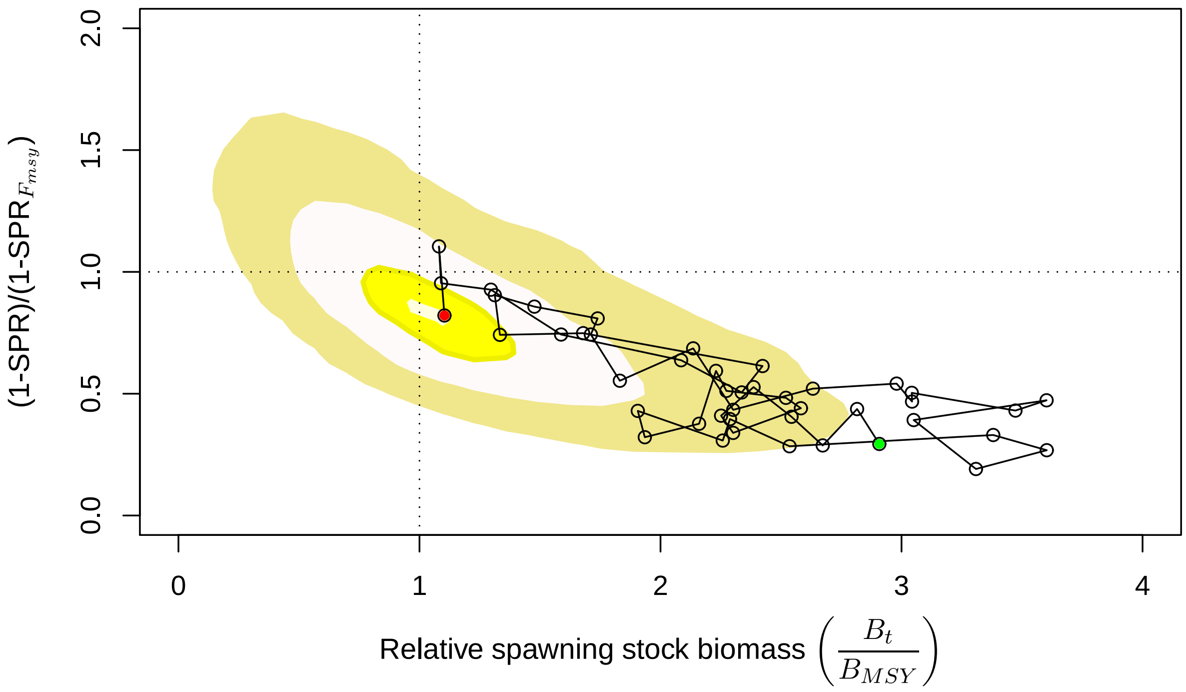

Figure h: Phase plot of the median relative fishing intensity versus the median relative spawning stock biomass. Contour levels (2.5%, 25%, 75%, and 97.5%) represent the uncertainty in 2009 .

2002 did the catch exceed optimal yields (OY) by 12.9%. In the past 3 years failures to obtain the full OY have been due to by-catch limits in the U.S. fisheries and fish not showing up in the traditional fishing grounds in Canadian waters. Note also that management in the Canadian zone permits annual carry overs if there is left over quota in the following fishing season; therefore the statistics in Table c may also have landings $>$ than OY due to the carry over.

Table c: Recent trend in Pacific hake management performance.

Year	Landings	OY (mt)	ABC (mt)	Landings/OY (%))
2000	230,820	290,000	290,000	79.6
2001	235,962	238,000	238,000	99.1
2002	182,911	162,000	208,000	112.9
2003	205,582	228,000	235,000	90.2
2004	334,672	501,073	514,441	66.8
2005	359,661	364,197	531,124	98.8
2006	360,683	364,842	661,680	98.9
2007	297,098	328,358	612,068	90.5
2008	321,546	364,842	400,000	88.1
2009	176,671	184,000	254,000	96.0

Forecasts

Forecasts are generated by applying the 40:10 harvest control rule to the maximum likelihood results. It is assumed that the estimated coast wide selectivity curve corresponds to the U.S.–Canada allocation agreement of 73.88% and 26.12%. Two alternative overfishing limits/targest were explored in generating stock forecasts: 1) an $F_{40\%}$ policy where the target fishing mortality rate reduces the spawning potential ratio to 40% of its unfished state, and 2) and F_{msy} (or F^*) policy where the target fishing mortality rate maximizes long-term sustainable yield (Table d). Note that estimates of $F_{40\%}$ are greater than estimates of F_{msy} (see Figure b).

Maximum likelihood catch options based on the 40:10 harvest control rule and the $F_{40\%}$ target start at 415,000 mt in 2010 which results in an estimated depletion level of 20% in 2011. Catch options based on the 40:10 adjustment and the F^* target start at 249,000 mt and result in a projected depletion level of 24% in 2011. With no strong year-classes recruiting to the fishery in the next few years (the 2005 year class is currently estimated to be below the long-term mean), projected spawning biomass are anticipated to decline even with relatively small OY's for the 2010 fishery.

Decision table

Catch streams for the decision table are based on the 40:10 harvest control rule using median values of F$_{40\%}$ reference point and the less conservative F^* reference point (see rows 1–3 and 4–6 in Table e, respectively). Alternative constant catch streams of 100,000, 150,000, 184,000, 235,000, 339,000, and 400,000 are also provided for comparison. The results in Table e are interpreted as

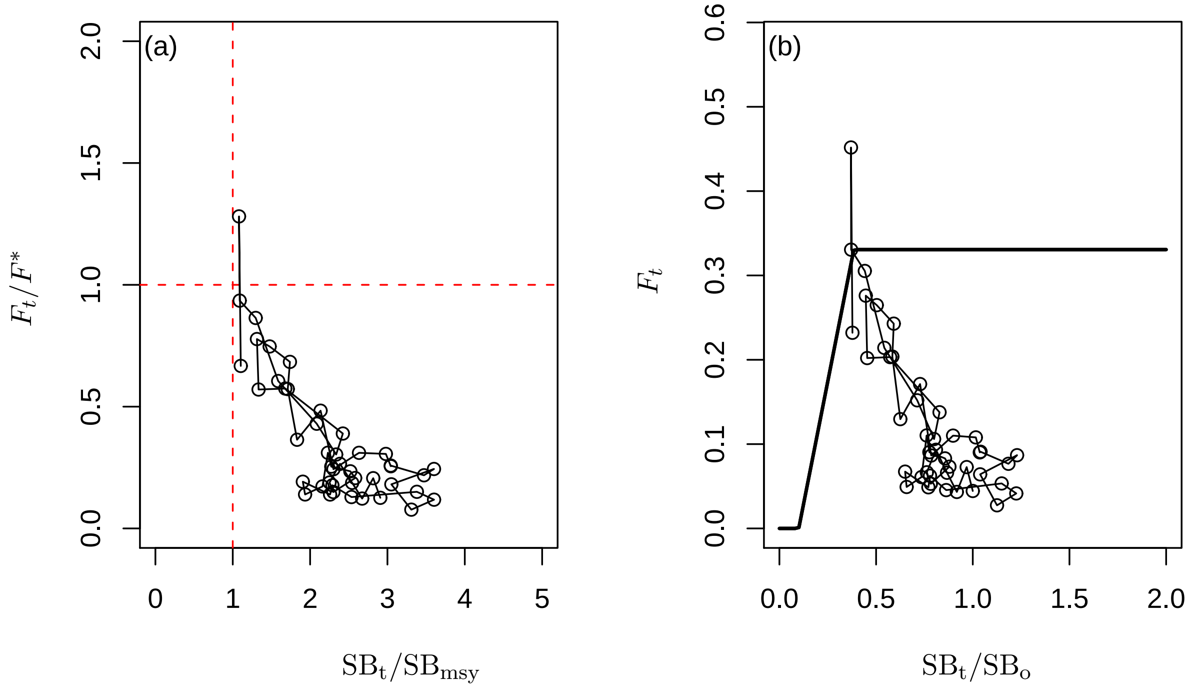

Figure i: Median estimates of the spawning stock biomass relative to the unfished spawning stock biomass versus the fishing mortality rate relative to F^* (a). In panel (b) the inferred 40:10 harvest control rule (thick line) based on the maximum likelihood estimate of F^* and the spawning stock biomass depletion levels versus median estimates of historical fishing mortality rates.

Table d: Three year projections of maximum likelihood-based Pacific Hake ABC, OY, female spawning biomass, spawning biomass depletion level, and relative SPR values based on the 40:10 harvest control rule with F_{40} (top three rows) and F^* (bottom three rows) overfishing targets.

Year	ABC	OY	SBt	Depletion	(1-SPR)/(1-SPR$_{Target=40}$)	(1-SPR)/(1-SPR$_{F_{msy}}$)
2010	415731	362912	1.17	0.29	0.98	1.24
2011	282972	191902	0.82	0.20	0.88	1.11
2012	235449	140541	0.73	0.18	0.84	1.06
2010	249148	217494	1.17	0.29	0.78	0.98
2011	207567	162360	0.98	0.24	0.73	0.92
2012	180878	132097	0.89	0.22	0.71	0.89

follows: given a 2010 OY of 150,000 mt the projected median estimate (50th percentile) of female spawning stock biomass in 2011 is 0.81 million mt, which corresponds to a depletion level of 35% and a projected SPR value of 0.49 relative to the SPR$_{40\%}$ target level. Catch advice greater than 100,000 mt results in further declines in projected female spawning stock biomass. Uncertainty in projected spawning stock biomass is large with estimated depletion levels of $<$20% at the 5th percentile and greater than 50% at the 95th percentile.

The default proxy of SPR$_{40\%}$ for maximum sustainable yield for Pacific hake is estimated to be less conservative from a fishing mortality perspective. Equilibrium yields are estimated to be maximized (i.e., MSY) at SPR values of 0.53, which corresponds to the F^* harvest policy, with a much more conservative overfishing/target fishing mortality rate. Relative spawning potential ratios for the alternative catch options under the SPR$_{40\%}$ proxy and F^* policies are shown in Table f.

Research and data needs

There are still some unresolved problems that seriously impede the stock assessments each year:

- Insufficient time to adequately review and analyze the assessment data before the STAR panel meeting; this has occurred in the past two years due to the protracted length of the fishery.
- Insufficient contrast in the acoustic survey data to clearly resolve the tradeoff between productivity and population scale (see Appendix C).
- Most recent acoustic biomass survey may be contaminated (biased upwards) due to the large quantities of humboldt squid (*Dosidicus gigas*) present during the survey. Currently there is no way to distinguish hake from humboldt squid using acoustics. An informative prior for the scaling parameter (q) in the 2009 survey will be required in future assessments if this point is to be used in future assessments.
- Acoustic survey selectivity is highly uncertain and confounded with estimates of C^* and M. This years STAR panel felt the age-composition data from the acoustic survey are biased and should not be used in the assessment. This is consistent with the high conditional maximum likelihood estimates of the variance in the residuals for the acoustic survey age comps in comparison to the fishery age-comps.
- There is insufficient time between the finalizing of stock assessment data and preparing stock assessment documents and catch advice (less than 10 days this year). This short time frame leads to rushed assessments that are more prone to error.
- 2009 mean weight-at-age data is needed to properly update this assessment.

Summary table

A summary of the Pacific hake reference points based on the joint posterior distribution is provided in Table h. Note that biomass based reference points are based on the most recent estimates of weights-at-age.

Table e: Decision table with three year projections of posterior distributions for Pacific hake female spawning stock biomass, depletion, and relative spawning potential ratio (1-SPR)/(1-SPR$_{Target=0.4}$; values $>$ 1 denote overfishing). Catch streams from 2010 to 2012 are based 1) on the 40:10 harvest control rule and median values of F$_{40\%}$, 2) median values of F^* and the 40:10 harvest control rule, and 3) arbitrary constant catch levels of 100,000, 150,000, 184,000, 235,000, 339,000, and 400,000 mt.

Coast wide catch (mt)		Female spawning biomass (million mt)					Spawning depletion (SB_t/SB_o)					Relative SPR (1-SPR)/(1-SPR$_{Target=40}$)				
Year	OY	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
2010	617700	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.80	0.98	1.02	1.05	1.09
2011	281900	0.29	0.41	0.54	0.72	1.13	0.14	0.19	0.23	0.30	0.43	0.66	0.85	0.94	1.00	1.07
2012	193100	0.26	0.36	0.46	0.61	0.96	0.12	0.16	0.20	0.25	0.38	0.53	0.78	0.89	0.99	1.09
2010	341900	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.53	0.69	0.78	0.86	0.97
2011	254700	0.33	0.51	0.69	0.95	1.55	0.16	0.23	0.30	0.39	0.57	0.51	0.65	0.74	0.83	0.94
2012	201100	0.30	0.46	0.61	0.84	1.36	0.15	0.21	0.26	0.34	0.50	0.47	0.63	0.73	0.82	0.94
2010	100000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.17	0.28	0.37	0.49	0.74
2011	100000	0.32	0.58	0.84	1.17	1.94	0.16	0.27	0.36	0.48	0.71	0.16	0.26	0.35	0.48	0.75
2012	100000	0.31	0.57	0.82	1.16	1.92	0.15	0.26	0.36	0.47	0.71	0.16	0.27	0.36	0.49	0.76
2010	150000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.25	0.38	0.49	0.64	0.90
2011	150000	0.29	0.56	0.81	1.14	1.91	0.15	0.25	0.35	0.47	0.70	0.23	0.37	0.49	0.65	0.96
2012	150000	0.26	0.52	0.77	1.12	1.87	0.12	0.24	0.33	0.45	0.69	0.24	0.39	0.52	0.69	1.02
2010	184000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.29	0.44	0.56	0.72	0.98
2011	184000	0.27	0.54	0.79	1.13	1.89	0.14	0.25	0.34	0.46	0.69	0.28	0.44	0.57	0.75	1.08
2012	184000	0.22	0.49	0.74	1.08	1.84	0.11	0.22	0.32	0.44	0.68	0.29	0.46	0.61	0.80	1.17
2010	235000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.35	0.52	0.66	0.82	1.08
2011	235000	0.24	0.51	0.76	1.10	1.86	0.12	0.23	0.33	0.45	0.68	0.34	0.53	0.68	0.87	1.23
2012	235000	0.16	0.44	0.69	1.04	1.80	0.08	0.20	0.30	0.42	0.66	0.36	0.56	0.74	0.95	1.40
2010	339000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.46	0.66	0.80	0.96	1.22
2011	339000	0.18	0.45	0.71	1.04	1.81	0.09	0.21	0.31	0.42	0.66	0.46	0.69	0.86	1.07	1.63
2012	339000	0.02	0.34	0.59	0.94	1.74	0.01	0.15	0.25	0.38	0.63	0.49	0.75	0.95	1.21	1.66
2010	400000	0.34	0.60	0.86	1.20	1.99	0.17	0.28	0.37	0.49	0.73	0.52	0.72	0.86	1.02	1.29
2011	400000	0.15	0.42	0.67	1.00	1.77	0.07	0.19	0.29	0.41	0.64	0.52	0.77	0.95	1.18	1.66
2012	400000	0.00	0.28	0.54	0.89	1.74	0.00	0.13	0.23	0.36	0.62	0.56	0.84	1.06	1.37	1.66

Table f: Decision table for relative spawning potential ratios with three year projections using two alternative SPR reference points. Note that the maximum likelihood estimate for the Spawning Potential Ratio when fishing at F_{msy} is 0.53.

Coast wide catch (mt)		Relative SPR (1-SPR)/(1-SPR$_{F_{msy}}$)					Relative SPR (1-SPR)/(1-SPR$_{Target=40}$)				
Year	OY	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
2010	617700	0.94	1.16	1.31	1.47	1.80	0.80	0.98	1.02	1.05	1.09
2011	281900	0.82	1.06	1.20	1.36	1.64	0.66	0.85	0.94	1.00	1.07
2012	193100	0.69	0.97	1.14	1.32	1.63	0.53	0.78	0.89	0.99	1.09
2010	341900	0.76	0.98	1.04	1.07	1.15	0.53	0.69	0.78	0.86	0.97
2011	254700	0.72	0.91	0.99	1.04	1.11	0.51	0.65	0.74	0.83	0.94
2012	201100	0.67	0.87	0.97	1.04	1.13	0.47	0.63	0.73	0.82	0.94
2010	100000	0.23	0.36	0.49	0.65	0.98	0.17	0.28	0.37	0.49	0.74
2011	100000	0.22	0.34	0.47	0.63	0.97	0.16	0.26	0.35	0.48	0.75
2012	100000	0.22	0.35	0.48	0.64	1.00	0.16	0.27	0.36	0.49	0.76
2010	150000	0.33	0.50	0.65	0.84	1.19	0.25	0.38	0.49	0.64	0.90
2011	150000	0.31	0.49	0.65	0.85	1.25	0.23	0.37	0.49	0.65	0.96
2012	150000	0.32	0.51	0.68	0.89	1.33	0.24	0.39	0.52	0.69	1.02
2010	184000	0.39	0.58	0.74	0.94	1.30	0.29	0.44	0.56	0.72	0.98
2011	184000	0.37	0.58	0.75	0.97	1.40	0.28	0.44	0.57	0.75	1.08
2012	184000	0.39	0.61	0.80	1.04	1.53	0.29	0.46	0.61	0.80	1.17
2010	235000	0.47	0.69	0.86	1.06	1.43	0.35	0.52	0.66	0.82	1.08
2011	235000	0.46	0.70	0.90	1.14	1.62	0.34	0.53	0.68	0.87	1.23
2012	235000	0.48	0.74	0.96	1.24	1.83	0.36	0.56	0.74	0.95	1.40
2010	339000	0.61	0.86	1.05	1.25	1.65	0.46	0.66	0.80	0.96	1.22
2011	339000	0.62	0.90	1.13	1.40	2.01	0.46	0.69	0.86	1.07	1.63
2012	339000	0.66	0.98	1.24	1.60	2.25	0.49	0.75	0.95	1.21	1.66
2010	400000	0.68	0.94	1.13	1.34	1.75	0.52	0.72	0.86	1.02	1.29
2011	400000	0.70	1.00	1.24	1.54	2.17	0.52	0.77	0.95	1.18	1.66
2012	400000	0.75	1.09	1.38	1.79	2.37	0.56	0.84	1.06	1.37	1.66

Table g: Summary of recent trends in Pacific hake exploitation and stock levels.

Quantity	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Coast wide landings (mt)	235,962	182,911	205,582	334,672	359,661	360,683	297,098	321,547	176,730	NA
ABC (mt)	238,000	208,000	235,000	514,441	531,124	661,680	612,068	400,000	253,582	NA
OY (mt)	238,000	162,000	228,000	501,073	364,197	364,842	328,358	364,842	184,000	NA
Relative SPR										
(1-SPR)/(1-SPRfmsy)	0.75	0.61	0.51	0.64	0.74	0.93	0.95	1.1	0.82	
2.50%	0.48	0.36	0.3	0.42	0.5	0.63	0.6	0.69	0.4	
97.50%	1.05	0.91	0.81	0.9	1.01	1.26	1.32	1.57	1.39	
Vulnerable Biomass (million mt)	1.46	1.93	2.70	2.66	1.98	1.45	1.14	0.95	0.94	1.01
3+Biomass (million mt)	1.92	4.20	3.34	2.94	2.08	1.84	1.35	1.45	1.40	1.24
Spawning biomass (million mt)	2.08	2.61	3.78	3.65	3.25	2.48	2.01	1.7	1.69	1.75
2.50%	1.39	1.8	2.66	2.57	2.31	1.74	1.38	1.04	0.87	0.65
97.50%	3.49	4.38	6.18	5.92	5.25	4.11	3.58	3.28	3.62	4.4
Age-1 Recruits	12.97	0.96	1.24	0.33	2.25	0.86	3.44	2.61	0.93	1.06
2.50%	7.04	0.35	0.42	0.11	0.72	0.24	0.91	0.56	0.16	0.15
97.50%	24.32	2.68	3.77	1.06	6.77	2.94	12.06	11.92	5.36	7.81
Depletion	0.45	0.57	0.83	0.8	0.71	0.54	0.44	0.37	0.37	0.38
2.50%	0.33	0.42	0.6	0.57	0.5	0.38	0.31	0.24	0.21	0.16
97.50%	0.63	0.79	1.16	1.16	1.02	0.79	0.65	0.59	0.65	0.78

Table h: Summary of the Pacific hake reference points based 5000 samples from the joint posterior distribution. Reference points for MSY levels are based on the most recent estimates of growth.

Quantity	Median	2.5% percentile	97.5% percentile
-Unfished female SBo (million mt)	1.931	1.411	2.88
-Unfished total biomass	4.868	3.456	7.496
-Unfished 3+ biomass	4.048	2.952	6.062
-Unfished age-1 recruits (billions)	3.145	1.84	5.779
REFERENCE POINTS based on SB$_{40\%}$			
-MSY proxy female spawning biomass SB$_{40\%}$	0.773	0.564	1.152
-SPR resulting in SB$_{40\%}$	0.54	0.472	0.634
-Exploitation fraction (ct/Bt3) resulting in SB$_{40\%}$	0.265	0.197	0.358
-Yield with SB$_{40\%}$	0.3	0.208	0.469
REFERENCE POINTS based on SPR$_{40\%}$			
-Female spawning biomass at SPR$_{40\%}$	0.412	0.039	0.645
-SPR	0.4	0.4	0.4
-Exploitation fraction (ct/Bt3) resulting in SPR$_{40\%}$	0.498	0.349	0.841
-Yield with SPR$_{40\%}$	0.266	0.029	0.436
REFERENCE POINTS based on MSY			
-Female spawning biomass at MSY	0.773	0.504	1.234
-SPR at MSY	0.539	0.411	0.67
-Exploitation fraction (ct/Bt3) at MSY	0.267	0.172	0.418
-MSY	0.301	0.207	0.474

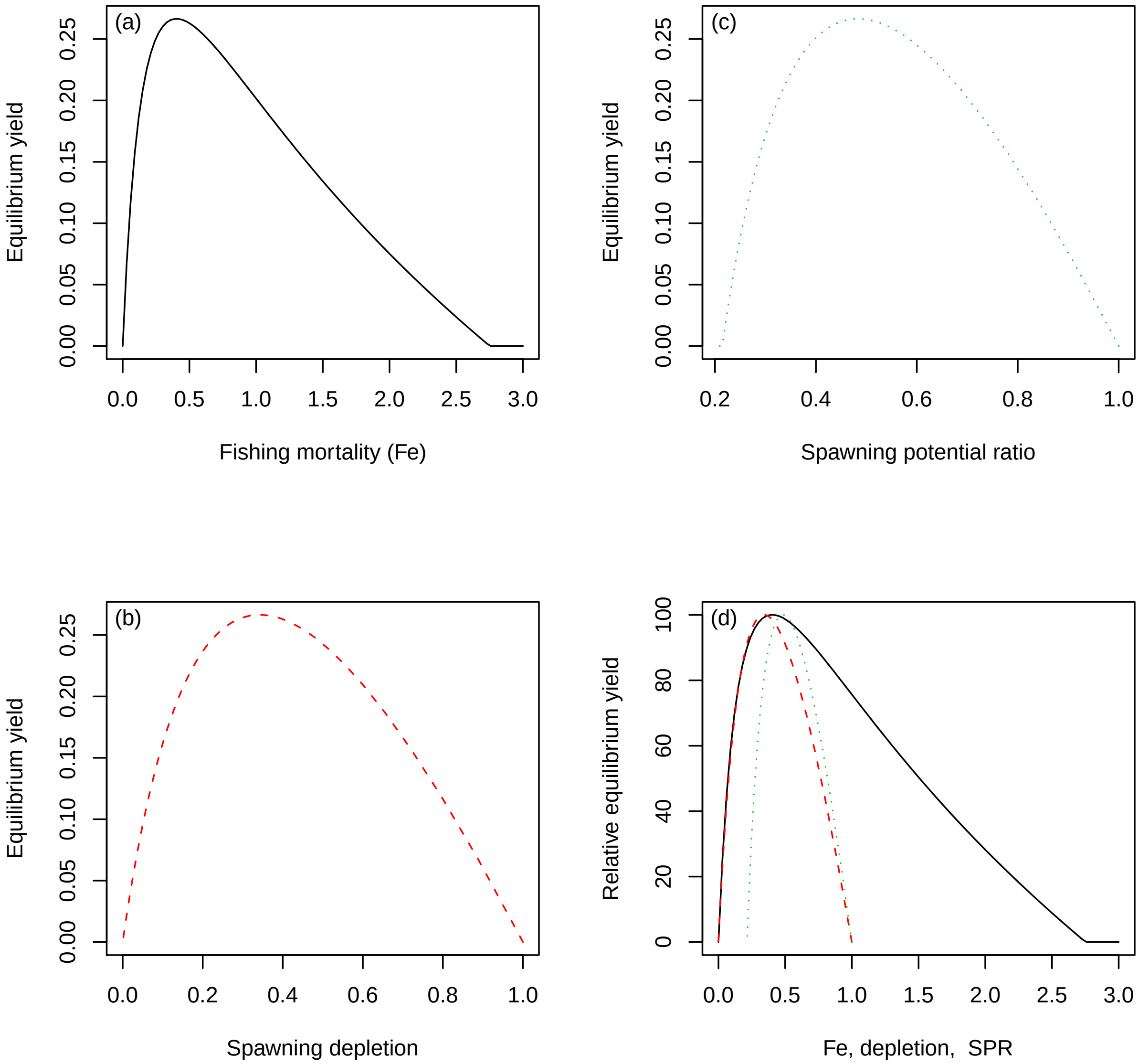

Figure j: Equilibrium yield curves versus instantaneous fishing mortality rate (a), relative depletion of spawning stock biomass (b), spawning potential ratio (c), and the relative equilibrium yields versus alternative performance measures (d). Note that F^* policy and the SB$_{40\%}$ policy result in similar maximum, whereas the SPR$_{40\%}$ policy would achieve roughly 20% of the maximum yield.

1 Introduction

1.1 Management

The Pacific hake (*Merluccius productus*) is a transboundary stock which is jointly managed by Canada and the USA. A treaty dealing with joint management was signed in 2003. The treaty specifies a number of committees and procedures for stock assessment and management. However, these are yet to be fully implemented. In the mean time, scientists from the USA and Canada have endeavored to continue the assessment process in the spirit of the treaty. In the current Pacific hake agreement, the United States is allocated 73.88% of the total coast-wide harvest and Canada 26.12% of the total coast-wide harvest.

1.2 Fishery

The directed Pacific hake fishery uses pelagic trawl gear to harvest fish and there is a small amount of hake by-catch taken in groundfish trawl fisheries. In Candian waters there has been a recent shift in the location of the fishery over the past 3 years to a more northerly location in Queen Charlotte Sound and in the Strait of Juan de Fuca in comparison to the traditional area off southwest Vancouver Island.

The following fisheries description was extracted from Stewart and Hamel (2010). Canadian Pacific hake catches were fully utilized in the 2005 fishing season with 85,284 mt and 15,178 mt taken by the domestic and joint venture fisheries, respectively. In 2006, the joint-venture and domestic fisheries harvested 13,700 mt and 80,000 mt, respectively. During the 2007 fishing season, Canadian fisheries harvested 85% of the 85,373 mt allocation. In 2008, Canadian fisheries harvested 78% of the 95,297 mt allocation with jointventure and domestic sectors catching 3,590 mt and 70,160 mt, respectively. During the 2009 season, no catches were made under joint-venture agreement. The Canadian domestic fishery harvested 55,620 mt in 2009, or 115.7% of the Canadian OY. DFO managers allow a 15% discrepancy between the quota and total catch. The quota may be exceeded by up to 15% in any given year, which is then deducted from the quota for the subsequent year.

The 2009 U.S. fishery caught 121,110 mt, or 89.1% of the U.S. OY. See Stewart and Hamel (2010) for more detailed description of the U.S. fishery in 2009 and previous years.

1.3 Problems with historical assessments

Previous assessments of Pacific hake (*Merluccius productus*) have been troubled by the lack of contrast in the acoustic survey data that allow for the estimation of the unfished biomass (B_o) and the steepness of the stock recruitment relationship. To cope with the lack of information in the acoustic survey data, the assessments have proceeded by fixing the value (h) of steepness for stock recruitment relationship and presented two alternative scenarios for the acoustic survey scaling parameter q. Fixing these parameters is necessary due to the lack of contrast in the acoustic survey data; however, it also results in a gross under-estimation of the uncertainty in model results and estimates of the reference points used in the determination of Acceptable Biological Catch (ABC).

At present, uncertainty in parameters that define the harvest control rule is only represented by the uncertainty associated with selectivity parameters in the various commercial fisheries as well as the acoustic survey itself. The parameters that define the underlying production function include the instantaneous natural mortality rate (M), the steepness of the stock recruitment relationship (h) and a measure of population scale (usually the unfished spawning stock size or B_o). In previous assessments, h and M are fixed, and the population scale is determined by the combined effects of selectivity in the acoustic survey and the survey scaler q (which is fixed at two different values). For example for a given value of q, estimates of the unfished biomass increase as the acoustic survey selectivity becomes more dome-shaped, and vice-versa.

Historically, management advice has been based on the application of the 40-10 harvest control rule. Three critical pieces of information were required to apply the harvest control rule: 1) an estimate of F_{MSY} and B_{MSY} which is approximated by F_{40} and B_{40}, respectively, 2) an estimate of the current level of depletion in the spawning stock biomass, and 3) a biomass forecast based on historical recruitment or the underlying stock recruitment relationship. Accurate estimates of F_{MSY} require accurate estimates of M and h, which are difficult to obtain in many (if not all) fisheries assessments; therefore a proxy F_{40} (which is the fishing mortality rate that reduces the spawning potential ratio to 40% of its unfished state) was used to approximate F_{MSY}. This approximation has been shown to achieve nearly 80% of the maximum yield over a wide range of stock recruitment parameters with a variety of stock recruitment models (Clark, 1991, 2002). Similarly, B_o was also difficult to estimate; therefore, the spawning potential ratio (SPR) is used as a measure of mortality rates. The current level of depletion is determined by comparing the ratio of present day spawning biomass to the estimated unfished spawning biomass. Finally, the forecast was based on current levels of depletion and estimates of h.

There are a few unresolved problems and inconsistencies in the input data for Stock Synthesis (SS) or any other age-structured model that incorporates the survey age-composition data. First there is a large inconsistency between information in the age-compositions and the acoustic survey biomass index. The age compositions suggest a buildup of biomass through the late 1980s owing to the strong 1980 and 1984 cohorts, yet the biomass index is relatively flat during this time period. Furthermore, (Helser et al., 2008) documented a clear contradiction in the age-composition information between the US, Canadian and Fisheries independent surveys. Each of these independent data sets contradict each other in terms of information content with respect to estimated model parameters in the assessment model that was used in 2008.

In contrast to previous assessments for Pacific hake, this assessment attempts to reduce the amount of prior information that is used on key population parameters that ultimately defines the harvest control rule and catch advice. To do this, I have implemented a age-structured model that is parameterized from a management oriented perspective, where the leading parameters are C^* and F^* . The assessment herein is based on the same assessment conducted by Martell (2009). I assume that the stock is at its unfished state in 1966, recruitment follows a Beverton-Holt stock-recruitment relationship, and the model is conditioned on the historical catch information. A total of 51 model parameters are conditionally estimated. I make no prior assumptions about the survey q, and no direct prior assumptions about the steepness of the stock recruitment relationship. The model parameterization is such that there is an implied prior for the steepness of the stock recruitment function; however, this prior is very diffuse in comparison to previous assessments (i.e., steepness was fixed in 2007). In this assessment, catch data from U.S. and Canadian operations are aggregated into a single fishery, and it is assumed that selectivity curve for the aggregate fishery and the acoustic trawl survey is asymptotic and time invariant.

Changes to this years assessment include: omitting the 1986 and 2009 acoustic biomass survey index, omitting all survey age-composition data, and partitioning the fisheries independent time series into two periods from 1977-1992 and 1995-2007 with two separate q's.

2 Methods

A summary of the input data and complete technical description of the model is provided in Appendix A and B, respectively. For technical details on the acoustic trawl surveys, please refer to Fleischer et al. (2005). For a more detailed description of the fishery and historical management of the fishery see Helser and Martell (2007b) for more details. The purpose of this section is three fold: 1) summarize the modeling approach, 2) provide documentation for informative prior distributions, and 3) provide a technical description on how the reference points and catch advice is formulated.

2.1 Modeling approach

The principle difference between the assessment here, and that of last years assessment using Stock Synthesis (SS), is that the leading parameters in this model pertain to the management parameters F^* (the fishing mortality rate that produced the maximum sustainable yield) and C^* (the maximum sustainable yield). Whereas, SS estimates the unfished biomass B_o and the steepness of the stock recruitment relationship h.

The approach was to fit and age-structured population dynamics model to time series information on relative abundance, and proportions-at-age in the commercial fishery using a Bayesian estimation framework. The commercial catch and age-composition information from Canada and the U.S. has been combined to represent a single fishery. The aggregation of the commercial catch data has the potential to create a bias in the predicted-age composition because it assumes that the age-specific fishing mortality rates between the two countries has been relatively consistent over time. Furthermore, the combining of the age-composition data is done using a weighted average, where the weights are based on the proportion of US or CAN landings by weight rather than by numbers.

The objective function contains 4 major components: 1) the negative loglikelihood of the relative abundance data, 2) the negative loglikelihood of the catch-at-age proportions in the commercial fishery, 3) the prior distributions for model parameters, and 4) two penalty functions that constrain the estimates of steepness to lie between 0.2 and 1, and to prevent annual exploitation rates from exceeding 1. Note that the value of the penalty functions was 0 for all samples from the posterior distribution. The joint posterior distribution is defined by equation (T19.6). This distribution was numerically approximated using the Markov Chain Monte Carlo routines built into AD Model Builder (Otter Research, 2008). Posterior samples were drawn systematically every 400 iterations from a chain of length 2,000,0000 (the first 2000 samples were dropped to allow for sufficient burnin). Convergence was diagnosed using various test provided in the R-package CODA (R Development Core Team, 2006), as well as, running medians and visual inspection of the trace plots. Where possible, we provide comparisons between the maximum likelihood estimates and median estimates from the marginal posterior distributions. Catch advice is based on the samples from the joint posterior distribution (T19.6).

2.1.1 Input data used

The input data that were used to estimate model parameters are provided in appendix A. First, TINSS is conditioned on the total landings where the fishing mortality rate each year is determined by solving the instantaneous Baranov catch equation using the observed total landings and the estimated vulnerable biomass. The Baranov catch equation is solved using a derivative based root finding method (see equations T18.9 and T18.10 in appendix B). The model is fit to the Acoustic biomass survey (Table 11), assuming that these data are proportional to the vulnerable biomass seen by the survey and observation errors are lognormal. Selectivity to the acoustic survey gear was assumed to follow a logistic distribution and age-2 fish were assumed to be 50% vulnerable with a standard deviation of 0.45 years.

The model is also fit to combined U.S. and Canadian proportions-at-age from 1977 to 2009 (Table 13). To combine the proportion-at-age data, proportions-at-age from the U.S. and Canadian fisheries were constructed using a weighted average, where the weights are given by the proportion of the total landings in the U.S. or Canadian fisheries. The model was not fit to the observed proportions-at-age in the acoustic biomass survey (these data are provided in Table 12) as the STAR panel felt that these data were not representative of the population age-structure. Lastly, the empirical weight-at-age data were used to convert numbers-at-age to weight-at-age and these data are provided in Table 14. Note that no new weight-at-age data were available at the time of conducting this assessment; therefore, the observed mean weight-at-age in the 2008 fishery were carried forward to the 2009 fishery.

2.1.2 Assumptions

There is no *a priori* assumption about the scaling parameter for the acoustic biomass survey (q), and the biomass index was treated as a relative abundance index that is directly proportional to the survey vulnerable biomass as the beginning of the year. The acoustic biomass index was split into two separate time periods (i.e., two separate q) to account for the incomplete spatial coverage between 1977-1992 and the complete spatial coverage since 1995. It is assumed that the observation errors in the relative abundance index are lognormally distributed. Fishing mortality in the assessment model is conditioned on the observed total catch weight (combined US and Canada catch), and it is assumed that total catch is known and reported without error. I further assume that fishing mortality and natural mortality occur simultaneously. Age-composition information is assumed to come from a multivariate logistic distribution where the predicted proportion-at-age is a function of the predicted population age-structure and the age specific vulnerability to the fishing gear. The likelihood for the age-composition data was evaluated at the conditional maximum likelihood estimate of the variance (i.e., no subjective weighting scheme was used to scale likelihood for the age-composition information). No aging errors were assumed in this assessment.

Historical observations on mean weight-at-age shows systematic changes, where the average weights-at-age have declined from the mid 1970s and increased again slightly late 1990s (Figure 1). A number of the historical cohorts have a growth trajectories that initially increase from age-2 to age-8 then decline or stay relatively flat (e.g., 1977 cohort in Figure 1). Given these data,

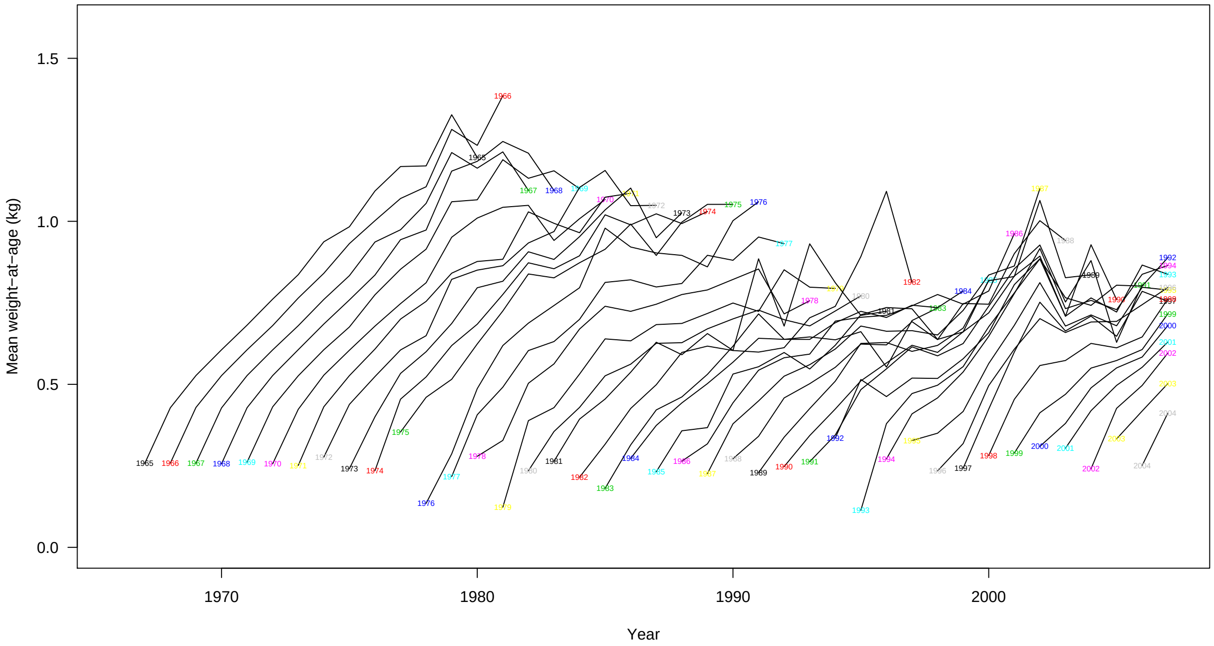

Figure 1: Observed mean weights-at-age by cohort in the commercial catch. Text labels for each line represent the cohort year.

there are at least three alternative explanations for the observed decreases in mean weight-at-age: 1) changes in condition factor associated with food availability, 2) intensive size selective fishing mortality with differential fishing mortality rates on faster growing indivuals, and 3) apparent changes in selectiviity over time. All three of these variables are confounded, and it is not possible to capture decreasing weight-at-age using the von Bertalanffy growth model and a fixed allometric relationship between length and weight. As such, the assessment model herein uses the observed mean weight-at-age data from the commercial fishery to scale population numbers to biomass.

The structural assumptions of the model assume that recruitment follows a Beverton-Holt type model and the process error terms are represented by a vector of deviation parameters (ω_j) that are assumed to be lognormally distributed. Both fishing mortality and natural mortality are assumed to occur simultaneously; instantaneous fishing mortality is based on the Baranov catch equation where the analytical solution for F_t is found using an iterative Newton-Rhaphson method with a fixed number of iterations to ensure the proper derivative information is carried forward in the autodiff libraries. Selectivity, or vulnerability-at-age, to the fishing gear is assumed to be age-specific, time-invariant, and is represented by an asymptotic logistic function (T16.5). Age-specific fecundity is assumed to be proportional to the product of body-weight and the proportion-at-age that are sexually mature.

2.2 Prior distributions

The underlying production function is defined by three key population parameters (C^* , F^* , and M) and the parameters that define age-specific selectivity ($v_a = f(\hat{a}_h, \hat{\gamma})$). Informative lognormal prior distributions were used for C^* , F^* , and M where the log means and log standard deviations are given in Table 1. These prior distributions were developed on an *ad hoc* basis and not necessarily derived from meta-analytic work that is the typical source of prior information.

Table 1: Prior distributions for model parameters.

Parameter	prior density	range	μ	σ	a	b
C^*	lognormal	(0.01-3.0)	0.200	0.5		
F^*	lognormal	(0.01-0.9)	0.35	0.262		
M	lognormal	(0.05-0.9)	0.23	0.1		
$\hat{a}$	uniform	(0.0-14.0)				
$\hat{\gamma}$	uniform	(0.05-5.0)				
$\bar{a}$	fixed	2.5				
$\bar{\gamma}$	fixed	0.45				
ρ	beta	(0.01-0.99)			3	12
φ	gamma	(0.02-100)			7.5	5.78

The global scaling parameter in this model is C^* ; the maximum long-term sustainable yield. Since 1966, the average annual landings removed from this population is 218,963.5 mt, and in the last decade 282,408.7 mt. We assume a rather diffuse lognormal prior for C^* with median value corresponding to 200,000 mt and a standard deviation of 500,000 mt. This represents a 95% confidence interval of roughly 75,000 mt to 532,000 mt. Assigning a prior density for C^* is nearly equivalent to assigning a prior density for the global scaling parameter q.

A lognormal prior was assumed for M with a mean corresponding to 0.23 (which is the assumed fixed value in Helser and Martell (2007b)) and a standard deviation of 0.1. This roughly corresponds to a 95% confidence interval of 0.19 and 0.28 for M, which is lower than the range reported in (e.g., Table 10 in Bailey et al., 1982, has values greater than 0.3 from 7 of 8 studies).

Uniform improper prior distributions were assumed for the selectivity parameters for the commercial fishery. The parameters are bounded between 0 and 14 years for the age at 50% vulnerability and 0.05 and 5.0 for the standard deviation in age at 50% vulnerability.

In comparison with Helser and Martell (2007b), a prior probability for F^* is nearly equivalent to a prior probability for steepness h. A lognormal prior was assumed for F^* , with a mean corresponding to 0.35 and a standard deviation of 0.262 (corresponds to a 95% confidence interval of 0.21 and 0.59). To derive the prior for F^* , a steady state age-structured model was developed to calculate spawning potential ratio based on growth parameters from Francis et al. (1982), a natural mortality rate of 0.23, and a logistic selectivity curve ($\hat{a} = 3.13, \hat{\gamma} = 0.8$). Arbitrarily, it was assumed that production is maximized somewhere between SPR=0.3 and SPR=0.45, and the corresponding values for F_{30} and F_{45} were then calculated. Based on the growth-maturity, natural mortality, and assumed selectivity the values correspond to $F_{30} = 0.48$ and $F_{45} = 0.25$, which were then assumed to be the 10th and 90th percentiles for a lognormal distribution. Note that the Spawning potential ratio curve is insensitive to the assumed value of steepness (Figure 2) and that F_{40} is the assumed proxy for F^* that is used by the Pacific Fisheries Management Council.

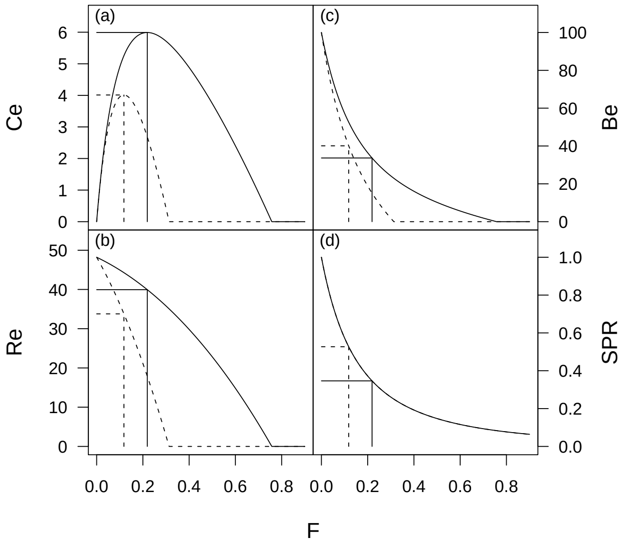

Figure 2: Relationship between equilibrium fishing mortality rate and yield (a), recruitment (b), biomass(c) and spawner per recruit(d) with an assumed value of h = 0.75 and $h = 0.5$. The vertical lines in each panel represent estimates of F^* (solid lines), F_{45}, and F_{30} (dotted lines). Note that the y axis scaling is arbitrary (i.e. B_o was assumed at 4 units of biomass).

The transition from (C^* ,F^*)$\Rightarrow$(B_o, h), that is carried out using the algorithm described in Table 16, implies a prior density for the steepness parameter in the stock recruitment relationship. The implied prior density for h used in this assessment is shown in Figure 3. Note that in the Beverton-Holt stock recruitment model, values of h range between 0.2 and 1.0, where 0.2 implies that recruitment is nearly proportional to spawner/egg production, and 1.0 implies that recruitment is unrelated to spawner/egg production. The implied prior for h is sensitive to two key model components: the assumed prior distribution for F^* , and the age at which fish recruit to the fishery relative to the age at which fish mature. Larger values of F^* imply a more productive stock and higher values of h for given selectivity and maturity schedules. Similarly, if fish recruit to the fishery prior to maturing then the levels of recruitment compensation (or h) must increase for a given value of F^* . Therefore, a critical piece of information is the maturity-at-age and weight-at-age schedules used to develop the age-specific fecundity relationship.

2.3 Reference points and catch advice

Catch advice in this model is based on the 40:10 harvest control rule with F_{40} as the target fishing mortality rate. I also provide catch advice using F^* as the target fishing mortality rate. Unless otherwise stated, the reference point calculations and catch advice is based on the most recent information about growth (Table 14) and maturity-at-age information from Dorn and Saunders (1997).

The reference points for the harvest control rule are F_{40} and SB_{40} . In this assessment F^*

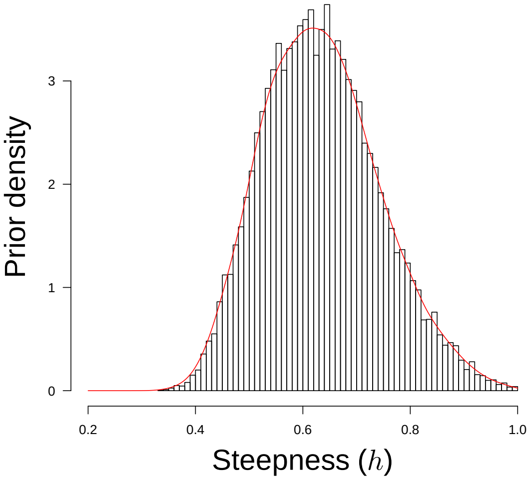

Figure 3: Implied prior for the steepness parameter in the stock recruitment relationship. Note that steepness is derived from the leading parameters Θ; therefore, any assumed prior information for Θ results in an implied prior for derived quantities such as h.

is estimated as a leading parameter, and SB_{40} is 40% of the unfished spawning biomass (SB_{o}). An alternative (but as it turns out, less conservative) harvest rule would be to use $\mathrm{SB}_{\mathrm{MSY}}$ as the reference point in the harvest control rule, where $\mathrm{SB}_{\mathrm{MSY}}$ =$R_e\phi_e$ evaluated at F^* and C^* .

Catch advice was generated by projecting the stock abundance forward to 2011 by applying catch options between 0 and 750,000 mt tons over 25 equally spaced intervals and then calculating various management objectives for each of the 5,000 samples from the joint posterior distribution. It was assumed in each simulated projection that the total catch option was fully utilized and implemented without error. In the stock projections, age-1 recruits for 2008-2011 were generated using the underlying Beverton-Holt stock recruitment model with annual lognormal recruitment deviates with standard deviation equal to the current estimate of standard deviation in the process errors (τ).

A decision table for catch advice (ABC options) was developed using measures of overfishing (probability that the ABC option will result in a fishing mortality rate that exceeds F^*), and four measures of spawning stock depletion. The first measure is the probability that the spawning stock biomass in 2010 will be less than the spawning stock biomass in 2009, and the second measure is the probability that the spawning stock biomass in 2010 will be less than $\mathrm{SB}_{\mathrm{MSY}}$. The third measure is the probability that the spawning stock biomass will be less than SB_{40} , and the fourth measure is the probability that the spawning stock biomass will fall below SB_{25}. For each sample from the joint posterior distribution the projection model loops over 25 increments of this ABC ranging from 0 to 750,000 mt and then calculates the corresponding fishing mortality rates and levels of spawning stock depletion. We then score the fishing rate and spawning stock depletion on a 0 or 1 scale (0 not overfishing or spawning stock biomass greater than or equal to management target) and fit a binomial (link logit) model versus ABC option to these data. The result is a sigmoid like curve or the cumulative probability of an ABC option versus management objective can be assessed.

Table 2: Alternative model descriptions and short hand notation for the evaluating the impact of the 2009 data on catch advice.

Label	Shorthand	Description
Model.1	C	2009 total catch data only included
Model.2	CA	Catch and 2009 fishery age data included
Model.3	CI	Catch and 2009 survey biomass index included
Model.4	CAI	Catch, fishery age, and survey biomass index only
Model.5	CIS	Catch, survey biomass index and survey age data included
Model.6	CAS	Catch, fishery age, and survey age data included
Model.7	CAIS	Catch, fishery age, survey biomass index, survey age (full model)

For specified levels of risk, ABC options for each management objective are then provided in a decision table. This cumulative probability distribution is also compared to the cumulative density function of catch advice produced by the 40/10 harvest control rule.

2.4 Sensitivity of ABC to new data

The TINSS assessment model was also run with alternative data configurations to show the impact of adding the 2009 data on 2010 ABC values. A summary of the alternative models and the shorthand notation is provided in Table 2. For each data configuration specified, projected 2010 ABC values, based on the 40:10 adjustment are calculated and compared against the full data (Model.7). I also examine how estimates of C^* , F^* , the survey catchability coefficient (q) and M are influenced by the new data collected in 2009 .

3 Results

3.1 Maximum likelihood estimates

Maximum likelihood estimates of the vulnerable biomass, fishing mortality rates, age-1 recruits and historical landings are summarized in Fig. 4. During the late 1960 and 1970s, annual landings averaged 169,000 tons and the corresponding fishing mortalities were less than 0.13 per year. During the 1980s catches increased from 90,000 tons to just over 300,000 tons and the fishing mortality rates during this period averaged less than 0.09 per year. Two exceptionally strong cohorts (1980, 1984) were responsible for a large increase in the vulnerable biomass during this time period. The vulnerable biomass peaked in the mid 1980s declined steadily to a low of 1.41 million tons in 2000 (Table 3). During this time period, there were no significant recruitment events (Fig. 4c), and also during this time period annual landings increased from 110,000 tons in 1985 to nearly 312,000 tons in 1999. The 1999 cohort was an exceptional year class, and the vulnerable biomass more than doubled from 1.41 millon tons in 2000 to 2.70 million tons in 2003 as a result. Catches declined as this year class recruited to the fishery, resulting in a reduction in fishing mortality to 0.16 in 2002. Catches increased again, reaching 360,000 tones in 2005 and 2006 resulting in an sharp increase in fishing mortality. As the 1999 year class passed through the fishery and was not replaced with another exceptional year class, catches remained high. Vulnerable and spawning biomass reached their historical minima following the 2008 fishery, and estimated fishing mortality in 2008 reached a record high of 0.58.

The 2009 OY was reduced to 184,000 metric tons for the 2009 fishery, and a combined 176,671 metric tons were landed by all sectors. The significant decrease in the 2009 OY resulted in an estimated fishing mortality rate of 0.30 and an exploitation fraction (catch divided by 3+biomass) of 0.13 in last years fishery. Estimated spawning stock biomass declined slightly from 1.23 million metric tons in 2009 to 1.18 million metric tons projected for the 2010 fishery. Vulnerable biomass increased slightly from 0.94 million mt in 2009, to 1.01 million mt in 2010 (Table 3).

Table 3: Maximum likelihood estimates of vulnerable biomass (B_t), spawning biomass (SB_t) and depletion, landings (C_t millions mt), instantaneous fishing mortality rates (F_t), 2+ and 3+ biomass ($B_{t,2+}, B_{t,3+}$), and total catch over 2+ and 3+ biomass ($C_t/B_{t,2+}$, $C_t/B_{t,3+}$), from 1966 to the begining of 2010 .

Year	B_t	SB_t	SB_t/SB_0	C_t	F_t	$B_{t,2+}$	$B_{t,3+}$	$C_t/B_{t,2+}$	$C_t/B_{t,3+}$
1966	3.59	4.05	1.00	0.14	0.05	4.71	4.22	0.03	0.03
1967	3.45	3.90	0.96	0.21	0.08	4.57	4.08	0.05	0.05
1968	3.26	3.67	0.91	0.12	0.05	4.19	3.88	0.03	0.03
1969	3.14	3.47	0.86	0.18	0.07	3.95	3.58	0.05	0.05
1970	2.87	3.21	0.79	0.23	0.10	3.72	3.33	0.06	0.07
1971	2.61	2.98	0.74	0.15	0.08	3.52	3.09	0.04	0.05
1972	2.50	3.00	0.74	0.12	0.06	4.14	3.02	0.03	0.04
1973	2.63	3.34	0.83	0.16	0.08	3.95	3.86	0.04	0.04
1974	2.96	3.27	0.81	0.21	0.09	3.61	3.34	0.06	0.06
1975	2.64	2.93	0.72	0.22	0.10	3.62	2.94	0.06	0.08
1976	2.39	2.85	0.70	0.24	0.13	3.35	3.14	0.07	0.08
1977	2.41	2.74	0.68	0.13	0.07	3.20	2.84	0.04	0.05
1978	2.22	2.46	0.61	0.10	0.06	2.66	2.58	0.04	0.04
1979	2.12	2.42	0.60	0.14	0.08	3.44	2.27	0.04	0.06
1980	2.11	2.87	0.71	0.09	0.06	3.53	3.47	0.03	0.03
1981	2.61	2.94	0.73	0.14	0.07	3.12	2.99	0.04	0.05
1982	2.56	3.24	0.80	0.11	0.05	5.88	2.80	0.02	0.04
1983	2.77	4.34	1.07	0.11	0.06	5.67	5.63	0.02	0.02
1984	4.18	4.69	1.16	0.14	0.04	4.94	4.91	0.03	0.03
1985	4.25	4.36	1.08	0.11	0.03	4.44	4.33	0.02	0.03
1986	3.44	4.03	0.99	0.21	0.07	6.59	3.51	0.03	0.06
1987	3.33	4.75	1.17	0.23	0.10	5.93	5.90	0.04	0.04
1988	4.11	4.61	1.14	0.25	0.08	5.00	4.75	0.05	0.05
1989	3.75	4.06	1.00	0.31	0.10	5.02	3.96	0.06	0.08
1990	3.31	4.06	1.00	0.26	0.10	5.20	4.41	0.05	0.06
1991	3.43	3.98	0.98	0.31	0.12	4.51	4.28	0.07	0.07
1992	3.16	3.52	0.87	0.30	0.12	4.27	3.53	0.07	0.08
1993	2.64	3.08	0.76	0.20	0.10	3.67	3.31	0.05	0.06

Table 3: *(continued)*

Year	B_t	SB_t	SB_t/SB_0	C_t	F_t	$B_{t,2+}$	$B_{t,3+}$	$C_t/B_{t,2+}$	$C_t/B_{t,3+}$
1994	2.56	2.87	0.71	0.36	0.19	3.21	3.00	0.11	0.12
1995	2.23	2.45	0.61	0.25	0.14	2.79	2.51	0.09	0.10
1996	1.84	2.29	0.57	0.31	0.23	3.12	2.43	0.10	0.13
1997	1.80	2.32	0.57	0.33	0.27	3.04	2.55	0.11	0.13
1998	1.63	1.96	0.49	0.32	0.29	2.45	2.08	0.13	0.15
1999	1.45	1.72	0.43	0.31	0.31	2.08	1.84	0.15	0.17
2000	1.41	1.72	0.42	0.23	0.23	2.20	1.75	0.11	0.13
2001	1.46	2.17	0.54	0.24	0.24	4.43	1.92	0.05	0.12
2002	1.93	3.22	0.79	0.18	0.16	4.38	4.20	0.04	0.04
2003	2.70	3.17	0.78	0.21	0.11	3.58	3.34	0.06	0.06
2004	2.66	2.83	0.70	0.33	0.16	2.99	2.94	0.11	0.11
2005	1.98	2.13	0.53	0.36	0.24	2.58	2.08	0.14	0.17
2006	1.45	1.70	0.42	0.36	0.36	1.98	1.84	0.18	0.20
2007	1.14	1.37	0.34	0.30	0.39	1.87	1.35	0.16	0.22
2008	0.95	1.29	0.32	0.32	0.58	1.78	1.45	0.18	0.22
2009	0.94	1.23	0.30	0.18	0.30	1.53	1.40	0.12	0.13
2010	1.01	1.18	0.29			1.39	1.24		

The maximum likelihood estimate of the 2010 spawning stock biomass is 1.50 millon tons (0.75 million metric tons for female spawning stock biomass), which corresponds to a depletion level of 0.35 (Fig. 5ab, Table 3). This is well below the management target of 0.4. By comparison, the estimated level of depletion in the assessment by Helser and Martell (2007b) was 0.309.

In this assessment we assume a constant age-selectivity curve for both the commercial and acoustic surveys (Fig. 6c). This is markedly different from previous assessments and other assessments run in parallel (i.e., Stock Synthesis) where selectivity is allowed to vary over specified time blocks. The conditional maximum likelihood estimates of the standard errors for the age-composition data is 1.85 for the commercial age composition data. These are very large errors in the age-composition information. When the survey age-composition data was included in the assessment, the conditional maximum likelihood estimate of the variance was nearly 3 times that of the commercial data; more emphasis (in terms of contribution to the likelihood component) is placed on the commercial age-composition information. For the acoustic trawl survey, there is reasonable correspondence in the observed and predicted age-comps for the 1980 and 1984 cohorts (Figs. 7-8). Since 1998, residual values in the acoustic survey age-composition are much smaller, and primarily negative for younger ages and positive for intermediate ages. Prior to the expansion of the acoustic biomass survey in 1995, age-composition data are likely biased due to the restricted spatial coverage.

In the commercial fishery, a time-invariant asymptotic selectivity curve was assumed and surprisingly good fits were obtained to the older age-classes in the commercial catch-age proportions (Figs. 9-10), with the exception of the persistent under-estimate of the proportions-at-age in the plus group in the late 1970s (this owes to an initialization of the numbers-at-age using a stable age distribution with a $Z = M$). The largest residual variation in the commercial age-composition data occurred in ages 2 and 14 (Fig. 11). The model tends to under estimate the 1980 and 1984

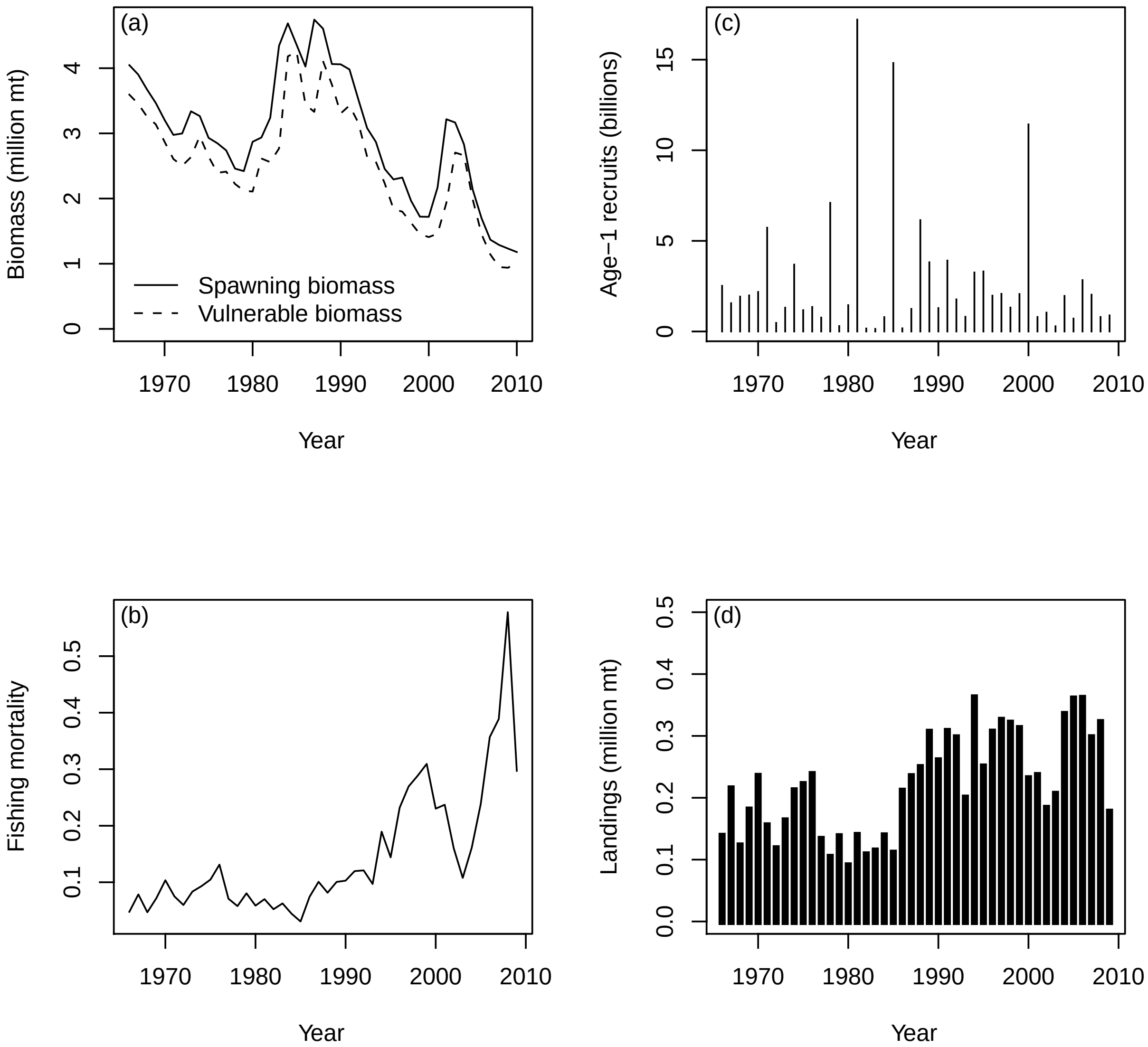

Figure 4: Maximum likelihood estimates of vulnerable and spawning biomass (panel a), fishing mortality (b), age-1 recruits (c) and the observed historical landings (d) for U.S. and Canadian fisheries combined.

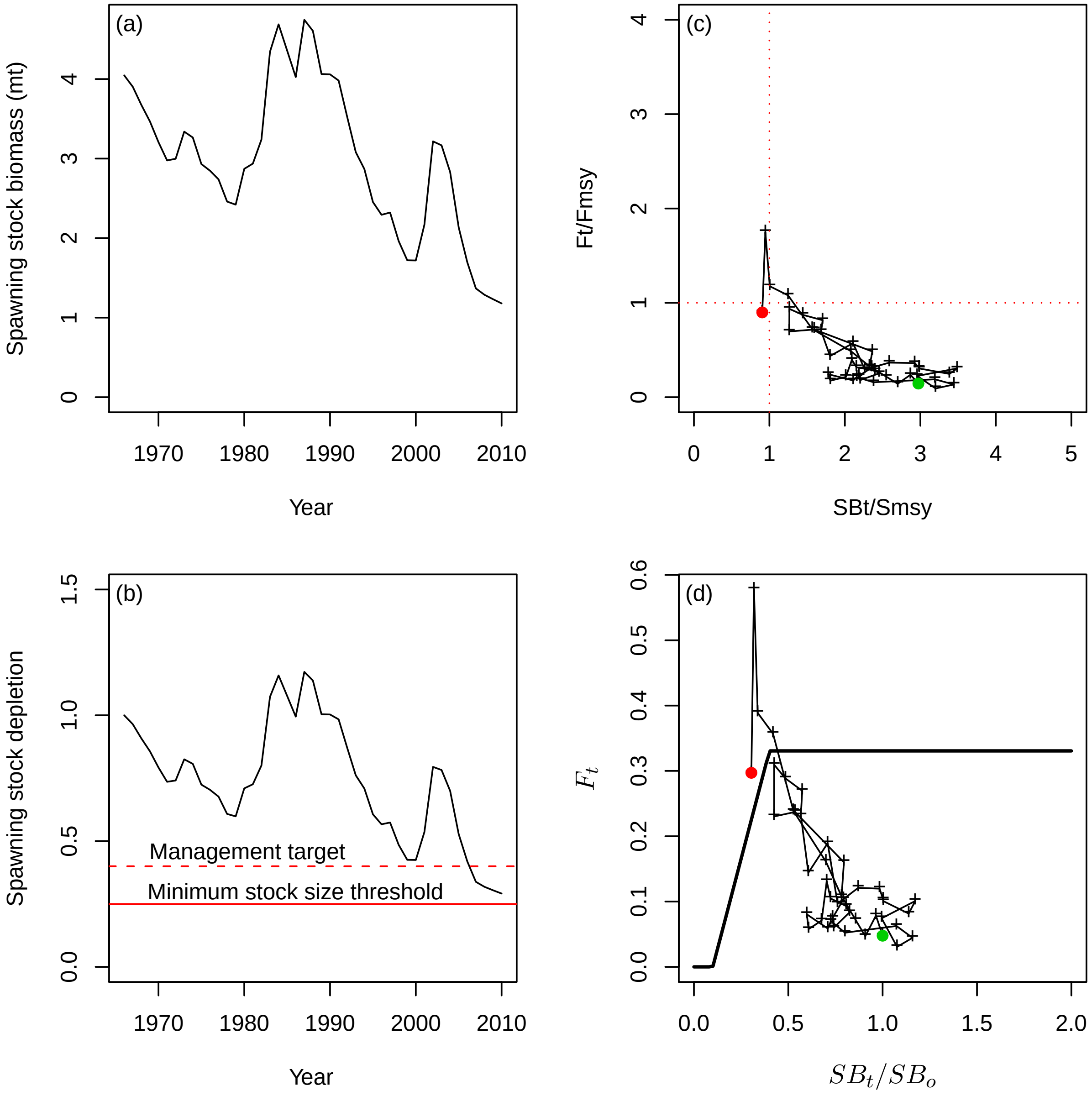

Figure 5: Maximum likelihood estimates of spawning stock biomass (a), spawning biomass depletion (b), the ratio of fishing mortality rates to C^* versus the spawning stock biomass to S_{msy} (c) and the harvest control rule (d). Note that the spawning stock biomass calculations include both male and females.

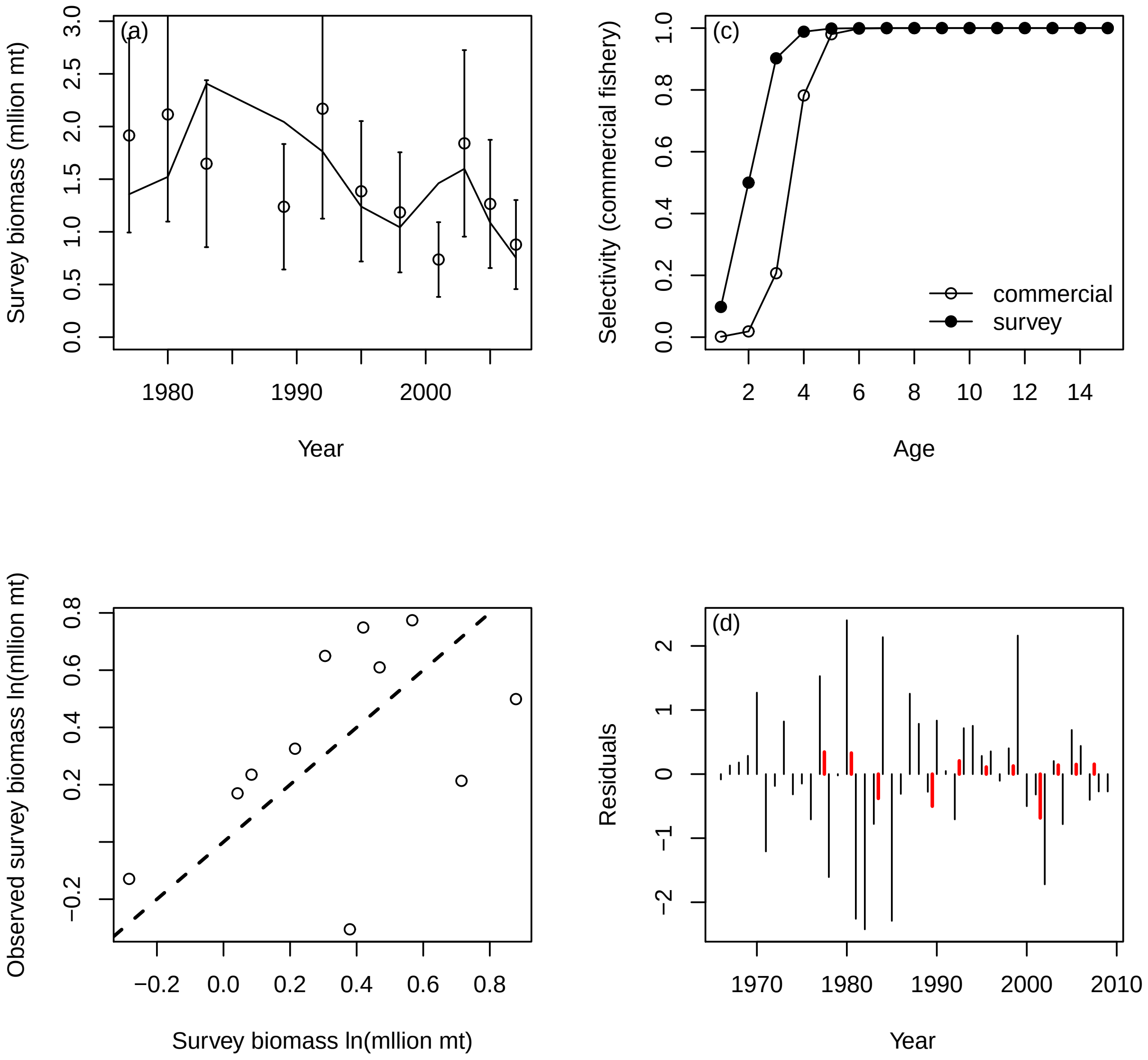

Figure 6: Predicted and observed survey biomass estimates (panel a-b, 1:1 line shown in panel b) based on the maximum likelihood fit to the data. Approximate 95% confidence intervals are shown for the survey points in panel (a) based on the estimated standard deviation in the survey. The estimated selectivity curves for commercial and survey selectivity (c), and the residuals between abundance indices (thick bars in panel d) and recruitemnt deviations (thin bars in panel d).

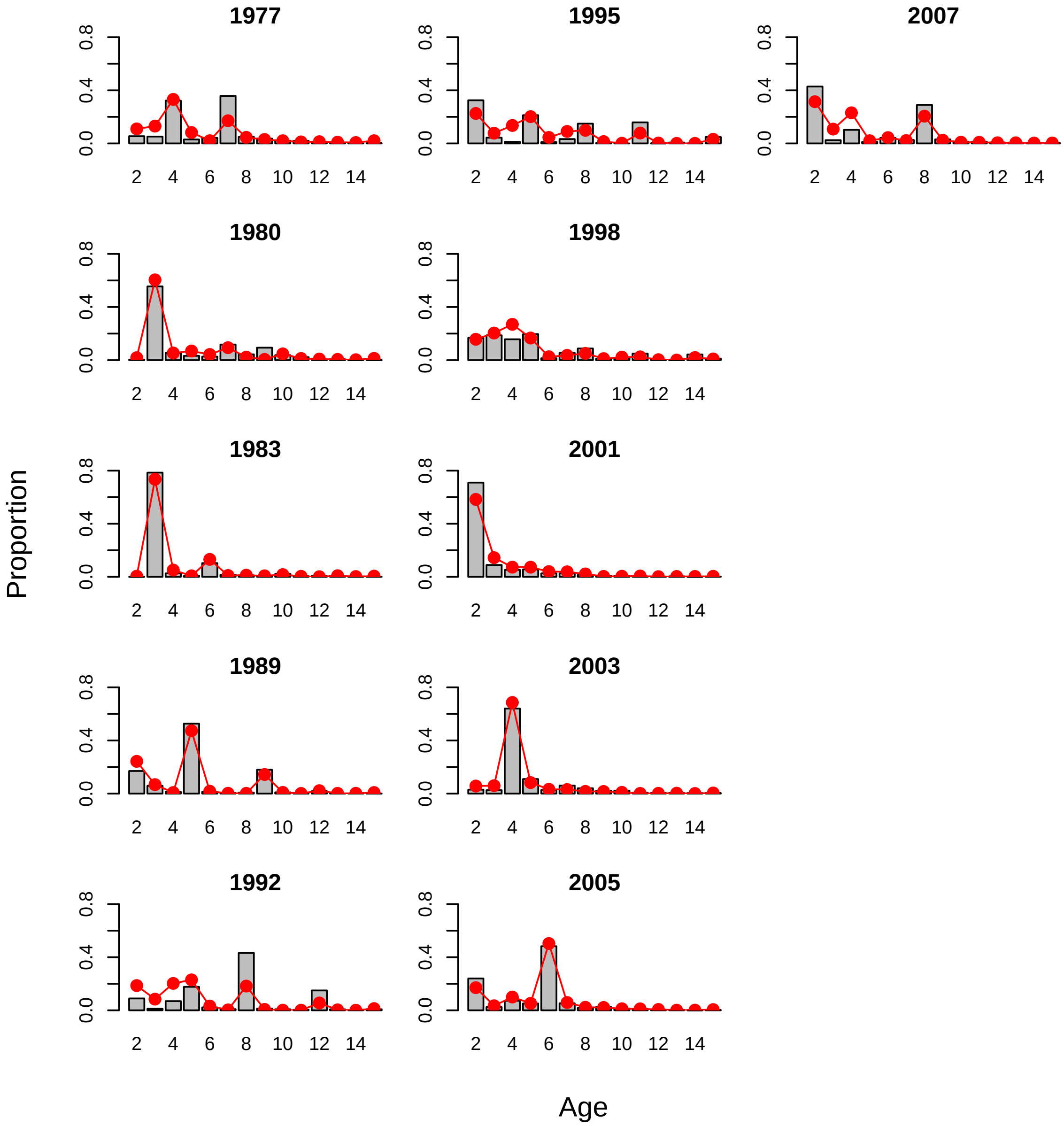

Figure 7: Observed (bars) and predicted (lines) proportions-at-age in the acoustic trawl surveys.

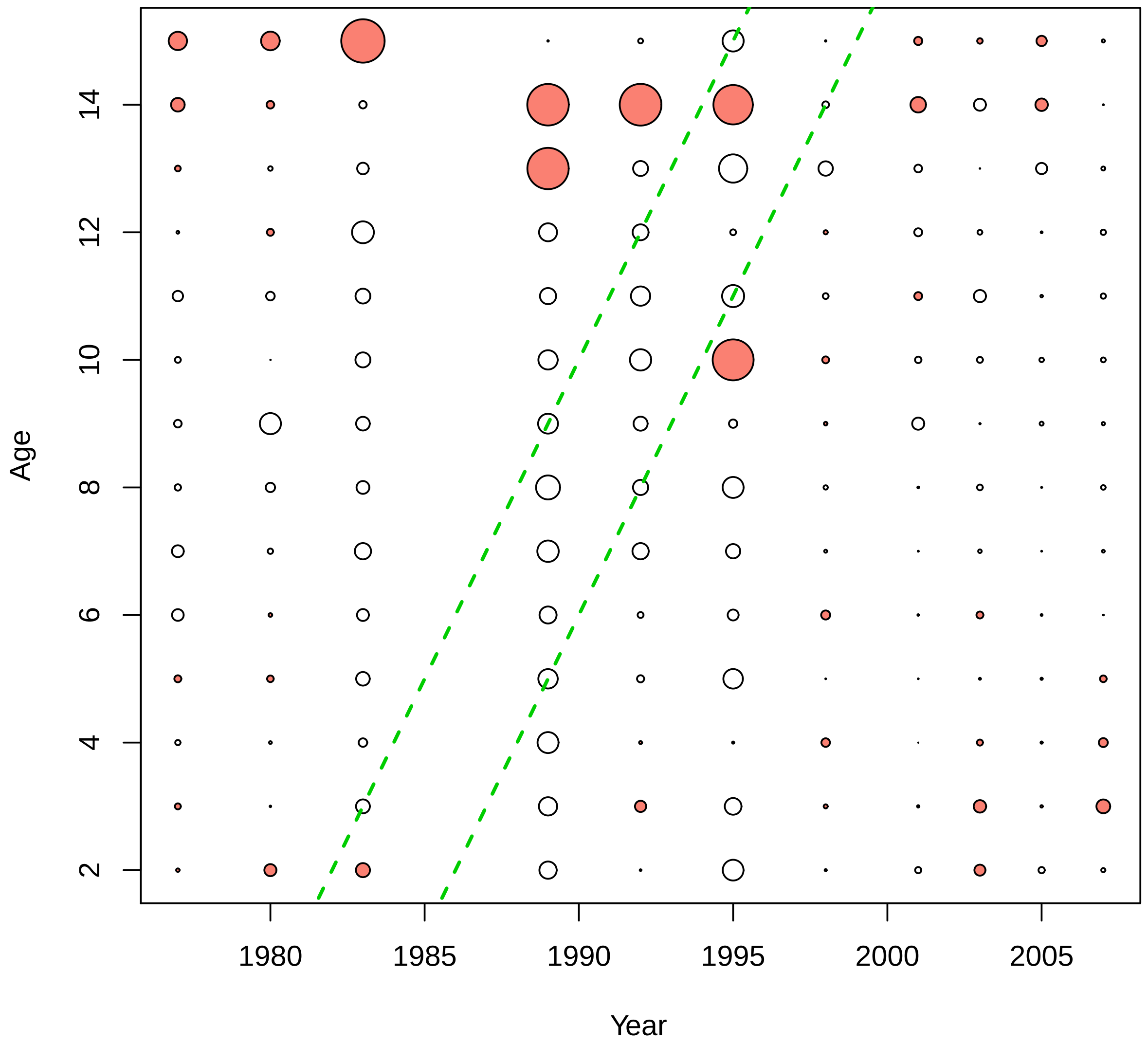

Figure 8: Bubble plots of the multivariate logistic residuals for the proportions-at-age in the acoustic trawl surveys. Diameter of the circle is proportional to the natural log of the residual, open circles are positive residuals (i.e., observed is greater than predicted). Dashed lines track the 1980 and 1984 cohorts.

cohorts at age-2 and over estimate the 1982 and 1985 cohorts at age-2. For the plus group, after 1984 there is no strong positive or negative residuals and no persistent pattern that would better suggest a dome-shaped selectivity curve; however, this residual pattern is in part determined by the instantaneous natural mortality rate M and lower values of M would lend more support for a hypothesis of a dome-shaped selectivity curve in the commercial fishery. Observed proportions-at-age are nearly all positive for the 2001 fishery with the exception of age-14. In 2000-2001, fish did not show up in the Canadian zone and the Canadian fleet operated in non-traditional fishing grounds in the north and landed older fish in comparison to the US fishery.

Overall, the constant selectivity assumption fits the commercial catch-age data reasonably well (Fig 9). The marked pattern in the residuals that appeared to correspond to an aging error pattern around above average cohorts prior to the 1980 cohort in seen in the previous assessment (Martell, 2009) now appears to be gone (Fig 11). This difference is likely due to not fitting the survey age-composition data, as previous assessments have noted contradictory information in the age-composition information (Helser and Martell, 2007a). Also there are some negative residuals for age-15+ from 1977 to 1983; these residuals arise due to the initialization of the numbers-at-age in 1966 where I assumed a stable age-distribution. Finally, in 2001 hake failed to show up in the traditional fishing grounds in Canada. The commercial fleet operated in non-traditional waters further to the North (Queen Charlotte sound) and landed much larger/older hake in comparison to the US fleet. This change in distribution of fishing operations is not very apparent in the residual patterns in 2001 because the aggregated age-proportions are dominated by the U.S. age comp data (Fig. 11).

3.2 Impact of 2009 data on 2010 ABC values

Prior to the 2010 STAR panel review, I evaluated the impact of the 2009 data on the projected ABC for the 2010 fishery. During the course of the STAR panel review, the 2009 data point was thrown out for this years assessment as well as all historical age-composition data collected in the acoustic biomass survey. The following two paragraphs describes the results of including the 2009 data prior to the STAR panel review.

The 2009 acoustic biomass index has the largest influence on estimated ABC values for the 2010 fishery (Figure 12). Projected ABC values for the 2010 fishery based on maximum likelihood parameter estimates and the 2009 landings data only are estimated at 171,612 mt. In other words, ignoring all other data (fishery age-comps, survey age-comps and the biomass index from the 2009 survey) results in the lowest ABC value for the 2010 fishery. The addition of the age composition data from the commercial fisheries in US and Canada (i.e., model.2) increase the 2010 ABC value to 218,039 mt. The addition of the survey age composition data (model.6) further increases the ABC value to 230,813 mt. All models that include the 2009 survey biomass index in the objective function result in a substantial increase in the 2010 ABC values, from 496,345 mt to 513,907 mt. The full model (using all available 2009 data, model.7) results in an ABC value of 497,466 mt.

Across the seven alternative data configurations explored, estimates of F^* and M are remarkably stable (Figure 13). Estimates of C^* were more variable with values ranging from 250,000 mt to 289,000 mt when the survey biomass index was excluded or included, respectively. Similarly, conditional maximum likelihood estimates of the survey catchability coefficient (negatively correlated with C^*) also ranged from 0.525 to 0.446 when the survey biomass index was included or

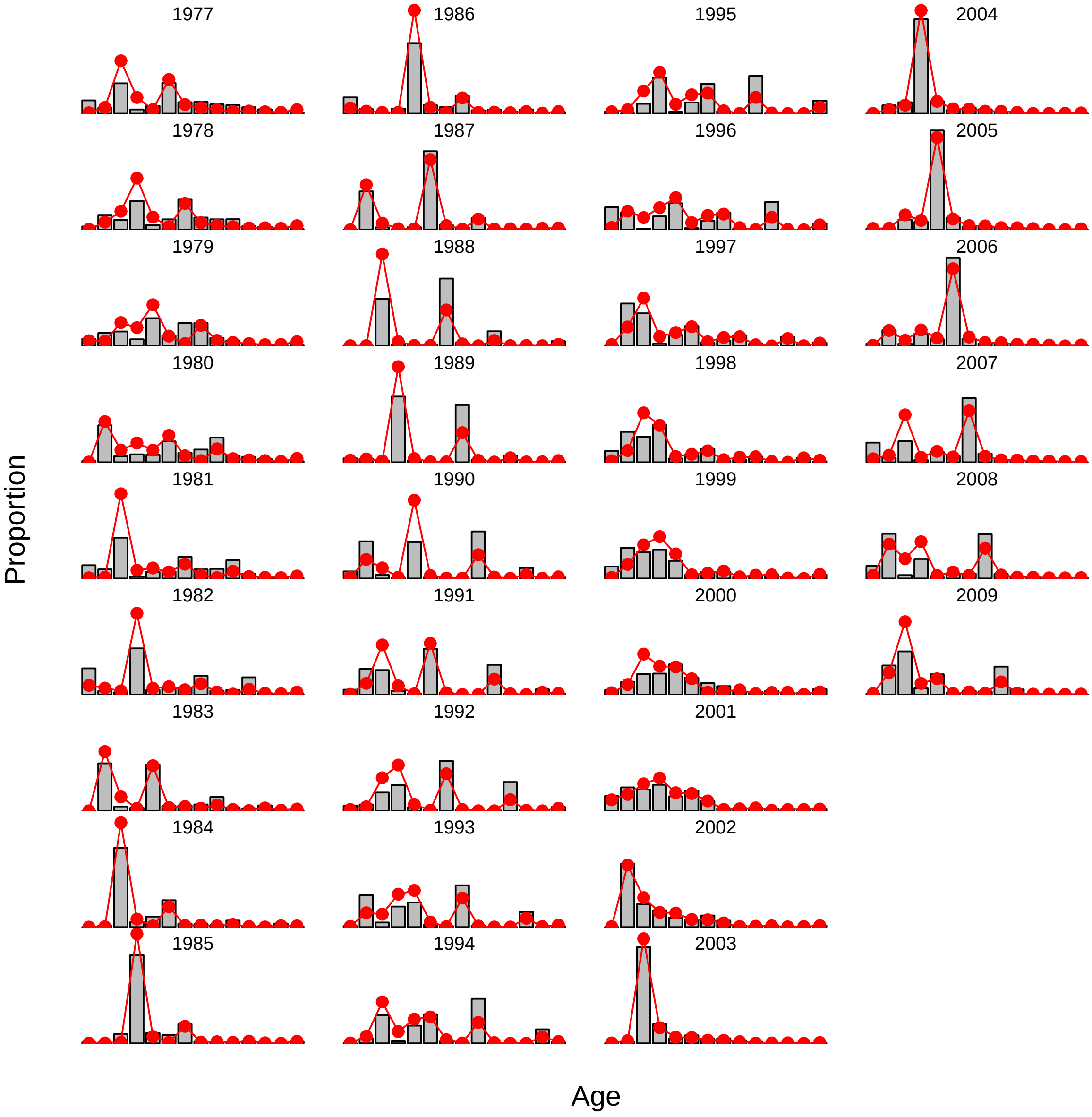

Figure 9: Observed (bars) and predicted (lines) proportions-at-age in the commercial age compositions.

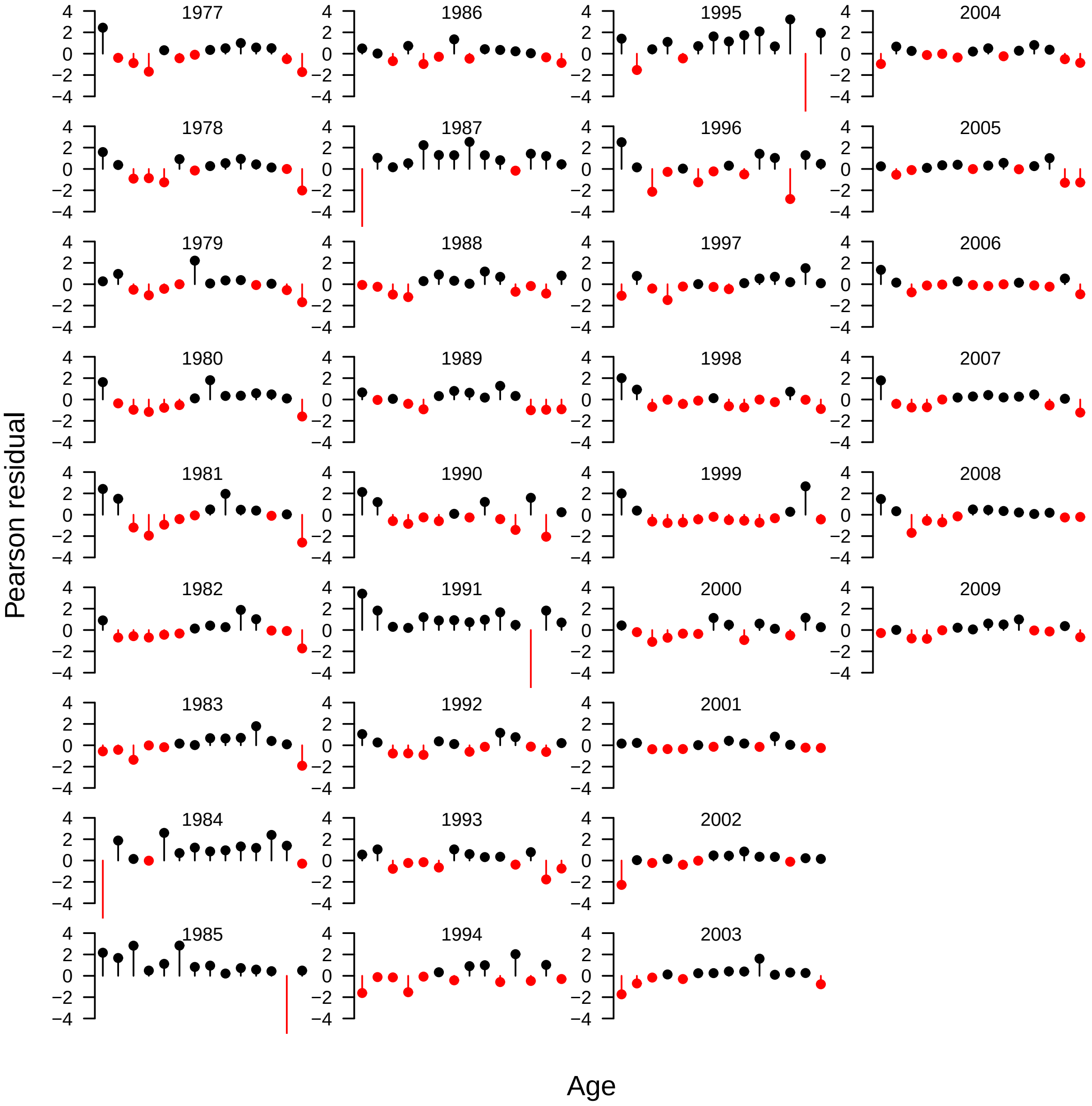

Figure 10: Pearson residuals for the proportions-at-age in the commercial age compositions.

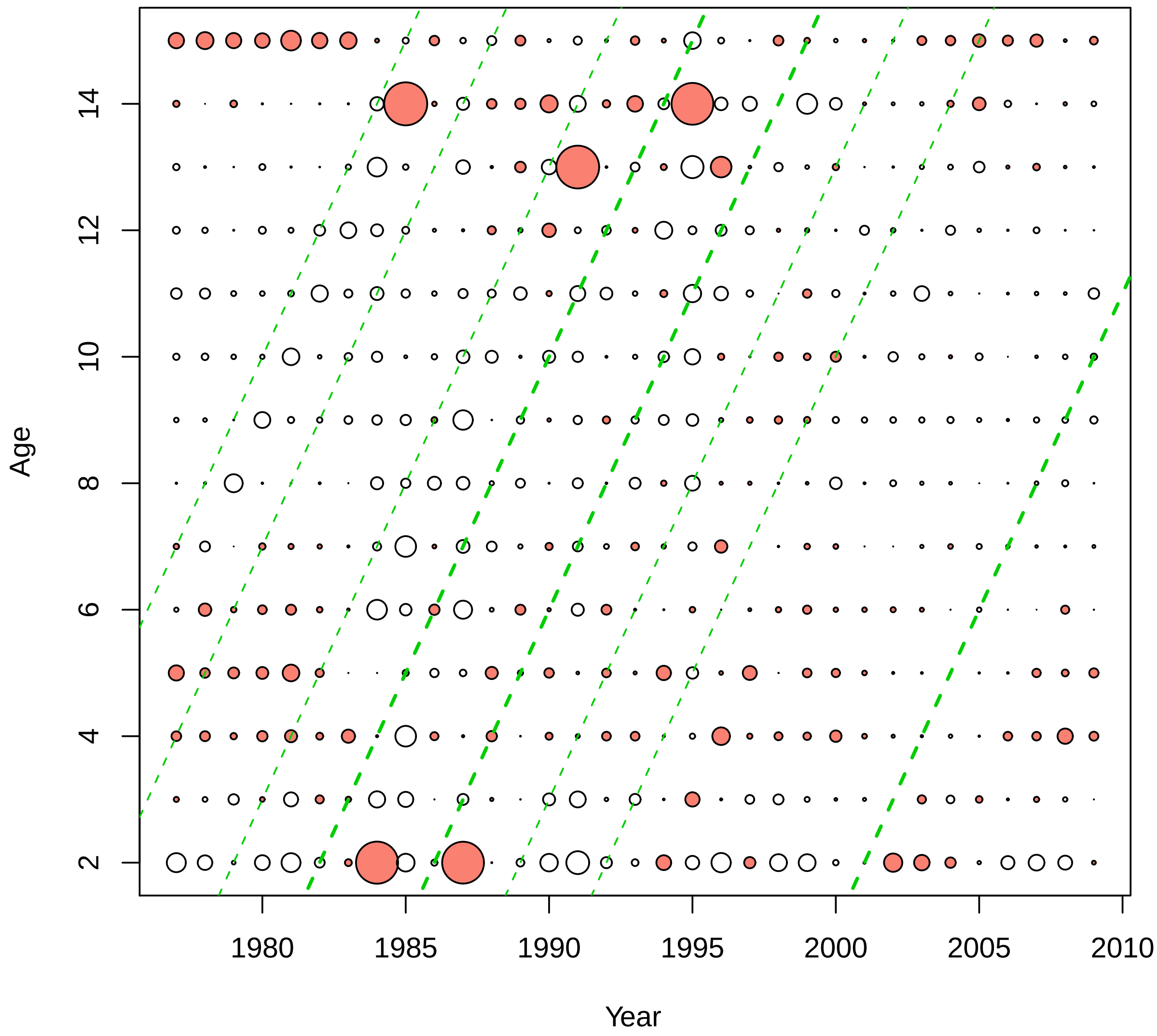

Figure 11: Bubble plots of pearson residuals for the proportions-at-age in the commercial age compositions. Dashed lines follow above average cohorts and the 1980, 1984 and 1999 cohorts are shown in bold dashed lines, positive residuals shown as transparent circles, negative residuals are shaded.

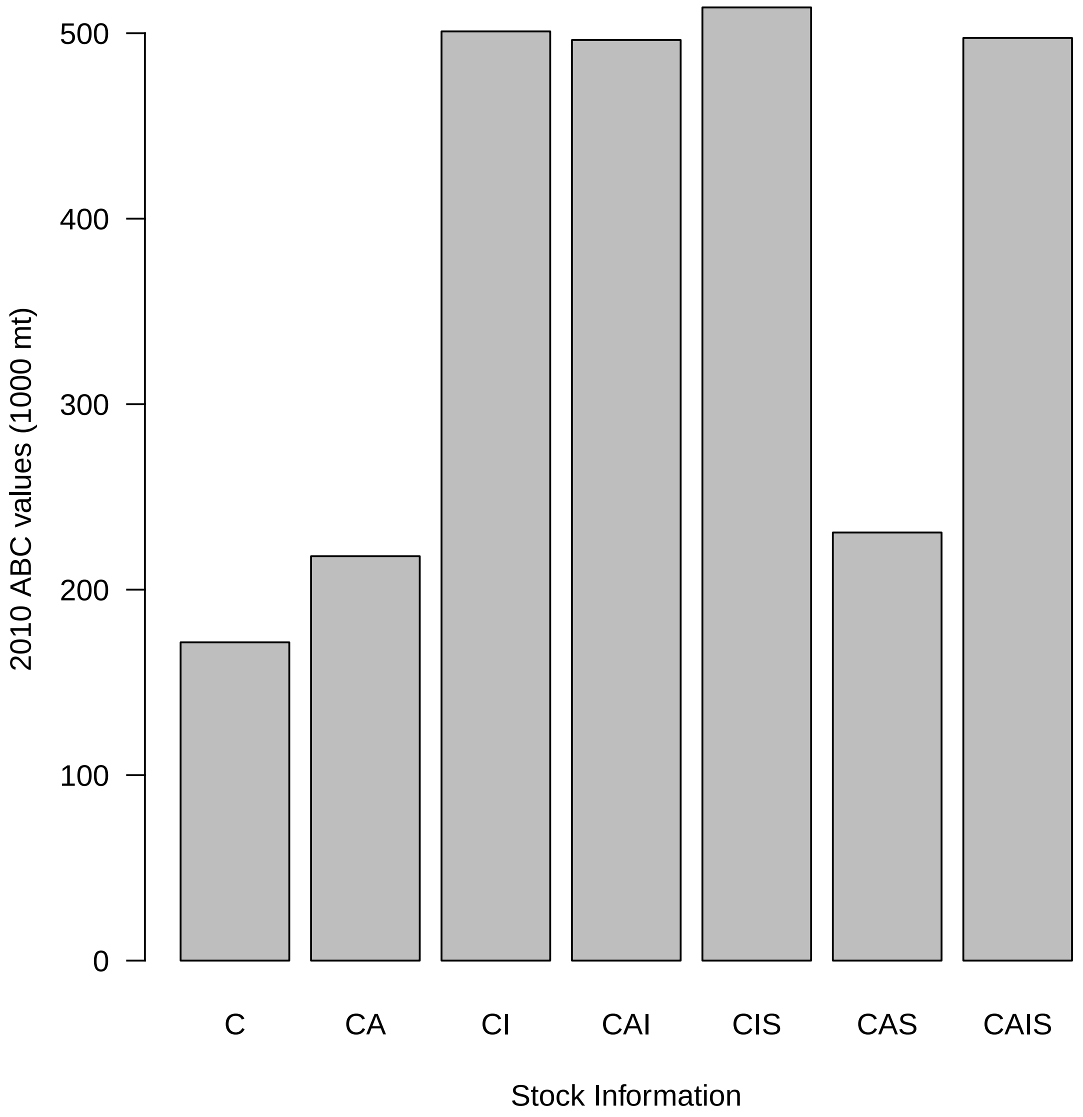

Figure 12: The impact of introducing the new 2009 data into the stock assessment model on ABC values for 2010 calculated using the 40:10 adjustment. Key: fishery **C**atch, fishery **A**ge comps, biomass **I**ndex, and **S**urvey age comps.

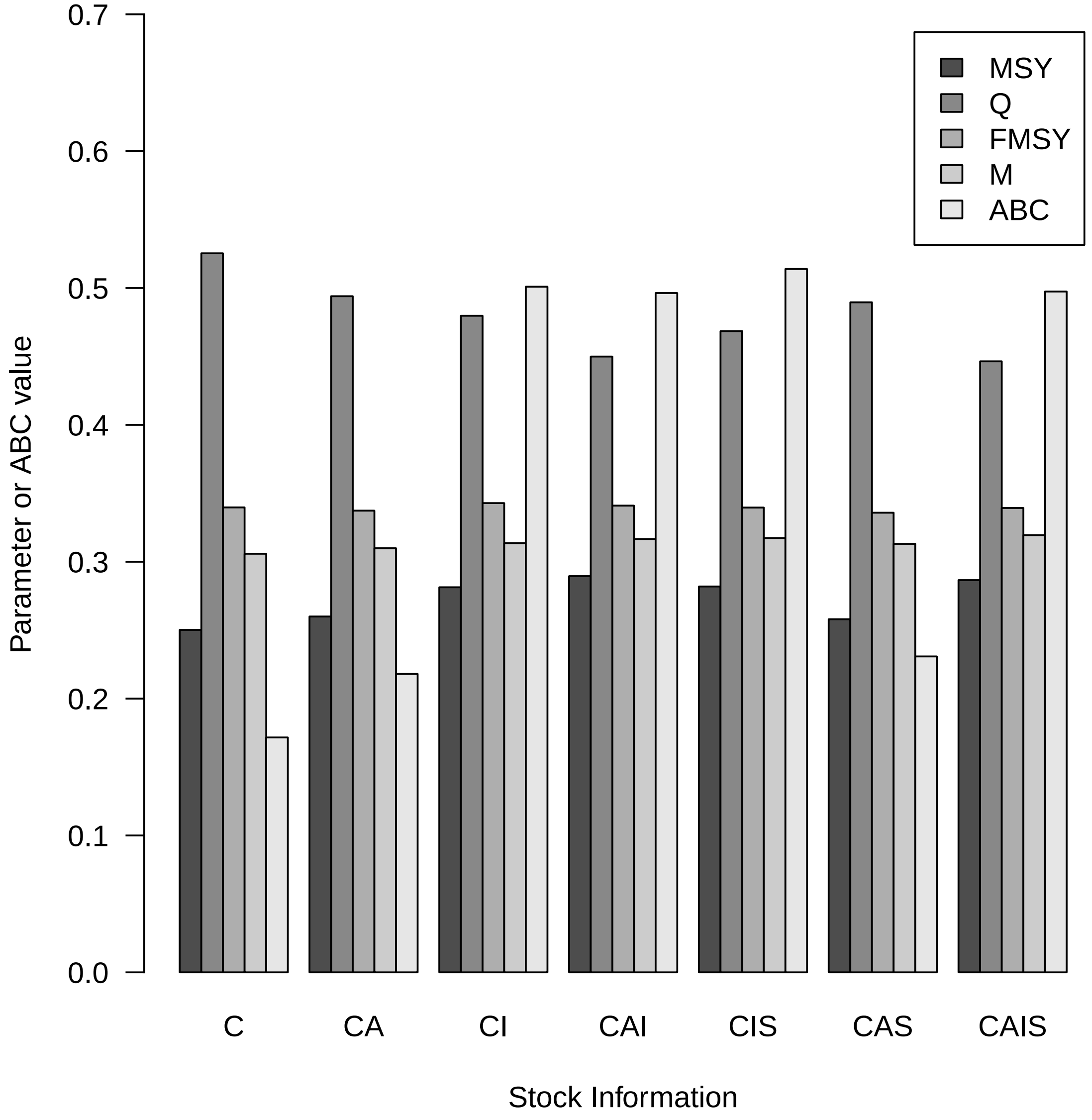

Figure 13: The impact of introducing the new 2009 data into the stock assessment model on estimates of C^* (million mt), F^* , M, survey catchability (Q) and ABC (million mt) values for 2010. Key: fishery **C**atch, fishery **A**ge comps, biomass **I**ndex, and **S**urvey age comps.

excluded from the assessment. The large changes in these scaling parameters (q and C^*) have profound affects on the estimates of 2010 ABC values (Figure 13).

3.3 Results from posterior integration

As reported in Martell et al. (2008), there is still insufficient trend information, and an apparent contradiction between the age-composition and trend information to reliably estimate overall population scale and productivity parameters (in this case C^* and F^* , and in previous assessments B_o and h). The relative abundance indices are relatively flat, with a slight downward trend between 1986 and 2000, an increase in 2003 followed by a decline through 2007, and most recently an increase from 879,000 mt in 2007 to 1,460,000 mt in 2009. There appears to be insufficient information to resolve parameter confounding between B_o and h, especially when age composition information is included in the analysis.

The marginal posterior density for F^* reflects the assumed prior information for F^* (Fig. 14). The median estimate for C^* is 0.304 million mt (Table 4), which is higher than the assumed prior median of 0.200 million mt and there appears to be some information in the data about the lower bound for C^* (Fig. 14). This information, however, is confounded with estimates of F^* and the instantaneous natural mortality rate (Table 5).

Median estimates of M=0.273 are also much higher than the assumed prior mean of 0.23 (Table 4). Information to estimate M comes from the age-composition information and is slightly positively correlated with the age at 50% vulnerability parameters ($\hat{a}$ and $\bar{a}$) in the selectivity curves. Note that if a dome-shaped selectivity curve was assumed, then estimates of M would likely decrease owing to the disappearance of older animals due to reduced selectivity. The median estimate of the age at 50% recruitment to the commercial gears is 3.6 years (Table 4). Also, note that survey selectivity parameter were fixed in this assessment. The median estimate of the variance ratio ρ is 0.219 (in comparison to 0.278 in last years assessment) and the inverse of the total variance φ^{-2} is 0.818 which corresponds to standard deviations of 0.265 and 0.954 for the observation errors and process errors, respectively (Table 4 and Table 6). There is a negative correlation between the inverse total error φ^{-2} and the proportion of observation error ρ. As values of ρ increases more of the total error is allocated to observation error in the surveys and the proportion of the process error remains relatively stable (i.e., information in the age-composition data are informative about process errors, Fig. 15).

Trends in the median estimates of vulnerable biomass and spawning stock biomass are exactly the same as the maximum likelihood estimates; however, in absolute terms the median estimates are slightly higher than the maximum likelihood estimates (Fig. 16a). Thus, uncertainty in biomass estimates is not normally distributed. In comparison to Helser and Martell (2007b), uncertainty is much greater in this assessment owing to the large amount of uncertainty admitted in the global scaling parameter (C^*) and productivity parameter (F^*). Although the survey catchability coefficient (q) is not directly comparable with the assumed values in Helser and Martell (2007b), the range of uncertainty in this assessment is much larger than the two options explored in previous assessments (Table 6).

Trends in historical recruitment are also comparable with Helser and Martell (2007b), and the median estimates are slightly higher than the maximum likelihood estimates (Fig. 17). The overall uncertainty in annual recruitment is also proportional to the overall uncertainty in the global scaling as well as uncertainty in the estimates of M. The largest cohorts in the past are the 1980, 1984, and 1999, and the 2005 cohort is estimated to be slightly below the long term mean historical recruitment but above the long-term median recruitment. There is a substantial amount of uncertainty in the estimates of age-1 recruits, and this uncertainty owes to the assumed uncer-

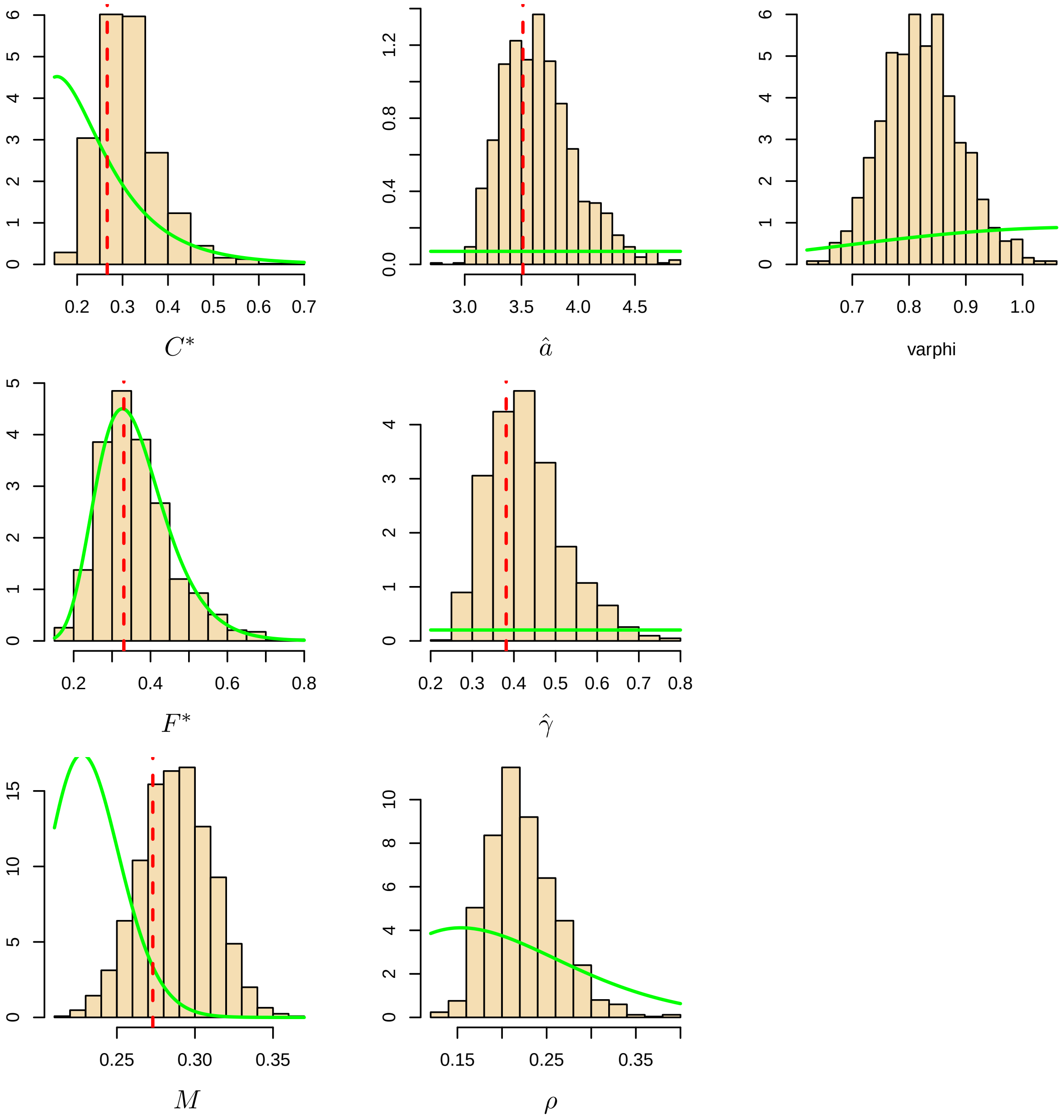

Figure 14: Marginal posterior (histograms) and prior distributions (lines) for key model parameters. Means and variances for the prior distributions are summarized in Table 1.

Table 4: Maximum likeliood estimates (MLE) of model parameters with asymptotic estimates of the standard deviation and median estimates with corresponding 2.5% and 97.5% quantiles from the marginal posterior distributions. Medians and quantiles are based on 5,000 samples from the joint posterior distribution.

	MLE		**Marginal densities**		
	Mean	Std	Median	2.5%	97.5%
C^*	0.266	0.049	0.304	0.209	0.480
F^*	0.331	0.083	0.349	0.216	0.587
M	0.273	0.022	0.287	0.244	0.334
$\hat{a}$	3.513	0.292	3.616	3.141	4.379
$\hat{\gamma}$	0.381	0.081	0.416	0.287	0.638
$\bar{a}$	0.216	0.037	2.000	2.000	2.000
$\bar{\gamma}$	0.882	0.074	0.450	0.450	0.450
ρ	-0.084	0.491	0.219	0.160	0.310
φ^{-2}	0.134	0.465	0.818	0.696	0.961

Table 5: Correlation among key model parameters based on 5,000 samples from the posterior distribution.

	C^*	F^*	M	$\hat{a}$	$\hat{\gamma}$	$\bar{a}$	$\bar{\gamma}$	ρ	φ^{-2}
C^*	1.000								
F^*	0.378	1.000							
M	0.535	-0.050	1.000						
$\hat{a}$	-0.274	0.014	0.151	1.000					
$\hat{\gamma}$	-0.270	0.002	0.060	0.956	1.000				
$\bar{a}$	0.014	-0.026	0.212	0.173	0.124	1.000			
$\bar{\gamma}$	-0.008	-0.042	-0.040	-0.012	-0.021	-0.030	1.000		
ρ	-0.222	-0.014	-0.195	0.078	0.089	-0.207	0.114	1.000	
φ^{-2}	-0.112	-0.015	-0.018	-0.039	-0.037	0.106	-0.085	-0.453	1

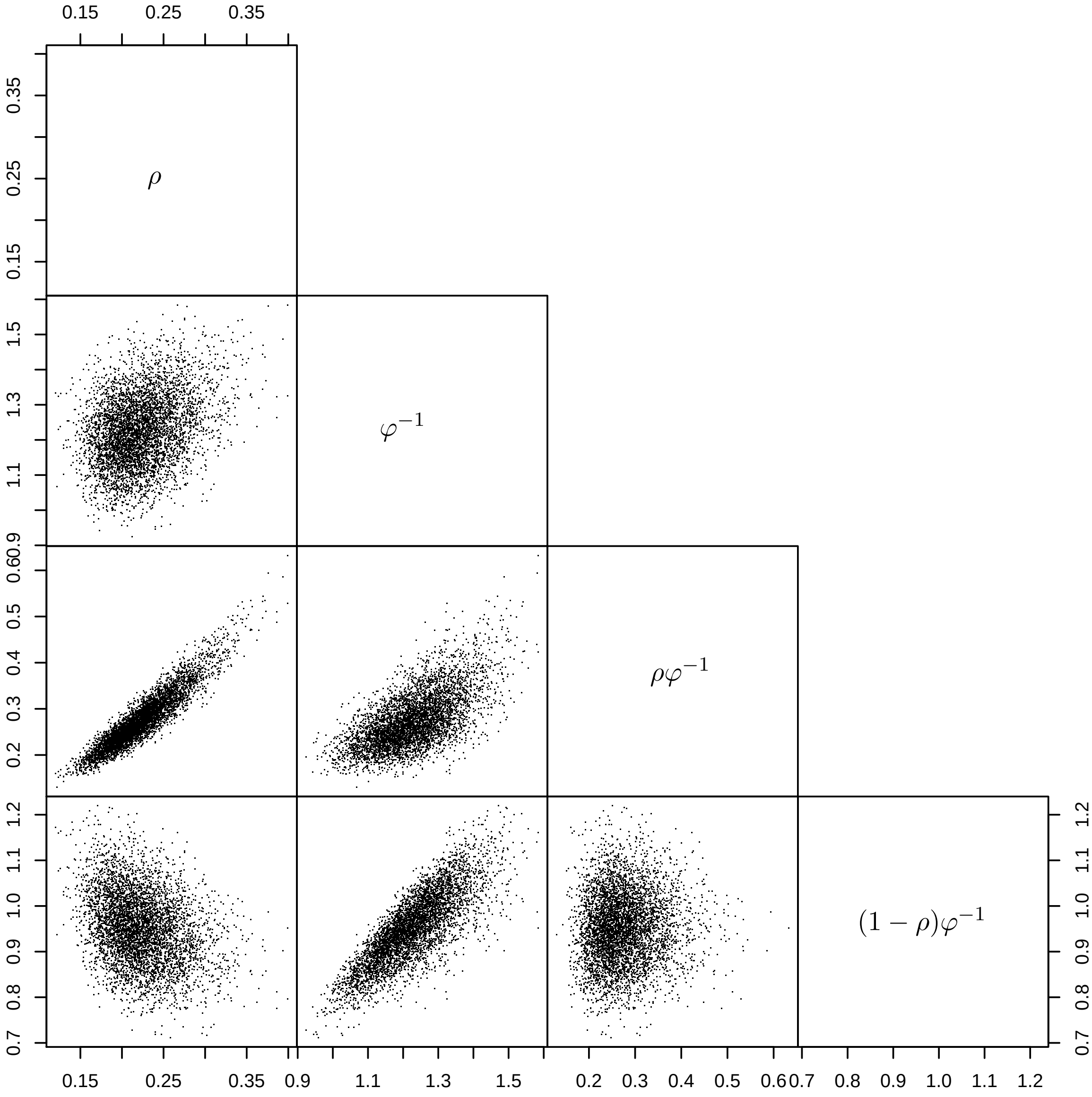

Figure 15: Pair plot of 5000 systematic samples from the joint posterior distribution of the variance components, where the standard deviation in observation and process errors is given by $\rho\varphi^{-1}$ and $(1-\rho)\varphi^{-1}$, respectively.

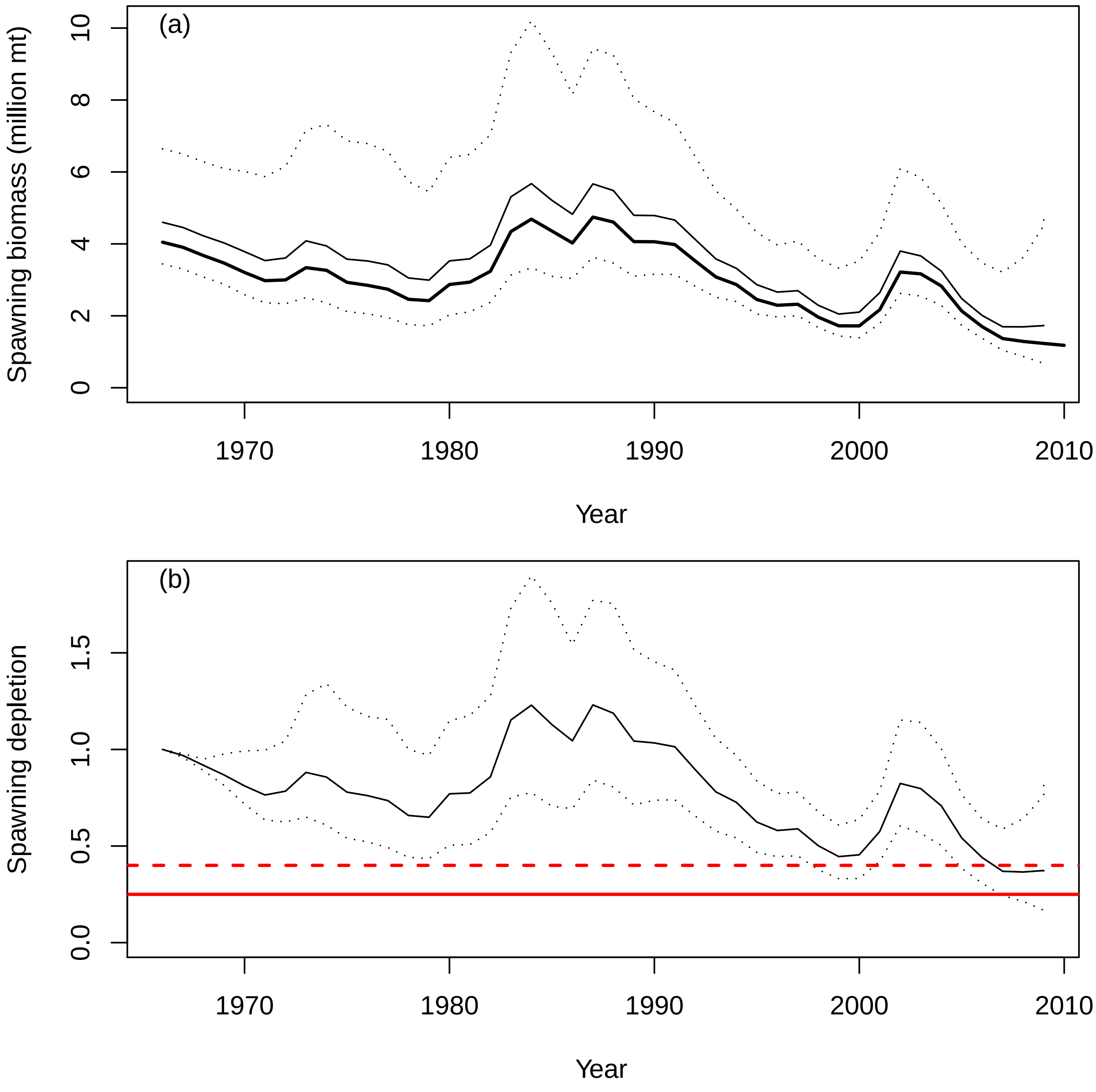

Figure 16: Maximum likelihood estimates (thick line) and median estimates (thin line) of the spawning stock biomass (a) and spawning stock depletion level with 40% and 25% horizontal reference lines (b). The dotted lines represent the 0.025 and 0.975 quantiles based on 5,000 systematic samples from the joint posterior distribution.

Table 6: Modal and median estimates of derived quantities of management interest. Medians and quantiles are based on 5,000 systematic samples from the joint positerior distribution, and the modal estimates correspond to the maximum likelihood estimates.

Derived quantity & Reference piont	Mode	Median	5%	95%
Survey catchability coefficient (q)	0.461	0.387	0.265	0.521
Steepness (h)	0.538	0.516	0.41	0.653
Spawning stock depletion (2010)	0.304	0.371	0.171	0.733
2010 ABC from 40/10 rule	0.22	0.333	0.035	0.906
Unfished total biomass (B_0)	5.015	5.725	4.335	8.11
Unfished 3+ biomass ($B_{0,3+}$)	4.218	4.805	3.725	6.627
Unfished spawning stock biomass (SB_0)	4.047	4.6	3.581	6.325
Unfished female spawning biomass	2.023	2.3	1.791	3.162
Spawning stock biomass at MSY (SB_{MSY})	1.361	1.579	1.137	2.297
Female spawning biomass at MSY	0.68	0.79	0.569	1.148
Spawning stock biomass in 2010 (million mt)	1.179	1.735	0.695	4.119
Female spawning stock biomass in 2010 (million mt)	0.59	0.867	0.348	2.06
Standard deviation in surveys (σ)	0.246	0.265	0.195	0.386
Standard deviation in process errors (τ)	0.889	0.949	0.825	1.082

tainty in the instantaneous natural mortality rate (M). In comparison to previous assessments the average long-term recruitment is higher; however, both the MLE and median estimates of M are substantially higher than the previously assumed value of 0.23.

The residual pattern from the acoustic abundance index was consistent across all 5,000 samples from the joint posterior distribution (Fig. 18). The 1989 and 2001 acoustic survey biomass estimates are roughly 50% below the predicted biomass. The greatest residual variation is in the 2007 biomass estimate, and this uncertainty is partly attributed to the uncertainty in recent recruitment. The median estimate of the survey catchability coefficient q was 0.387 with a 5% and 95% credible intervals of 0.265 and 0.521, respectively (Table 6). Note however, that this q is for the entire survey time series (excluding the 1986 and 2009) points and is shown here for comparative purposes with previous assessments that assumed a single q. The two separate q are not show here due to time constraints in assembling this document for the PFMC and the SSC briefing book.

The median estimate of the female spawning stock biomass in 2010 is 0.867 million mt (Table 6) and the modal estimate is 0.59 million mt. Less than 5% of 2009 spawning stock biomass it consists of the 1999 cohort (Fig. 19b) and as much as 70% of it consists of the smaller cohorts produced in 2004 and later. Absent any significant recruitment, the spawning stock biomass is expected to decline rapidly as the 1999 cohort continues to disappear.

Catch advice based on the 40:10 harvest control rule (ABC in 2010) and F^* as the target reference point is highly uncertain, ranging from 35,000 mt to 733,000 mt (5$^{\mathrm{th}}$th and 95$^{\mathrm{th}}$ percentiles, Table 6). The median estimate for the 40/10 rule is 333,000 mt and the modal estimate is 220,000 mt. The marginal posterior samples for the 2010 ABC based on the 40/10 adjustment is highly skewed with a long tail and reflects the huge amount of uncertainty in the 2010 vulnerable biomass estimate.

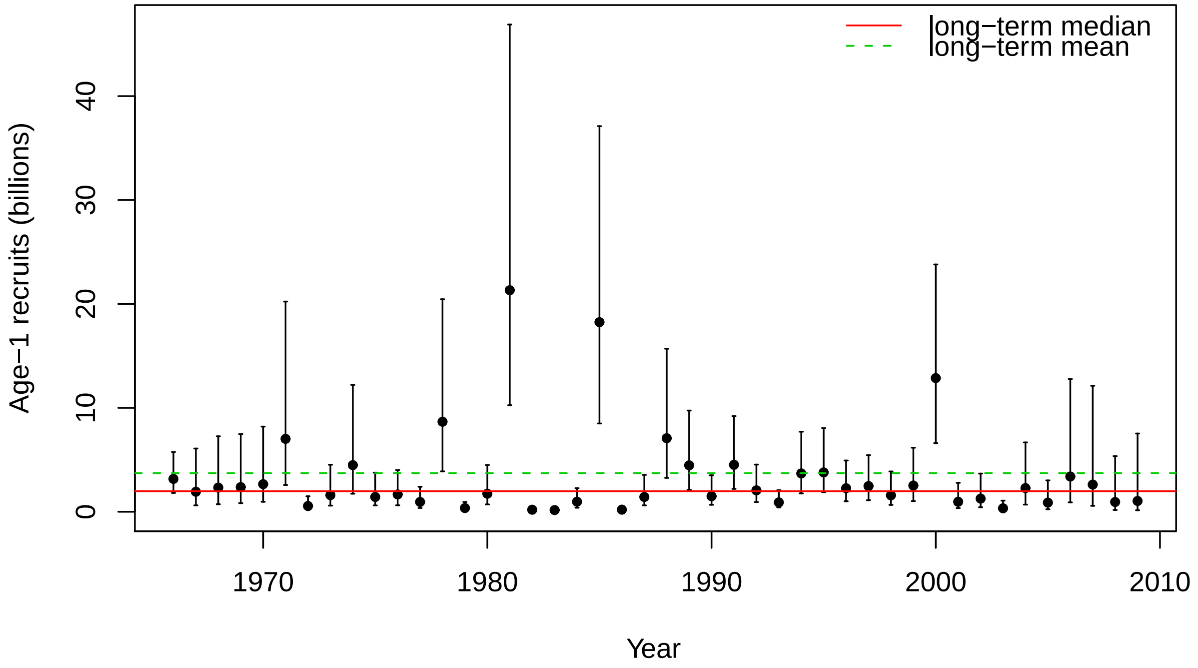

Figure 17: Median (circles) estimates of age-1 recruits, error bars represent the 0.025 and 0.975 quantiles based on 5,000 systematic samples from the joint posterior distribution. Long term average and median recruitment levels are shown as dashed and solid horizontal lines, respectively.

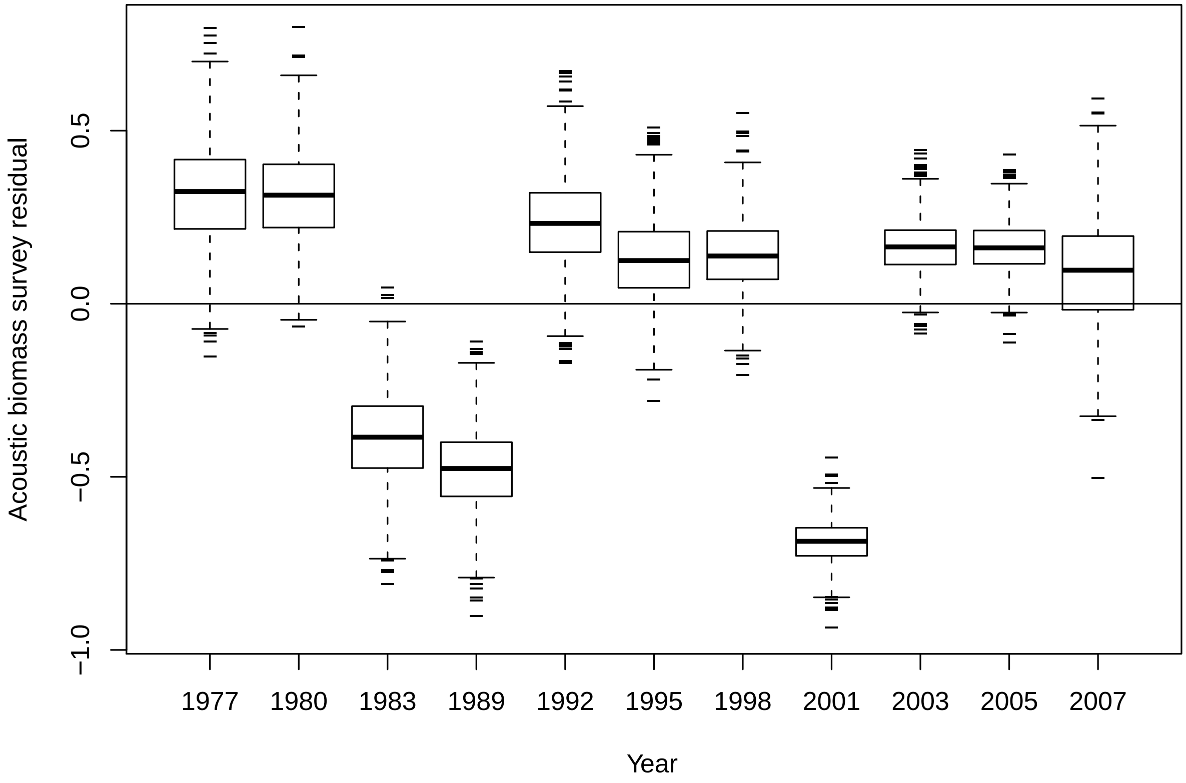

Figure 18: Boxplots of the marginal posteriors for the residuals in the acoustic survey.

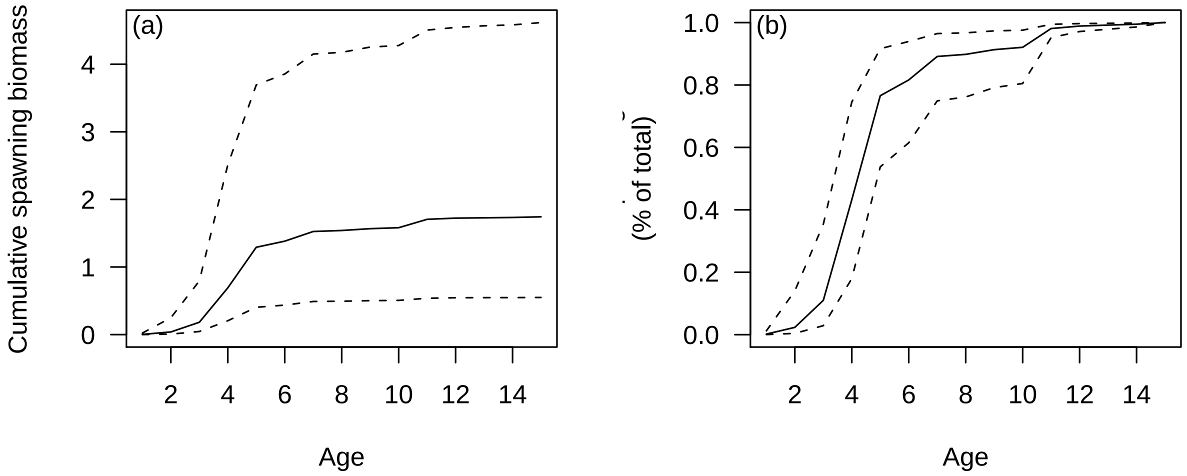

Figure 19: Cumulative spawning stock biomass at-age in 2009. Panel (a) is the cumulative total biomass where the solid line represents the median estimate, and the dashed lines represent the 0.025 and 0.975 quantiles. The cumulative spawning biomass-at-age relative to the total biomass is shown in panel (b).

3.4 Risk analysis

Five different criteria were examined in developing risk profiles for various catch options in 2009. The first criterion is the probability of the fishing mortality rate exceeding the estimated value of F^* (Fig. 20a). First, let 0.25, 0.5 and 0.75 probabilities represent definitions of risk averse, risk neutral, and risk prone, respectively. The preliminary risk averse ABC option for the 2010 fishing season based on exceeding the target fishing rate of F^* is 218,000 mt (Table 7). The preliminary risk neutral and risk prone ABC options are 344,000 and 470,000 mt, respectively. The second criterion is the probability of the spawning stock declining between 2010 and 2011 (Fig. 20b). Under this criterion the risk averse to risk prone ABC options are 0, 51,000 and 238,000 mt, respectively (Table 7 column 3). The third criterion examines the probability that the spawning stock biomass in 2011 will fall below the estimate of $\mathrm{SB}_{\mathrm{MSY}}$ (Fig 20c). Under this criterion the probability of the spawning stock falling below $\mathrm{SB}_{\mathrm{MSY}}$ is fairly high with no fishery (P$<$0.35); the risk neutral and risk prone policies call for ABCs of 262,000 and 792,000 mt (Table 7).

In summary, catch options in excess of 344,000 mt result in a fairly significant probability of overfishing (P $\geq$ 0.5), further declines in spawning stock biomass over present levels, and a significant probability of reducing the spawning stock biomass below $\mathrm{SB}_{\mathrm{MSY}}$ (P $\geq$ 0.6).

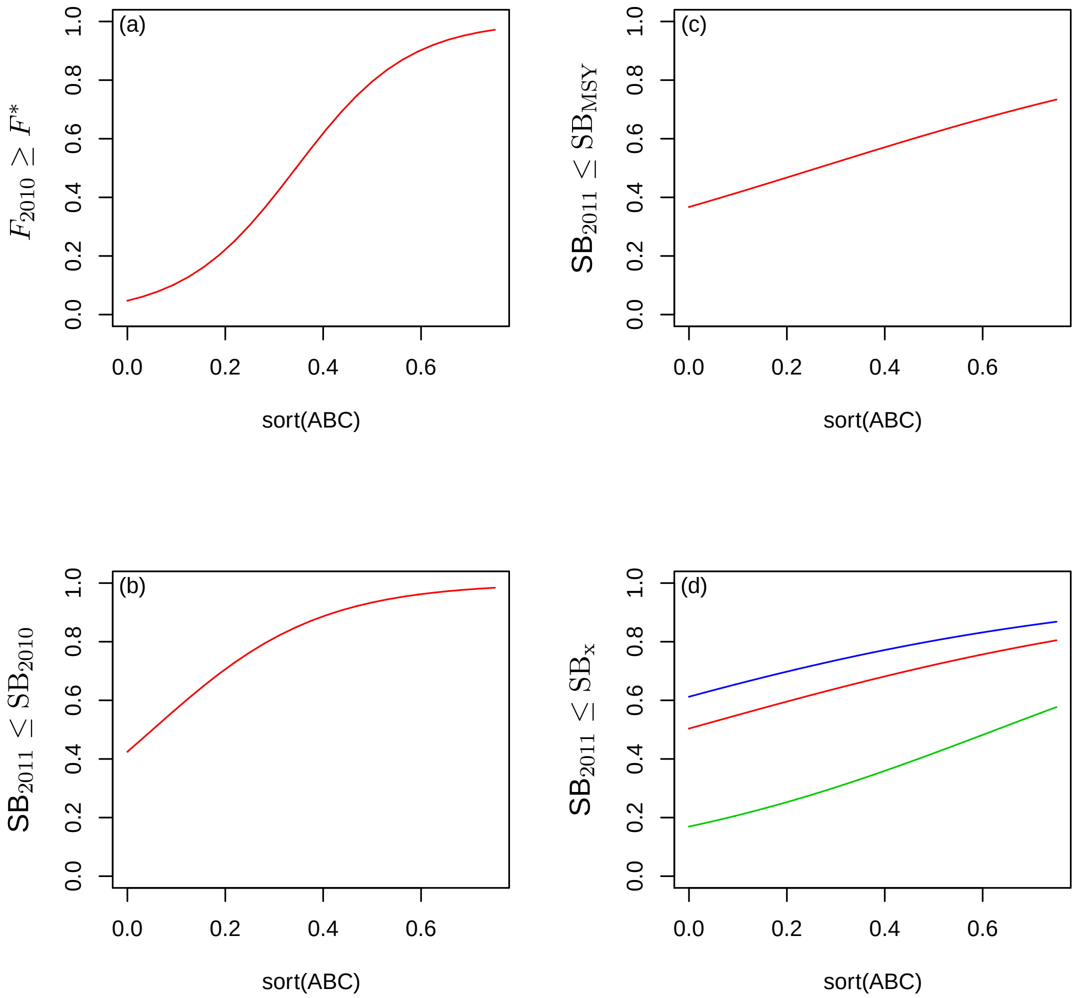

Figure 20: Probability of $F_{2010} > F^*$ (panel a) versus ABC option, (b) probability of a decline in spawning biomass ($\mathrm{SB}_{2010} < \mathrm{SB}_{2009}$) versus ABC option, (c) probability of the SB_{2010} falling below $\mathrm{SB}_{\mathrm{msy}}$, and (d) probability of SB_{2010} falling below SB_{25} (bottom line) or SB_{40} (middle line) and the probability of the SB_{2010} is below SB_{2000} (top line) which corresponds to the lowest biomass estimate in previous assessments.

3.5 Retrospective analysis

Retrospective analysis was conducted to examine the sensitivity of spawning biomass, fishing mortality rates and age-1 recruits to to the addition of new data (Figure 21). There is a slight retrospective bias in spawning stock biomass in years when data is excluded; there is a downward retrospective bias in spawning biomass. For example, as data are removed from estimates of

Table 7: Decision table for catch advice. The risk level represents the probability of exceeding a specified management target for a given ABC option. The interpretation of this table is as follows; if the management goal is not to exceed the target fishing mortality rate of F^* in 2009 with a 0.25 probability, then the ABC option should be set at 0.067 million mt or less. If the management target is prevent further decline in spawning stock biomass with a 0.5 probability then the ABC should be set at 0.111 million mt or less.

Risk level	$F_{2010} \geq F^*$	$SB_{2011} \leq SB_{2010}$	$SB_{2011} \leq SB_{MSY}$	$SB_{2011} \leq SB_{40}$	$SB_{2011} \leq SB_{25}$
0.05	0.007	0.000	0.000	0.000	0.000
0.10	0.092	0.000	0.000	0.000	0.000
0.15	0.145	0.000	0.000	0.000	0.000
0.20	0.185	0.000	0.000	0.000	0.081
0.25	0.218	0.000	0.000	0.000	0.194
0.30	0.247	0.000	0.000	0.000	0.294
0.35	0.273	0.000	0.000	0.000	0.384
0.40	0.298	0.000	0.067	0.000	0.468
0.45	0.321	0.017	0.166	0.000	0.549
0.50	0.344	0.051	0.262	0.000	0.628
0.55	0.367	0.085	0.359	0.100	0.707
0.60	0.391	0.120	0.458	0.209	0.788
0.65	0.415	0.156	0.561	0.324	0.873
0.70	0.442	0.195	0.671	0.446	0.963
0.75	0.470	0.238	0.792	0.581	1.062
0.80	0.504	0.286	0.930	0.735	1.176
0.85	0.543	0.345	1.098	0.921	1.313
0.90	0.597	0.424	1.321	1.169	1.496
0.95	0.682	0.550	1.681	1.569	1.791

spawning stock biomass in 2002 become smaller. As more data has accumulated the strength of the 1999 cohort continues to increase as indicated by the estimates of age-1 recruits in the year 2000 (Figure 21). Due to the fixed selectivity curve, it is possible that the strength of recent cohorts (e.g., 2005 cohort) could increase over time as these fish fully recruit to the fishing gear.

Including the 2009 data (not shown in Fig 21) has markedly increased estimates of overall population scale, and dramatically reduced estimates of historical fishing mortality rates (Figure 21). The 2005 cohort appears to be getting larger as this cohort recruits to the fishing gear.

Retrospective estimates of unfished spawning stock biomass SB_o and the parameters that defined the underlying production also show very little in the way of trends as data are sequentially removed from the analysis (Figure 22). Estimates of SB_o are relatively stable as data from 2000 and onward are included in the assessment, and estimates of M are also relatively stable. Steepness, which is a derived quantity in this assessment and a function of selectivity, has been relatively stable with slight increases based on the last 5 years of data. Overall, the retrospective analysis suggest that the underlying production function is relatively stable, and change in estimates of spawning stock biomass is due to retrospective changes in age-1 recruits.

3.6 Sensitivity to priors

The following sensitivity runs were done prior to the STAR panel meeting and have not been repeated due to time constraints to get this into the SSC and PFMC briefing book.

3.6.1 Prior for ρ

In the previous assessment of TINSS (Martell, 2008, 2009) a major influence on the estimates of unfished biomass in 1966 was the relative weighting of the age-composition data and the assumed variances in the recruitment deviations and observation errors. The assessment herein makes fewer subjective assumptions about how much weight to place on the age-composition data, and the catch advice is partially influenced by the assumed prior distribution on the variance ratio ρ that partitions the total error in to observation and process error components. The assumed beta prior for ρ has an expected value of 0.2 (i.e., 20% of the total error is observation error), and a standard deviation of 0.1. As the assumed proportion of observation errors increases the overall catch advice decreases (Table 8). Estimated rate parameters (e.g., M and F^*) are relatively insensitive to the assumed prior distribution for ρ; however M does decline slightly as more of the error is assumed to be observation error. The global scaling parameters (e.g., C^* and unfished spawning stock biomass) is somewhat sensitive to the assumed value of ρ; catch advice varies by less than 130,000 tons over a wide range of hypotheses about ρ.

3.6.2 Prior for F^*

I also examined the sensitivity of maximum likelihood estimates of the catch advice, based on the 40/10 adjustment, to alternative assumptions about the prior distribution for F^* (see Fig. 23). Increasing or decreasing the mean value for the F^* prior by 20% and maintaining the same standard deviation of the lognormal prior results in a ABC estimate that is roughly 75,000 mt higher or lower, respectively. Increasing the prior standard deviation from 0.262 to 0.5 results in a minor

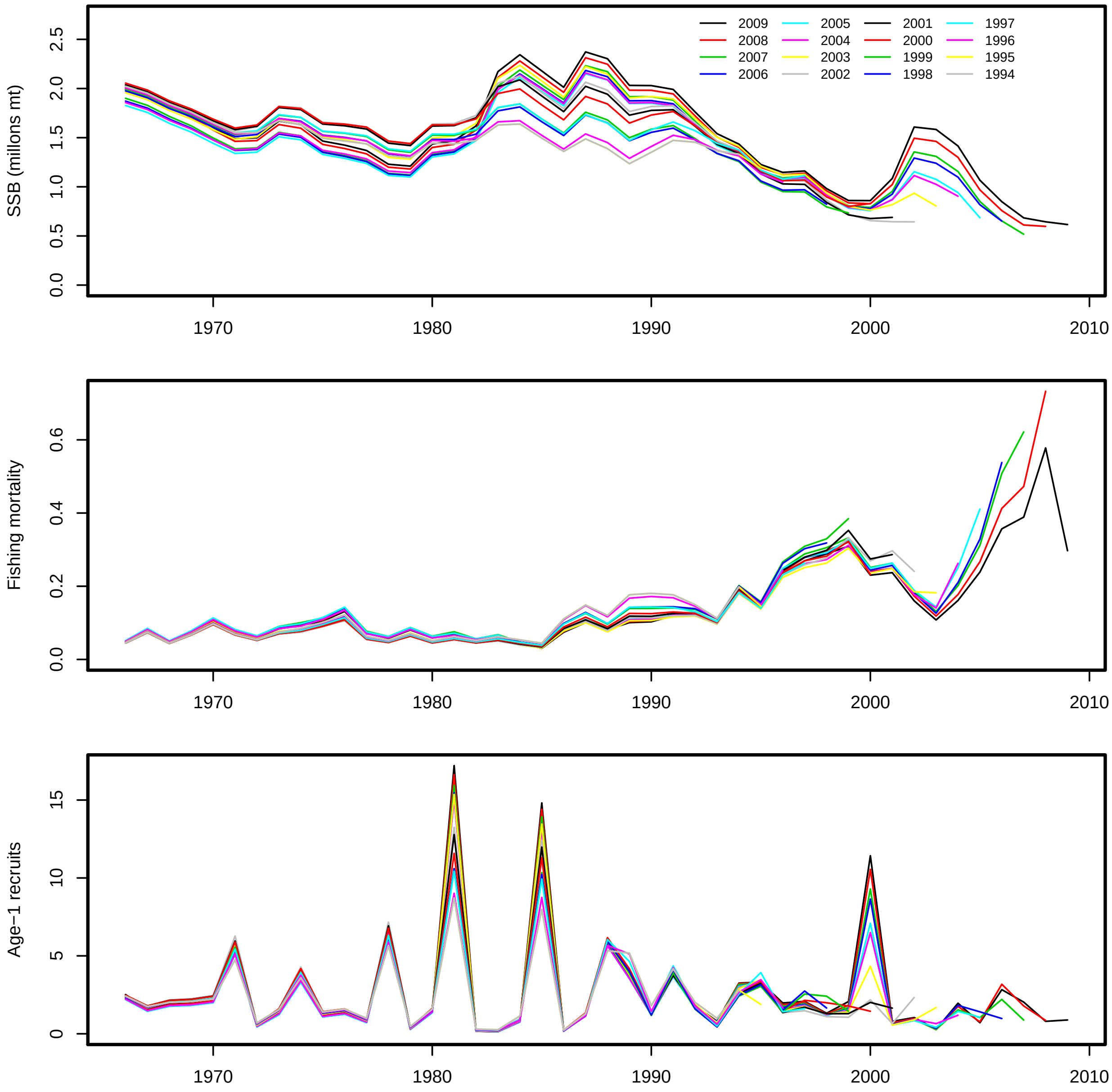

Figure 21: Retrospective maximum likelihood estimates of spawning stock biomass, instantaneous fishing mortality and age-1 recruits based on removal of data from 2009 to 1994.

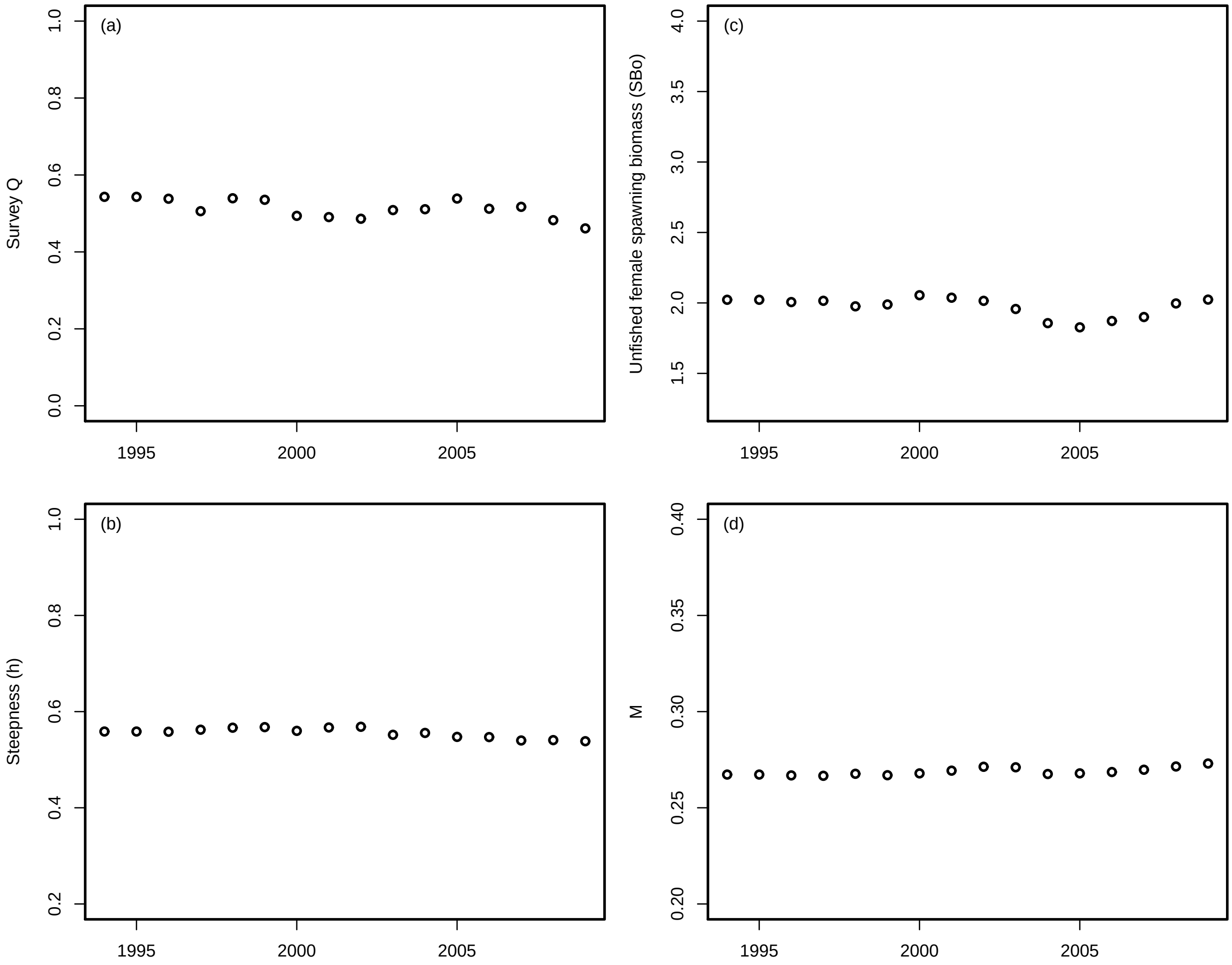

Figure 22: Retrospective maximum likelihood estimates of key parameters. Note that the y-axis for the unfished female spawning stock biomass spans the historical range of biomass estimates in 1966 from stock assessments dating back to 1991.

Table 8: Maximum likelihood estimates of unfished female spawning stock biomass (SB_o), C^* , instantaneous natural mortality rate (M) and Acceptable Biological Catch (ABC t) versus assumed expected value of ρ with a standard deviation equal to 0.1 in the prior distribution.

$E(\rho), \sigma_\rho = 0.1$	SB_o (million mt)	C^* (million mt)	M	40/10 ABC (mt)	ΔABC
0.1	2.373	0.289	0.320	509,017	11,571
0.2	2.354	0.287	0.319	497,446	-
0.3	2.297	0.278	0.317	462,812	(34,634)
0.4	2.221	0.267	0.315	416,559	(80,887)
0.5	2.145	0.256	0.312	370,110	(127,336)

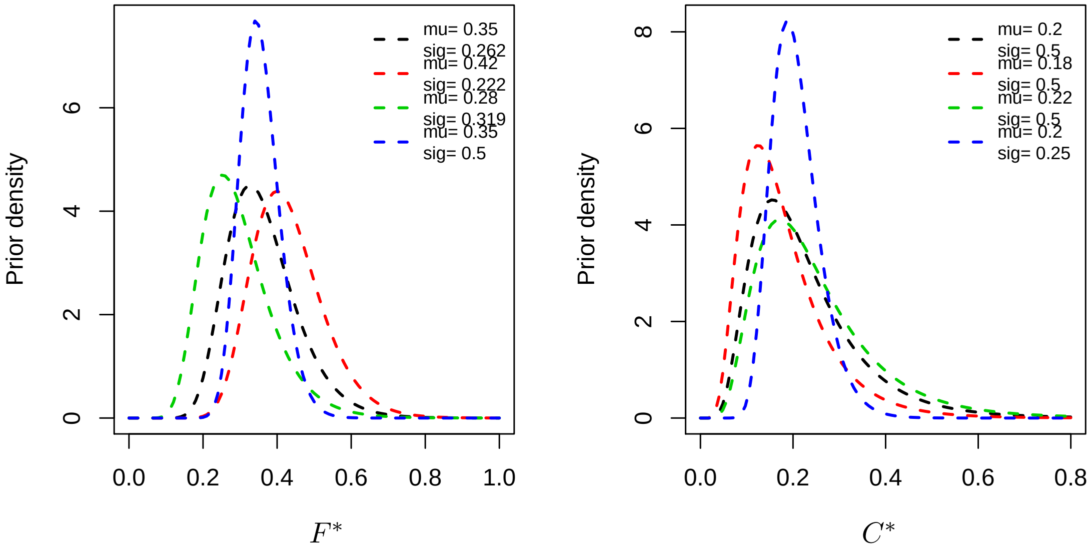

Figure 23: Alternative prior distributions for F^* and C^* in the sensitivity analysis presented in Tables 9 and 10. Note that the black distribution corresponds to the assumed distribution that was used to generate the catch advice.

Table 9: Sensitivity of catch advice (40/10 ABC in metric tons) to alternative prior distributions forF^* . Note the results here correspond to the MLE estimates.

Prior parameters						
μ	σ	C^* (million mt)	F^*	M	40/10 ABC(mt)	ΔABC
0.35	0.262	0.287	0.339	0.319	497,446	-
0.28	0.319	0.309	0.406	0.318	572,316	(74,870)
0.42	0.222	0.260	0.275	0.322	421,503	75,943
0.35	0.5	0.279	0.319	0.320	473,901	23,545

increase of 23,545 mt. Overall, the catch advice is fairly robust to the specified prior distribution for F^* (Table 9) in comparison to the influence of the 2009 biomass index on the 2010 ABC values.

3.6.3 Prior for C^*

Catch advice was slightly sensitive to the assumed mode of the prior distribution for C^* . As the mode of the prior distribution for C^* was decreased by 20% from 208,000 metric tons to 167,000 metric tons, the 2010 catch advice (maximum likelihood estimate of ABC based on the 40/10 rule) decreased from 497,446 tons to 466,642 tons (roughly and 6.2% decease in ABC). As the mode of the prior for C^* was increased by 20% to 250,000 metric tons, the catch advice increased by 26,749 metric tons (roughly a 5.3% increase in ABC, Table 10). Maximum likelihood estimates of C^* were also sensitive to the mode of the prior distribution, but estimates of F^* and M were relatively insensitive.

Table 10: Sensitivity of catch advice (40/10 ABC in metric tons) to alternative prior distributions for C^* . Results correspond to the maximum likelihood estimates.

Prior parameters							
mode	μ	σ	C^* (million mt)	F^*	M	ABC	ΔABC
0.208	0.268	0.5	0.287	0.339	0.319	497,446	-
0.167	0.214	0.5	0.275	0.331	0.318	466,642	(30,804)
0.250	0.322	0.5	0.296	0.346	0.321	524,195	26,749
0.208	0.365	0.75	0.297	0.347	0.321	525,787	28,341

3.6.4 Prior for M

Management advice and the global scaling are extremely sensitive to the assumed prior value for the instantaneous natural mortality rate. There is a fairly strong positive correlation between M and C^* and virtually no correlation between M and F^* (Table 5). As the mean of the prior for M increases, the overall scaling of the population increases along with the catch advice. For example changing the mean of the prior for M from 0.23 to 0.28 results in an increase in C^* from 287,000 mt to 327, mt. The catch advice for 2010 increases from 220,276 mt to 607,032 mt. Reducing the standard deviation for the prior on M from 0.1 to 0.05 results in a overall reduction in C^* from 287,000 to 229,000 mt, and the catch advice based on the 40/10 adjustment is 320,788 mt and spawning biomass depletion in 2010 is estimated at 42%.

4 Discussion

Uncertainty in previous assessments of Pacific hake was under-represented due to the use of assumed fixed values for the steepness of the stock recruitment relationship and survey catchability coefficients. This assessment attempts to integrate over this uncertainty by using less informative prior information for these key parameters. The relative abundance indices alone lack sufficient information to resolve confounding between the global scaling and stock productivity (see appendix C for more discussion on this subject). Addition of the age-composition information further confounds this problem because there appears to be some conflict between expected trends in abundance due to the exceptional 1980 and 1984 cohorts and the downward trend in abundance between the 1986 and 1989 survey points. Helser et al. (2008) also reported similar contradictions in the age composition information between the US and Canadian fishery as well as the fisheries independent survey. Previous assessments have omitted the 1986 survey due to pre- and post-survey calibration problems. However, it appears that the 1986 survey point is consistent with trends inferred from the age-composition data, but the 1989 survey point is inconsistent with these trends. Also, the 2001 survey points is considerably low relative to estimated trends in abundance.

In the previous assessment by Martell (2008), the catch advice was extremely sensitive to the relative weighting of the age-composition information. Minor changes in the assumed effective sample size (e.g., from 10 to 33) resulted in a near doubling of the catch advice (e.g., 142,000 mt to 305,000 mt). In this assessment, I've attempted to remove this subjectivity by using a less informative likelihood for the age-composition data, where the conditional maximum likelihoods of the variance terms are used to weight the age-composition information (see Schnute and Richards, 1995, for more details on this method). The standard procedure of using the mulitinomial distribution and iterative re-weighting procedures (as described in MCALLISTER and IANELLI, 1997) for weighting age-composition fails in cases where there is complete contradictions in 2 or more independent sets of proportion-at-age data. When independent sets of age-composition information are contradictory, the iterative re-weighting procedure fails to converge to an effective sample size.

It is clear that there have been changes in selectivities over time for the commercial gears in the two different countries. Evidence for this is not hard to find; for example, interannual variation in northward migration has profound effects of selectivity, age-specific estimates of F continue to increase for strong cohorts in the VPA models (Sinclair and Grandin, 2008). Treating the selectivity curves as constant over time (whether or not a logistic or dome-shaped selectivity curve is assumed) will obviously affect estimates of relative cohort strengths. Under the mulitinomial likelihood of last years assessment, down weighting the age-composition data was necessary to reduce the amount of retrospective bias, but this down weighting was completely subjective. The multivariate logistic model is much more robust to weighting problems as this likelihood kernel can be evaluated at its conditional maximum likelihood estimate of the variance; this is also known as a concentrated likelihood (Harvey, 1990).

Perhaps the most controversial issue this year is the acoustic biomass survey index. There are some indications that this index is bias upwards due to the vast amounts of humboldt squid present off the west coast. At this time this draft was prepared, there has been an significant increase in the upward scaling of the absolute biomass estimates over last years assessment. Removing the 2009 biomass index has profound affects on the 2010 catch advice. Using all the available data including the age-composition information from both the commercial fisheries and the acoustic biomass survey, but ignoring the 2009 survey biomass index results in more than a 50% reduction in the catch advice for the 2010 fishery. At the time of preparing this manuscript (February 15, 2010), I have chosen to weight the 2009 survey data equally as all other survey years and expect that the STAR panel review will ask for additional runs with alternative weighting schemes for the 2009 (or other survey years) fishery.

Acknowledgments

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References

Bailey, K., Francis, R., Stevens, P., Oceanic, N., Administration, A., Northwest, (US, A. F. C., and States, U. (1982). *The Life History and Fishery of Pacific Whiting, Merluccius Productus*. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest and Alaska Fisheries Center.

Clark, W. G. (1991). Groundfish exploitation rates based on life history parameters. *Canadian Journal of Fisheries and Aquatic Sciences*, 48(5):734–750.

Clark, W. G. (2002). F_{35} Revisited Ten Years Later. *North American Journal of Fisheries Management*, 22(1):251–257.

Dorn, M. and Saunders, M. (1997). Status of the coastal Pacific whiting stock in US and Canada in 1997. *Pacific Fishery Management Council, Appendix: Status of the Pacific Coast groundfish fishery through*.

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

Fournier, D. A., Sibert, J. R., Majkowski, J., and Hampton, J. (1990). Multifan a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (thunnus maccoyii). *Can. J. Fish. Aquat. Sci.*, 47:301–317.

Francis, R., Oceanic, N., Administration, A., Northwest, (US, A. F. C., and States, U. (1982). *On the Population and Trophic Dynamics of Pacific Whiting, Merluccius Productus*. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest and Alaska Fisheries Center, Resource Ecology and Fisheries Management Division.

Goodyear, C. P. (1980). Compensation in fish populations. In Hocutt, C. and Stauffer, C. J., editors, *Biological monitoring of fish*. Lexington Books, D.C. Heath Co., Lexington MA.

Harvey, A. C. (1990). *Forecasting structural time series models and the Kalman filter.* Cambridge University Press.

Helser, T. and Martell, S. (2007a). Stock Assessment of Pacific Hake (whiting) in US and Canadian Waters in 2007. *Pac. Fish. Manage. Counc., Portland, Oreg*, 362.

Helser, T. E. and Martell, S. J. D. (2007b). Stock Assessment of Pacific Hake (whiting) in U.S. and Canadian Waters in 2007. Technical report, Northwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration 2725 Montlake Blvd., East Seattle, WA 98112, USA.

Helser, T. E., Stewart, I. J., and Hamel, O. S. (2008). Stock Assessment of Pacific Hake (whiting) in U.S. and Canadian Waters in 2008. Technical report, Northwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration 2725 Montlake Blvd., East Seattle, WA 98112, USA.

Hilborn, R. and Mangel, M. (1997). *The ecological detective: confronting models with data*. Princeton Univ Pr.

Martell, S. (2008). Assessment and management advice for pacific hake in u.s. and canadian waters in 2008. Technical report, Northwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration 2725 Montlake Blvd., East Seattle, WA 98112, USA.

Martell, S. (2009). Assessment and management advice for pacific hake in u.s. and canadian waters in 2009. *DFO Can. Sci. Advis. Sec. Res. Doc.*, 2009/021:iv+54p.

Martell, S. J. D., III, P. W. E., and Walters, C. J. (2008). Parameterizing age-structured models from a fisheries management perspective. *Can. J. Fish. Aquat. Sci.*, 65:1586–1600.

MCALLISTER, M. and IANELLI, J. (1997). Bayesian stock assessment using catch-age data and the sampling: importance resampling algorithm. *Canadian journal of fisheries and aquatic sciences(Print)*, 54(2):284–300.

Otter Research (2008). *An introduction to AD Model Builder for use in nonlinear modeling and statistics*. Otter Research Ltd., Nanaimo, B.C.

R Development Core Team (2006). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.

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

Schnute, J. and Richards, L. (1995). The influence of error on population estimates from catch-age models. *Canadian Journal of Fisheries and Aquatic Sciences*, 52(10):2063–2077.

Schnute, J. T. and Richards, L. J. (1998). Analytical models for fishery reference points. *Can. J. Fish. Aquat. Sci.*, 55:515–528.

Sinclair, A. and Grandin, C. (2008). Canadian fishery distribution, index analysis, and virtual population analysis of pacific hake 2008. Technical report, Northwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration 2725 Montlake Blvd., East Seattle, WA 98112, USA.

A Input data

Table 11: Combined historical landings (mt) for the U.S. and Can. fisheries, mean age of the catch, and survey abundance indices (millions mt) from the acoustic-trawl survey.

Year	C_t	$\bar{a}$	I_t	Year	C_t	$\bar{a}$	I_t
1966	137700			1988	248804	7.22	
1967	214375			1989	305916	6.97	1.238
1968	122180			1990	259792	6.90	
1969	180131			1991	307258	6.72	
1970	234584			1992	296910	7.51	2.169
1971	154612			1993	199435	6.82	
1972	117546			1994	361529	7.84	
1973	162639			1995	249770	8.24	1.385
1974	211259			1996	306075	7.01	
1975	221360			1997	325215	6.05	
1976	237521			1998	320619	5.30	1.185
1977	132693	6.82	1.915	1999	311855	5.36	
1978	103639	7.11		2000	230820	6.50	
1979	137115	6.84		2001	235962	5.47	0.737
1980	89936	7.03	2.115	2002	182911	4.91	
1981	139121	6.67		2003	205582	4.94	1.840
1982	107734	6.53		2004	334672	5.40	
1983	113924	6.13	1.647	2005	359661	6.18	1.265
1984	138441	5.76		2006	360683	6.51	
1985	110401	5.84		2007	297098	6.48	0.879
1986	210617	6.55	2.857	2008	321546	5.91	
1987	234147	6.35		2009	176671	5.93	1.460

Table 12: Age-composition (reported in percentages) of the combined U.S. and Can. commercial catch from 1977-2009. Age-15 represents a plus group.

Year	age.2	age.3	age.4	age.5	age.6	age.7	age.8	age.9	age.10	age.11	age.12	age.13	age.14	age.15
1977	9.11	3.93	20.86	2.85	5.32	21.12	7.83	7.99	6.36	5.85	4.38	2.96	0.76	0.68
1978	2.30	10.19	6.86	19.91	3.34	7.20	20.84	8.46	7.22	7.30	2.47	2.10	1.31	0.50
1979	4.95	8.96	10.03	4.66	19.19	7.12	15.98	15.84	5.64	3.77	1.62	1.03	0.65	0.58
1980	0.93	25.46	4.21	5.43	5.05	14.38	6.52	8.78	16.95	4.61	3.76	2.31	0.89	0.71
1981	9.12	6.28	28.09	1.29	4.54	4.76	14.88	6.27	6.64	12.60	3.12	1.24	0.97	0.21
1982	18.14	2.59	1.70	31.90	3.26	4.57	4.51	13.10	2.74	3.39	11.96	1.10	0.69	0.36
1983	0.03	32.74	3.04	2.18	31.89	3.45	3.75	4.44	9.53	2.43	1.79	3.77	0.73	0.24
1984	0.00	1.04	54.65	3.54	7.23	18.51	2.38	2.08	1.43	4.53	0.95	0.79	2.44	0.41
1985	0.68	0.63	6.52	60.70	7.04	5.81	13.24	1.16	0.69	0.71	1.35	0.28	0.00	1.19
1986	11.16	3.12	0.78	3.41	48.53	5.80	4.40	12.21	2.29	2.66	1.45	2.66	0.44	1.10
1987	0.00	26.47	1.63	0.39	1.79	54.09	3.23	1.66	8.07	0.39	0.18	0.55	0.98	0.57
1988	0.29	0.29	32.55	1.21	0.70	1.08	46.47	2.13	0.99	10.17	0.19	0.42	0.13	3.38
1989	2.68	2.25	0.96	45.23	1.03	0.46	0.61	39.46	1.53	0.68	4.45	0.09	0.12	0.46
1990	4.86	25.56	2.41	0.23	25.11	0.66	0.17	0.10	32.39	0.39	0.02	7.24	0.01	0.85
1991	3.48	17.69	16.94	2.71	0.73	31.67	1.21	0.13	0.13	20.61	0.39	0.00	3.68	0.64
1992	3.52	4.42	12.66	17.77	2.18	0.75	34.46	0.62	0.13	0.39	19.89	0.50	0.04	2.67
1993	0.73	21.97	3.21	14.16	16.97	1.43	0.75	28.77	0.81	0.11	0.04	10.46	0.05	0.55
1994	0.04	3.38	19.46	1.38	12.18	20.01	1.31	0.48	30.70	0.24	0.41	0.03	9.61	0.77
1995	1.52	0.17	6.78	24.76	1.20	7.60	20.45	1.77	0.31	25.92	0.24	0.38	0.00	8.91
1996	15.52	11.98	0.80	9.26	18.30	1.14	6.30	11.76	0.72	0.48	19.21	0.02	0.12	4.41
1997	0.33	29.28	22.56	1.51	7.69	13.79	2.35	3.83	7.34	1.56	0.18	6.38	0.88	2.32
1998	7.90	20.98	17.64	25.66	2.67	5.13	9.25	0.97	1.73	3.90	0.43	0.11	3.06	0.57
1999	8.16	21.17	18.10	19.68	12.13	2.45	4.37	4.59	0.97	1.61	2.67	0.67	0.71	2.72
2000	3.12	8.78	14.15	14.58	20.90	11.70	7.92	5.87	2.01	2.07	2.56	1.49	1.09	3.76
2001	10.19	16.17	14.72	18.01	10.02	13.87	6.83	1.82	1.96	2.05	1.19	1.10	0.92	1.16
2002	0.04	43.73	15.85	11.58	6.38	5.11	8.00	4.47	1.00	0.86	1.22	0.17	0.48	1.12
2003	0.06	0.99	66.26	13.19	3.41	5.51	3.03	3.42	1.93	0.98	0.30	0.53	0.11	0.28
2004	0.04	5.69	7.80	64.99	8.64	2.40	3.94	2.90	1.32	1.27	0.33	0.30	0.17	0.22
2005	0.87	0.48	7.04	5.50	68.40	8.41	2.18	2.84	1.98	1.04	0.81	0.26	0.04	0.15
2006	1.60	10.93	1.61	8.60	4.73	60.66	5.06	1.79	1.97	1.24	0.93	0.47	0.15	0.25
2007	13.53	3.06	14.55	1.56	7.07	4.19	44.18	5.91	1.84	1.86	1.23	0.43	0.46	0.15
2008	8.64	30.77	2.32	13.43	0.94	3.55	3.33	30.52	3.21	1.09	0.89	0.54	0.33	0.44
2009	0.72	20.12	29.83	4.45	14.07	1.42	2.60	2.21	19.35	3.62	0.50	0.43	0.39	0.30

Table 13: Age-composition (percent) from acoustic surveys from 1977-2009. Note that age-15 represents a plus group. Proportions-at-age were constructed by multiplying the conditional age-length data by the length frequencies and collapsing over each size interval.

Year	age.2	age.3	age.4	age.5	age.6	age.7	age.8	age.9	age.10	age.11	age.12	age.13	age.14	age.15
1977	5.31	4.41	23.03	2.71	4.68	39.08	7.21	5.10	3.84	2.45	1.35	0.55	0.17	0.11
1980	0.16	27.80	2.84	5.60	4.84	23.14	6.23	16.63	6.84	3.84	0.92	0.78	0.18	0.20
1983	0.36	64.90	1.50	1.25	20.05	1.75	2.17	1.92	3.25	1.15	0.87	0.70	0.14	0.00
1986	40.10	1.29	0.54	2.28	41.70	4.55	2.85	5.02	0.52	0.49	0.13	0.43	0.06	0.02
1989	7.25	2.35	0.79	56.08	1.15	0.67	0.94	27.39	1.18	0.16	1.87	0.00	0.00	0.17
1992	10.21	1.73	9.12	19.69	2.37	0.86	38.46	1.29	0.67	0.34	13.89	0.67	0.00	0.71
1995	33.02	4.07	1.25	20.71	1.08	3.73	14.85	0.31	0.00	15.78	0.04	0.72	0.00	4.46
1998	13.50	19.82	15.12	18.89	1.54	4.37	10.21	1.64	0.94	6.31	0.14	0.55	5.08	1.89
2001	69.78	10.41	5.79	5.42	2.57	2.49	1.52	0.50	0.52	0.34	0.21	0.20	0.05	0.21
2003	3.01	2.53	64.05	10.95	2.75	6.01	3.96	2.20	2.23	0.73	0.43	0.44	0.31	0.42
2005	21.57	2.27	7.24	5.30	50.03	5.49	1.86	2.61	1.48	1.17	0.49	0.27	0.04	0.19
2007	35.45	2.39	10.19	1.19	4.57	3.01	33.88	3.62	1.74	1.71	0.92	0.80	0.37	0.17
2009	0.33	31.36	45.45	1.90	7.10	0.59	1.10	1.47	7.85	1.73	0.53	0.31	0.27	0.02

Table 14: Assumed mean weights-at-age in the commercial catch.

Year	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10	age 11	age 12	age 13	age 14	age 15
1966	0.258	0.428	0.527	0.606	0.681	0.762	0.837	0.935	0.988	1.079	1.155	1.213	1.269	1.590
1967	0.258	0.428	0.527	0.606	0.681	0.762	0.837	0.935	0.988	1.079	1.155	1.213	1.269	1.590
1968	0.258	0.428	0.527	0.606	0.681	0.762	0.837	0.935	0.988	1.079	1.155	1.213	1.269	1.590
1969	0.258	0.429	0.527	0.606	0.681	0.762	0.837	0.935	0.988	1.079	1.154	1.212	1.268	1.591
1970	0.256	0.428	0.527	0.606	0.680	0.763	0.837	0.935	0.989	1.079	1.155	1.213	1.269	1.589
1971	0.261	0.428	0.527	0.606	0.682	0.762	0.838	0.936	0.988	1.079	1.156	1.213	1.269	1.591
1972	0.256	0.431	0.527	0.606	0.680	0.761	0.837	0.935	0.987	1.077	1.153	1.211	1.267	1.592
1973	0.251	0.423	0.526	0.606	0.680	0.765	0.836	0.935	0.991	1.081	1.155	1.214	1.270	1.582
1974	0.277	0.431	0.528	0.606	0.685	0.760	0.840	0.937	0.987	1.079	1.159	1.215	1.271	1.600
1975	0.241	0.438	0.527	0.604	0.676	0.759	0.833	0.932	0.983	1.073	1.145	1.204	1.261	1.593
1976	0.235	0.400	0.524	0.608	0.679	0.775	0.835	0.936	1.002	1.093	1.162	1.223	1.277	1.554
1977	0.354	0.454	0.533	0.605	0.700	0.748	0.853	0.944	0.974	1.070	1.168	1.218	1.274	1.653
1978	0.135	0.460	0.523	0.600	0.649	0.754	0.812	0.915	0.973	1.054	1.106	1.169	1.231	1.573
1979	0.217	0.287	0.515	0.619	0.686	0.822	0.841	0.951	1.060	1.154	1.211	1.282	1.327	1.435
1980	0.279	0.407	0.487	0.624	0.684	0.796	0.850	0.877	1.010	1.066	1.184	1.163	1.233	1.196
1981	0.123	0.328	0.491	0.619	0.725	0.776	0.816	0.864	0.884	1.043	1.189	1.245	1.213	1.385
1982	0.235	0.389	0.503	0.604	0.688	0.838	0.873	0.907	0.934	1.029	1.049	1.132	1.209	1.095
1983	0.264	0.355	0.428	0.563	0.631	0.742	0.827	0.854	0.883	0.969	0.994	0.941	1.155	1.095
1984	0.215	0.393	0.429	0.531	0.670	0.699	0.796	0.873	0.894	0.953	1.104	0.965	1.008	1.100
1985	0.181	0.316	0.455	0.526	0.639	0.740	0.813	0.979	0.914	1.020	1.035	1.155	1.074	1.067
1986	0.273	0.314	0.426	0.537	0.562	0.633	0.724	0.821	0.921	0.992	0.989	1.102	1.048	1.086
1987	0.232	0.374	0.422	0.499	0.629	0.626	0.683	0.746	0.799	0.903	0.895	1.023	0.950	1.049
1988	0.264	0.358	0.443	0.461	0.598	0.591	0.628	0.687	0.775	0.809	0.896	0.998	0.993	1.026
1989	0.226	0.317	0.367	0.502	0.531	0.617	0.656	0.670	0.717	0.790	0.896	0.860	1.052	1.030
1990	0.272	0.379	0.443	0.532	0.568	0.617	0.604	0.604	0.701	0.749	0.822	0.880	1.002	1.052
1991	0.229	0.341	0.449	0.543	0.554	0.641	0.716	0.599	0.885	0.728	0.724	0.854	0.952	1.060
1992	0.248	0.338	0.458	0.525	0.582	0.598	0.638	0.638	0.612	0.679	0.698	0.851	0.716	0.932
1993	0.263	0.343	0.426	0.502	0.560	0.593	0.547	0.638	0.645	0.704	0.931	0.679	0.798	0.756
1994	0.335	0.344	0.424	0.510	0.552	0.608	0.694	0.620	0.689	0.636	0.739	0.812	0.725	0.794
1995	0.114	0.515	0.484	0.511	0.626	0.623	0.679	0.706	0.713	0.724	0.662	0.892	0.711	0.772
1996	0.271	0.379	0.462	0.547	0.565	0.628	0.621	0.663	0.712	0.736	0.705	0.553	1.092	0.724
1997	0.328	0.409	0.472	0.519	0.615	0.620	0.601	0.692	0.665	0.741	0.732	0.743	0.696	0.813
1998	0.234	0.350	0.458	0.497	0.518	0.587	0.598	0.619	0.637	0.651	0.776	0.638	0.735	0.734
1999	0.243	0.318	0.417	0.538	0.554	0.578	0.625	0.661	0.672	0.748	0.727	0.746	0.661	0.786
2000	0.282	0.424	0.496	0.564	0.647	0.677	0.658	0.740	0.719	0.818	0.746	0.835	0.786	0.820
2001	0.289	0.454	0.599	0.608	0.681	0.778	0.780	0.806	0.854	0.832	0.831	0.901	0.863	0.962
2002	0.310	0.413	0.558	0.752	0.702	0.812	0.916	0.885	0.885	0.927	0.893	1.064	1.002	1.100
2003	0.304	0.380	0.469	0.573	0.664	0.659	0.679	0.732	0.709	0.766	0.752	0.709	0.827	0.941
2004	0.241	0.419	0.489	0.550	0.626	0.709	0.691	0.713	0.758	0.765	0.742	0.880	0.928	0.836
2005	0.333	0.426	0.497	0.550	0.573	0.611	0.647	0.693	0.679	0.728	0.721	0.804	0.629	0.761
2006	0.251	0.418	0.497	0.552	0.584	0.607	0.646	0.786	0.745	0.798	0.838	0.868	0.802	0.805
2007	0.241	0.408	0.512	0.580	0.618	0.639	0.641	0.697	0.779	0.743	0.776	0.796	0.805	0.863
2008	0.211	0.366	0.516	0.592	0.646	0.672	0.692	0.719	0.759	0.842	0.802	0.795	0.800	0.789
2009	0.211	0.366	0.516	0.592	0.646	0.672	0.692	0.719	0.759	0.842	0.802	0.795	0.800	0.789

B Model description and documentation

The stock assessment model used herein consists of 4 major components: 1) a component for initializing the model based on steady-state conditions, 2) a component for updating the state variables, 3) a component that relates the state variables to observations on relative abundance and composition information, and 4) a statistical criterion for evaluating how likely these data are for a given set of model parameters. We have broken the description of the assessment model into these four components and use a series of tables to document model equations. Symbols and their definitions are defined in Table 15; furthermore, we have divided the estimated parameter set into life-history parameters Φ and population parameters Θ for clarity.

I have adopted a management oriented approach tho the parameterization of the age-structured model where the leading parameters that define population scale and productivity correspond to MSY (hereafter C^*) and Fmsy (hereafter F^*). The basic idea here is to change the question to how likely are the data given C^* and F^* and derive the corresponding B_o and slope of the stock recruitment relationship rather than the traditional approach of estimating these values directly. There are a few statistical advantages of using this approach (i.e., reduced confounding between the leading parameters Schnute and Richards, 1998), but perhaps the biggest advantage is to increase the transparency by which the application of informative priors influence model results (Martell et al., 2008).

Table 15: Description of symbols and indices used in TINSS

Symbol	Description
Indices	
i, j, k, l	index for age,year, fleet, and size interval
Estimated population parameters (Θ)	
F^*	Optimal fishing mortality rate
C^*	Maximum sustainable yield
M	Instantaneous natural mortality rate
a_{h_k}	Age at 50% selectivity
γ_k	Standard deviation in selectivity
Estimated life-history parameters (Φ)	
l_∞	mean asymptotic length
k	growth coefficient
t_o	age at 0 length
a, b	parameters for length-weight relationship
λ_1, λ_2	parameters for standard deviation in length-at-age
Derived variables	
B_o	unfished steady-state biomass
κ	recruitment compensation ratio (Goodyear, 1980)
R_e	equilibrium age-1 recruitment
$\iota_i, \hat{\iota}_i$	survivorship to age i, unfished and fished
ϕ_E, ϕ_e	eggs per recruit, unfished and fished
ϕ_B, ϕ_b	vulnerable biomass per recruit, unfished and fished
ϕ_q	vulnerable biomass available to the fishery

B.1 Model initialization

To initialize the model, we must first derive B_o and κ from C^* and F^* as well as other life-history parameters Φ and the vulnerability schedule. In other words, first we must transform the management parameters C^* and F^* into population parameters B_o and κ. This transformation starts with the equilibrium yield equation (e.g. Fig 24a), differentiating this function with respect to F_e, setting this equation equal to 0 and solving for κ (for the full derivation see Martell et al., 2008). Next substitute κ back into the equilibrium recruitment equation to obtain estimates of the unfished biomass B_o.

An alternative way to envision this transformation is to think about it graphically. For any given model (e.g., a simple production model or a complex age-structure model) we can derive a system of equation that results in the equilibrium yield for any specified equilibrium fishing mortality rate. This same system of equations can also be used to derived equilibrium values of recruitment (e.g., Fig 24b), equilibrium biomass (e.g., Fig 24c) and the spawners per recruit (Fig. 24d). The traditional approach would then differentiate the catch equation with respect to F_e, solve this expression for F_e to determine the corresponding value of F^* , then substitute the corresponding F^* into the catch equation and calculate C^* conditional on estimates of B_o and κ. What differs in the management oriented approach is that we estimate C^* and F^* directly and then derive B_o and κ conditional on the estimates of C^* and F^* .

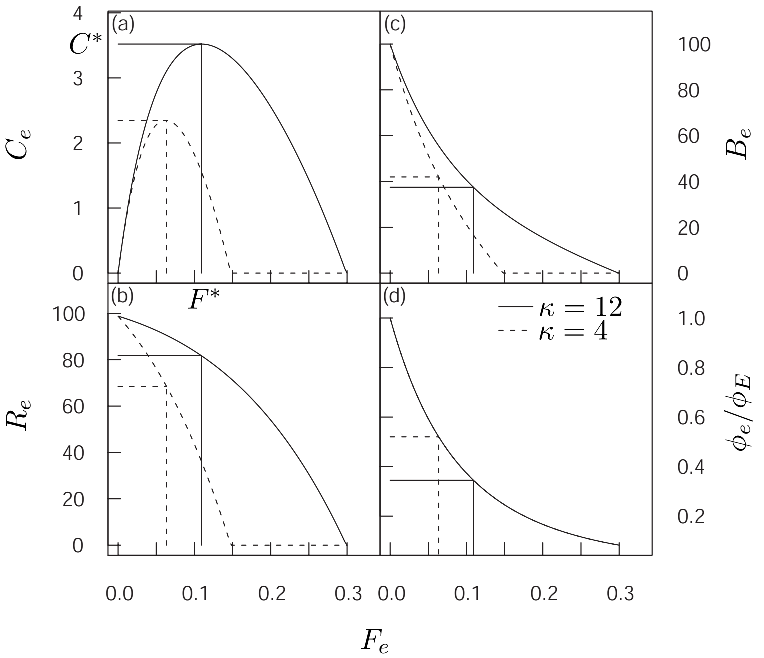

Figure 24: Relationship between equilibrium values for yield (a), recruitment (b), biomass (c) and spawners per recruit (d) versus instantaneous fishing mortality rate for a hypothetical stock with high ($\kappa = 12$) and low ($\kappa = 4$) recruitment compensation parameters.

The system of equation used to derive B_o and κ are laid out in Table 16. The purpose of laying out the equations in a tabular format is two fold, 1) documentation of the model structure and 2) to provide an algorithm or pseudo code in which to implement the model. First given initial estimates of the life-history parameters Φ (T16.2), calculate the corresponding age-schedule information (T16.3)–(T16.6). Note that this does not assume that growth or maturity is constant over time, only that some average, or steady state, growth occurred for the cohorts that are used to initialize the numbers-at-age. Next, calculate the survivorship (T16.7) of an individual recruit based on the instantaneous natural mortality rate M. These survivorship functions (T16.7) and (T16.8) are used to calculate the per recruit incidence functions for unfished and fished conditions, respectively. An incidence function is the sum of age-specific schedules that express the population units on a per recruit basis. For example the total biomass per recruit is given by (T16.10) and the total unfished biomass is the product $R_o\phi_E$. For notational purposes the prefix ϕ denotes an incidence function and the corresponding subscript denotes the type of incidence function (see Table 15 for definitions); we also use upper and lower case subscripts to denote unfished and fished conditions, respectively.

The eggs per recruit for unfished and fished conditions are defined by (T16.9), the biomass per recruit by (T16.10), and the vulnerable biomass per recruit available to the fishery is defined by (T16.11). Note that we assume both natural and fishing mortality operate simultaneously and ϕ_q represents the Barnov catch equation. To derive κ, we differentiate

$$C_e = F_e R_e \phi_q \tag{1}$$

with respect to F_e and solve this equation for κ. Using the chain rule, the derivative of (1) is

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

To derive the recruitment compensation parameter (T16.12) it is necessary to substitute (T16.11) and (T16.13) into (2), set the corresponding expression equal to zero and then solve for κ. The partial derivatives for (T16.12) are defined in Table 17. Equation (T16.13) is the equilibrium recruits that corresponds to the equilibrium fishing mortality rate F_e and (T16.14) corresponds to the unfished biomass.

B.1.1 Initialization with multiple fleets

Although the catch data are aggregated into a single fleet for this assessment, the following describes an algorithm for implementing the management oriented approach for multiple fleets that have different age-specific fishing mortality rates. In essence, the algorithm derives F-multipliers for each fleet.

The catch equation (1) considers a single fishery with a unique vulnerability-at-age curve. In the case of multiple fisheries with different vulnerability-at-age curves, it is necessary to allocate the proportion of the total fishing mortality (F^*) to each fleet such that the sum of catches from each fleet is equal to C^* . For example, consider two separate fishing fleets A and B and assume that fleet A harvest younger fish that fleet B and that the allocation of C^* is assigned equally to each fleet. In this case a higher proportion of F^* would be assigned to fleet B because this fleet harvest fewer, older fish, in comparison to fleet A which harvest more abundant younger fish. Thus, if some sort of allocation agreement exists between two or more fleets, a multiplier on the fishing mortality rate must be used to allocate the total catch among these fleets. For a given allocation arrangement (e.g., where the fraction of C^* assigned to fleet k is denoted as Λ_k), the equilibrium catch of fleet k can be represented as:

$$\Lambda_k C^* = \tau_k F^* R_e \phi_q^{(k)} \tag{3}$$

where τ_k is the fleet specific multiplier on F^* , R_e is defined in (T16.13), and $\phi_q^{(k)}$ is the fleet specific vulnerable biomass per recruit which is defined as

$$\begin{aligned} \phi_q^{(k)} &= \sum_i \frac{\hat{\iota}_i w_i v_{i,k}}{Z_i} \left(1 - e^{-Z_i}\right), \\ \text{where} \quad Z_i &= M + F^* \sum_k \tau_k v_{i,k}, \\ \hat{\iota}_i &= \begin{cases} 1 & i = 1 \\ \hat{\iota}_{i-1} e^{-Z_{i-1}} & i > 1. \end{cases} \end{aligned} \tag{4}$$

Note that τ_k appears multiple times in (4) in the Z_i and $\hat{\iota}_i$ terms, as well as the derivation of R_e (see eq. T16.13), and there is no analytical solution for τ_k (at least that we could find using symbolic math languages). Therefore, τ_k must be solved for iteratively. Solving (3) for τ_k results in an update of τ_k:

$$\tau_k = \frac{\Lambda_k C^*}{R_e F^* \phi_q^{(k)}} \tag{5}$$

A simple algorithm to numerically calculate τ_k proceeds as follows

1. set initial values of the fishing multiplier equal to the allocation proportion: $\tau_k = \Lambda_k$ (Note that if the vulnerability-at-age curves are the same for each fleet, then τ_k is exactly equal to Λ_k, i.e., the vulnerable biomass per recruit is the same for all fleets).

2. calculate the age-specific total mortality rates for all fleets combined

$$Z_i = M + F^* \sum_k \tau_k v_{i,k}.$$

3. calculate survivorship ($\hat{\iota}_i$), and per-recruit incidence functions that lead to R_e (eqs. T16.8–T16.13) based on the age-specific total mortality rate in step 2.

4. for each fleet k, calculate the vulnerable biomass per-recruit ($\phi_q^{(k)}$) using (4).

5. update τ_k using (5), and repeat steps 2-5 until estimates of τ_k converge (Note this take 6-20 iterations depending on how different the vulnerability-at-age curves are for each fleet.

6. Check that the sum catches for each fleet equal C^* .

The algorithm outline above is based on the allocation arrangement among the various fleets (Λ_k) and is not intended to optimize the allocation arrangement based on differences in vulnerability among the various fishing fleets. This is an entirely different policy issue that is not addressed here. If there is no formal allocation arrangement, then historical catch proportions to each fleet could be used as a starting point for values of Λ_k. Recall, that the approach adopted here is to simple express the population parameters B_o and κ as analytical functions of management parameters C^* and F^* .

B.2 Updating state variables

Equations used to update the state variables are defined in Table 18. We aggregate the catch data from the CAN and US fisheries into a single catch time series (T18.1) and treat both fisheries as a single fishery with the same selectivity pattern over time. This data simplification reduces the number of estimated parameters but further assumes that the relative mortalities imposed by the two different fisheries has been constant over time. We also aggregate the catch-age samples from the commercial fisheries ($A_{i,j}$) into a single catch age matrix. Catch-age data for the US portion of the fishery are available back to 1976, and age-composition information for the CAN portion of the fishery are available back to 1988. The age-compositions were combined from 1988 to 2006 using a weighted average, where the weights are the proportions landed by each nation.

Process errors are represented as a vector of annual recruitment deviations ω_j which are assumed to be lognormal with an estimated variance τ^2. These annual deviations are estimated parameters and included in the objective function calculation with a bias correction term for the log-normal distribution (T19.1).

The relative abundance data (I_j) corresponds to the abundance index derived from the acoustic surveys, and here we assume these indices are proportional to abundance and use the conditional maximum likelihood estimate of the scaling parameter in the calculation of the residuals (T18.13). I assume that observation errors in the acoustic survey data are lognormal and the likelihood function for acoustic survey data are given by (T19.2).

Residuals between the observed proportions and predicted proportions-at-age for each fleet (the joint US and CAN fleet and the fisheries independent surveys) were assumed to come from a multivariate logistic distribution. Age composition information are generally thought to arise from a multinomial distribution where the probability of sampling a fish of a given age is conditioned on the product of proportions-at-age in the population and the probability of sampling a fish age-i given the sampling gear. However, the multinomial likelihood kernel generally results in errors that are unrealistically small due to the large samples taken for ageing (Schnute and Richards, 1995). The advantage of the multivariate logistic distribution is that the likelihood kernel can be weighted by the conditional maximum likelihood estimate of the variance; this is given by the mean squared error of the residual terms $\eta_{i,j,k}$ for each fleet k. The likelihood of the age composition information for both fleets k (commercial and acoustic survey) is given by (T19.3).

Table 16: Steady-state age-structured model assuming unequal vulnerability-at-age, age-specific natural mortality, age-specific fecundity and Beverton-Holt type recruitment.

Parameters

$$\Theta = (C^*, F^*, M, \hat{a}, \hat{\gamma}); \quad C^* > 0; F^* > 0; M > 0 \tag{T16.1}$$

$$\Phi = (l_\infty, k, t_o, a, b, \dot{a}, \dot{\gamma}) \tag{T16.2}$$

Age-schedule information

$$l_i = l_\infty(1 - \exp(-k(a - t_o))) \tag{T16.3}$$

$$w_i = a(l_i)^b \tag{T16.4}$$

$$v_i = (1 + \exp((\hat{a} - a)/\hat{\gamma}))^{-1} \tag{T16.5}$$

$$f_i = w_i(1 + \exp((\dot{a} - a)/\dot{\gamma}))^{-1} \tag{T16.6}$$

Survivorship

$$\iota_i = \begin{cases} 1, \quad i = 1 \\ \iota_{i-1}e^{-M}, \quad i > 1 \\ \dfrac{\iota_{i-1}}{1 - e^{-M}}, \quad i = A \end{cases} \tag{T16.7}$$

$$\hat{\iota}_i = \begin{cases} 1, \quad i = 1 \\ \hat{\iota}_{i-1}e^{-M-F^* v_{i-1}}, \quad i > 1 \\ \dfrac{\hat{\iota}_{i-1}}{1 - e^{-M-F^* v_i}}, \quad i = A \end{cases} \tag{T16.8}$$

Incidence functions

$$\phi_E = \sum_{i=1}^{\infty} \iota_i f_i, \quad \phi_e = \sum_{i=1}^{\infty} \hat{\iota}_i f_i \tag{T16.9}$$

$$\phi_B = \sum_{i=1}^{\infty} \iota_i w_i, \quad \phi_b = \sum_{i=1}^{\infty} \hat{\iota}_i w_i v_i \tag{T16.10}$$

$$\phi_q = \sum_{i=1}^{\infty} \frac{\hat{\iota}_i w_i v_i}{M + F^* v_i}\left(1 - e^{(-M-F^* v_i)}\right) \tag{T16.11}$$

Derived variables

$$\kappa = \frac{\phi_E}{\phi_e} - \frac{F^* \phi_q \dfrac{\phi_E}{\phi_e^2} \dfrac{\partial \phi_e}{\partial F^*}}{\phi_q + F^* \dfrac{\partial \phi_q}{\partial F^*}} \tag{T16.12}$$

$$R_e = \frac{C^*}{F^* \phi_q} \tag{T16.13}$$

$$B_o = \phi_B \frac{R_e(\kappa - 1)}{\kappa - \phi_E/\phi_e} \tag{T16.14}$$

Table 17: Partial derivatives, based on components in Table 16, required for the derivation of κ and B_o using the Beverton-Holt recruitment model.

Mortality & Survival

$$Z_i = M + F^* v_i \tag{T17.1}$$

$$S_i = 1 - e^{-Z_i} \tag{T17.2}$$

Partial for survivorship

$$\frac{\partial \hat{\iota}_i}{\partial F^*} = \begin{cases} 0, & i = 1 \\ e^{-Z_{i-1}} \left(\dfrac{\partial \hat{\iota}_{i-1}}{\partial F^*} - \hat{\iota}_{i-1} v_{i-1} \right), & i > 1 \\ \dfrac{e^{-Z_{i-1}}}{1 - e^{-Z_i}} \left(\dfrac{\partial \hat{\iota}_{i-1}}{\partial F^*} - \hat{\iota}_{i-1} v_{i-1} \right) - \hat{\iota}_{i-1} e^{-Z_{i-1}} v_i e^{-Z_i}, & i = A \end{cases} \tag{T17.3}$$

Partials for incidence functions

$$\frac{\partial \phi_e}{\partial F^*} = \sum_{i=1}^{\infty} f_i \frac{\partial \hat{\iota}_i}{\partial F^*} \tag{T17.4}$$

$$\frac{\partial \phi_q}{\partial F^*} = \sum_{i=1}^{\infty} \frac{w_i v_i S_i}{Z_i} \frac{\partial \hat{\iota}_i}{\partial F^*} + \frac{\hat{\iota}_i w_i v_i^2}{Z_i} \left(e^{-Z_i} - \frac{S_i}{Z_i} \right) \tag{T17.5}$$

Partial for recruitment

$$\frac{\partial R_e}{\partial F^*} = \frac{R_o}{\kappa - 1} \frac{\phi_E}{\phi_e^2} \frac{\partial \phi_e}{\partial F^*} \tag{T17.6}$$

Table 18: Statistical catch-age model using the Baranov catch equation and C^* and F^* as leading parameters.

Data

$$C_j = C_j^{\mathrm{US}} + C_j^{\mathrm{CA}} \tag{T18.1}$$

$$I_j, A_{i,j,k} \tag{T18.2}$$

Parameters

$$\Theta = (C^*, F^*, M, \hat{a}, \hat{\gamma}, \bar{a}, \bar{\gamma}, \{\omega_j\}_{j=1}^{J-1}, \rho, \vartheta^2) \tag{T18.3}$$

$$\sigma^2 = \rho\vartheta^2, \quad \tau^2 = (1-\rho)\vartheta^2, \quad \sum_t \omega_t = 0 \tag{T18.4}$$

Unobserved states

$$N_{i,j}, B_j, E_j, F_j \tag{T18.5}$$

Initial states (t=1)

$$N_{i,j} = B_o/\phi_B \iota_i \tag{T18.6}$$

State dynamics (t>1)

$$E_j = \sum_i N_{i,j} f_i \tag{T18.7}$$

$$Z_{i,j} = M + F_j v_i \tag{T18.8}$$

$$\hat{C}_j = \sum_i \frac{N_{i,j} w_i F_j v_i \left(1 - e^{-Z_{i,j}}\right)}{Z_{i,j}} \tag{T18.9}$$

$$F_{j_{i+1}} = \ F_{j_i} - \frac{\hat{C}_j - C_j}{\hat{C}'_j} \tag{T18.10}$$

$$N_{i,j} = \begin{cases} \dfrac{s_o E_{j-1}}{1 + \beta E_{j-1}} \exp(\omega_j - 0.5\tau^2) & i = 1 \\ \\ N_{i-1,j-1} \exp(-Z_{i-1,j-1}) & i > 1 \end{cases} \tag{T18.11}$$

$$B_j = \sum_i N_{i,j} w_i v_i \tag{T18.12}$$

Residuals

$$\epsilon_j = \ln\left(\frac{I_j}{B_j}\right) - \frac{1}{n} \sum_{j \in I_j} \ln\left(\frac{I_j}{B_j}\right) \tag{T18.13}$$

$$\eta_{i,j,k} = \ln(p_{i,j,k}) - \ln(\bar{p}_{i,j,k}) - \frac{1}{I-1} \sum_{i=2}^{I} [\ln(p_{i,j,k}) - \ln(\bar{p}_{i,j,k})] \tag{T18.14}$$

Table 19: Likelihoods and priors used in the statistical estimation of Θ from Table 18.

Negative log-likelihoods

$$\ell(\Theta)_1 = \sum_{j=1}^{J-1} \left[\ln(\tau) + \frac{(\omega_j + 0.5\tau^2)^2}{2\tau^2} \right] \tag{T19.1}$$

$$\ell(\Theta)_2 = \sum_{j \in I_j} \left[\ln(\sigma) + \frac{\epsilon_j^2}{2\sigma^2} \right] \tag{T19.2}$$

$$\ell(\Theta)_3 = \sum_k \left\{ (I-2) J_{j\in k} \ln \left(\frac{1}{(J_{j\in k} - 2)I} \sum_{j=1}^{J_{j\in k}} \sum_{i=2}^{I} \eta_{i,j,k}^2 \right) \right\} \tag{T19.3}$$

$$\ell(\Theta) = \sum_{i=1}^{3} \ell(\Theta)_i \tag{T19.4}$$

Constraints

$$\kappa > 1.0 \tag{T19.5}$$

Posterior distribution

$$P(\Theta) \propto \exp[-\ell(\Theta)] p(C^*) p(F^*) p(M) p(\rho) p(\vartheta^2) \tag{T19.6}$$

C Lagged Recruitment Growth Survival Model

For comparison a much simpler biomass dynamics model was fit to the survey biomass index data only (Table 20). The model, which is referred to as the lagged recruitment growth survival model (LRGS) is documented in Hilborn and Mangel (1997). In this assessment I assume the unfished conditions in 1966, 3+ biomass are fully recruited to the fishery and sexually mature, and that the acoustic biomass index is directly proportional to the 3+ biomass in the stock. The model is conditioned on the historical landings from both the Canadian and U.S. fisheries combined, and is an observation error only model (there are no estimated recruitment anomalies). The joint posterior distribution (defined as the sum of ℓ and the priors defined in Table 20) was numerically integrated using the Metropolis Hastings Algorithm that is built into the ADMB software (Otter Research, 2008). A total of 4 model parameters were estimated.

Using the LRGS model maximum likelihood estimates of depletion given all the survey data is 0.39, and the 50 percentile is 0.447. Proxy reference points are assumed to correspond to a 3+ biomass depletion of 40%, and catch advice based on the 40:10 adjustment and the maximum likelihood estimates of model parameters is 194,931 mt. Based on parameters sampled from the joint posterior distribution ABC values for the 2010 fishery are estimated at 395,370 mt (95% credible interval of 82,796 mt to 1,856,400 mt).

There is considerable uncertainty in the estimate of unfished 3+ biomass with the median estimate at 2.68 million mt (95% credible interval 1.33-714 million mt) and this uncertainty is largely associated with the large variance in the assumed prior distributions for B_o, κ, and S in the LRGS model (Figure 26). The relative abundance information lack sufficient contrast to resolve the uncertainty in the overall scale of the population and how productive it is. Statistically, the best fit to the relative abundance data is probably a straight line given this simple model structure. In the case of the LRGS model there is a fairly strong positive correlation between unfished biomass and the growth survival term S. In other words, the biomass and catch data are just as likely to come from a small productive population or a large unproductive population.

Table 20: Lagged Recruitment Growth Survival Model where the assumed age at recruitment (k) is 3 years.

Data

$$C_t \tag{T20.1}$$

$$I_t \tag{T20.2}$$

$$k = 3 \tag{T20.3}$$

Estimated parameters

$$\theta = \{B_o, \kappa, S, \tau\}, \quad \text{where:} \quad \kappa > 1; 0 < S < 1 \tag{T20.4}$$

Initial states $t = 1966$

$$B_t = B_o \tag{T20.5}$$

$$a = \kappa(1 - S) \tag{T20.6}$$

$$b = (\kappa - 1)/B_o \tag{T20.7}$$

Dynamic states$t > 1966$

$$B_{t+1} = SB_t + R_t - C_t \tag{T20.8}$$

$$R_t = \begin{cases} B_o(1 - S) & \text{if} \quad t \leq 1966 + k \\ \dfrac{aB_{t-k}}{1 + bB_{t-k}} & \text{if} \quad t > 1966 + k \end{cases} \tag{T20.9}$$

Residuals

$$\epsilon_t = \ln(I_t) - \ln(B_t) - \frac{1}{n}\sum_{t \in I} \ln(I_t) - \ln(B_t) \tag{T20.10}$$

Negative loglikelihood and priors

$$\ell = -0.5n\ln(\tau) + 0.5\tau\sum_{t \in I} \epsilon_t^2 \tag{T20.11}$$

$$P(B_o) \sim \text{lognormal}(\ln(2.5), 0.75) \tag{T20.12}$$

$$P(\kappa) \sim \text{lognormal}(\ln(30), 0.5) \tag{T20.13}$$

$$P(S) \sim \text{beta}(\alpha = 15.0, \beta = 4.0) \tag{T20.14}$$

$$P(\tau) \sim \text{gamma}(\alpha = 1.1, \beta = 1.1) \tag{T20.15}$$

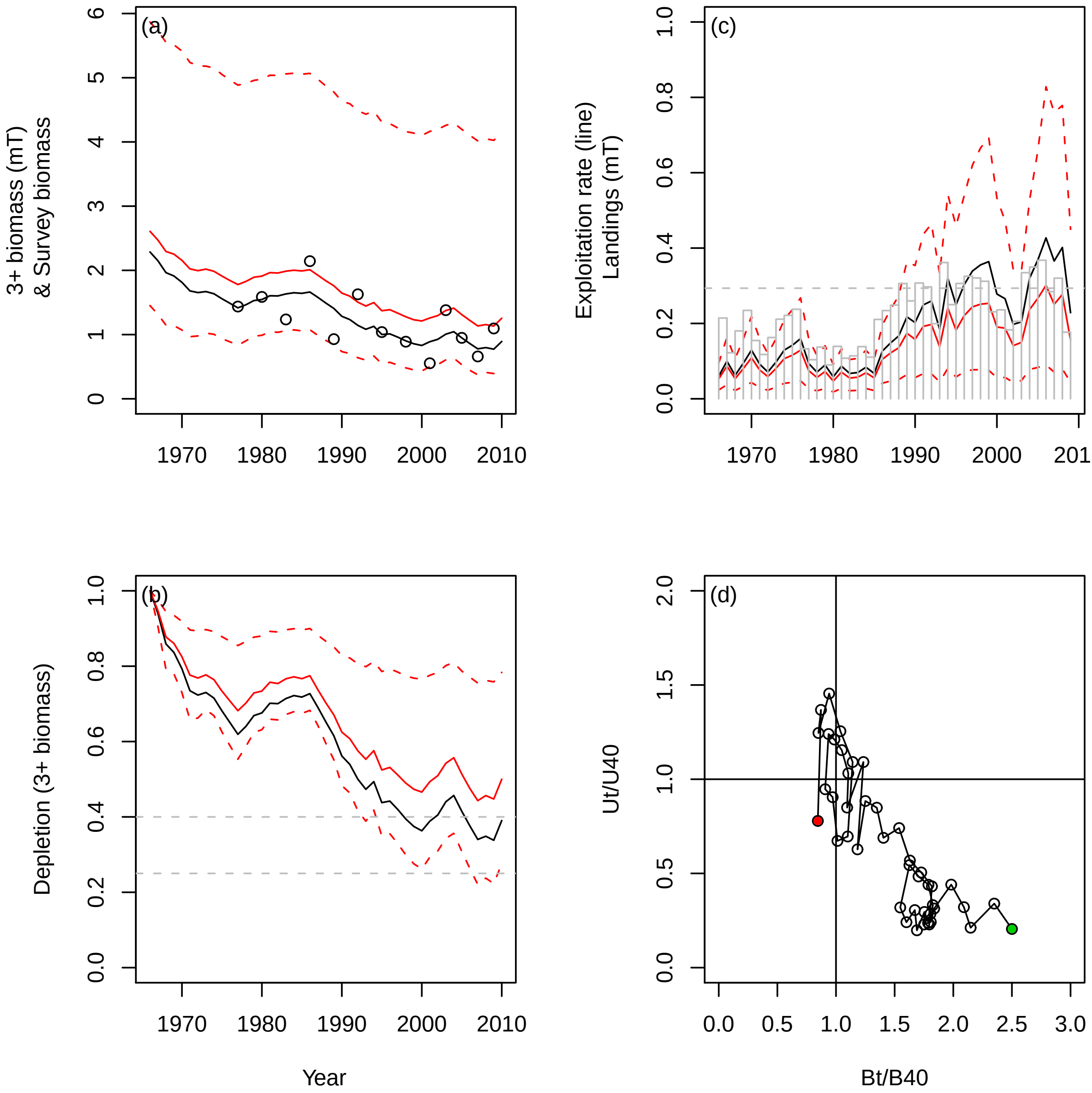

Figure 25: Summary estimates of biomass, depletion, exploitation rate and stock status based on the LRGS model. Maximum likelihood estimates shown in black and quantiles (0.05, 0.5, 0.95) estimates based on the joint posterior distribution shown in red (or grey if black and white). In panel (a) the biomass index survey data are scaled to the maximum likelihood estimate, depletion (panel b) assumes unfished state in 1966, and exploitation rate (c) is based on catch divided by 3+ biomass. U40 is the exploitation rate that would reduce the 3+ biomass to 40% of its unfished state.

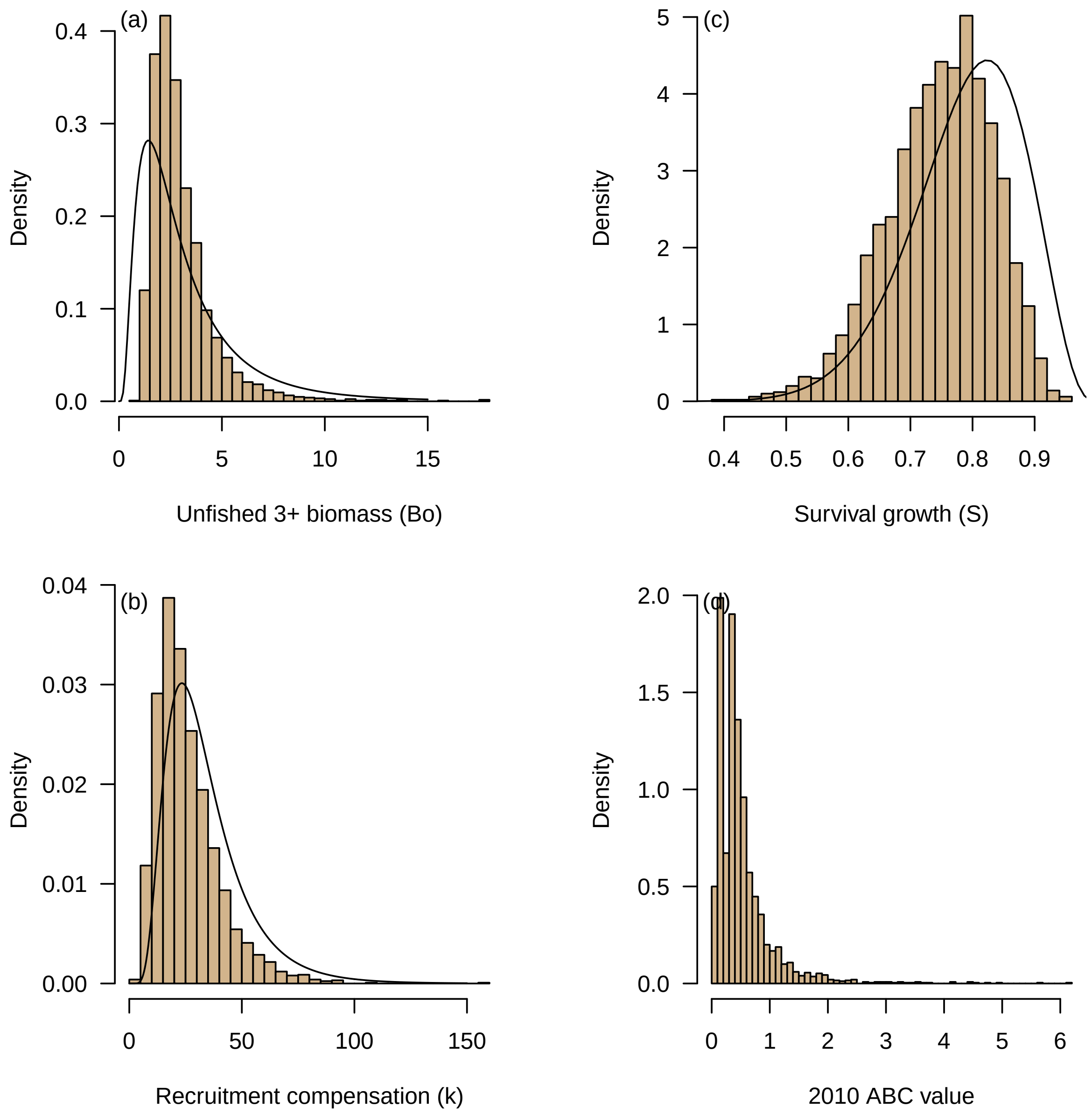

Figure 26: Marginal posterior densities (shown as bars) for unfished 3+ biomass (a), recruitment compensation (b), and the survival growth parameter (c) in the LRGS biomass dynamics model. Prior densities for each parameter is shown as a line, and the resulting marginal posterior density for the 2010 catch advice using 40% of the 3+ biomass as a target reference point in the 40-10 harvest control rule.