Investigation of some alternative stock assessment model structures for Mid-East Coast orange roughy

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EXECUTIVE SUMMARY

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This report describes the assumptions, input data, and preliminary runs of an assessment model for the Mid-East Coast (MEC) orange roughy stock. The MEC stock covers the area off the east coast of New Zealand from the Ritchie Bank, east of Hawke's Bay, south as far as Banks Peninsula, and includes the quota management areas ORH 2A South, ORH 2B, and ORH 3A.

The assessment model described in this report assumed a spatial structure, where orange roughy recruited to flat areas of the continental slope, then later moved to hill areas, with spawning fish coming from either the latter or both areas. The model assumed two strata ('flat' and 'hill'), and three fisheries ('flat', 'hill', and 'spawning'). This contrasts with previous orange roughy stock assessment models, in which there was only a single stock area. A single area model was completed alongside this work, and was accepted for stock assessment in 2011. Details of the one-area model are reported elsewhere.

The majority of this report describes the observational data used to inform the spatial model, and then tables and figures of model fits. The observational data were catches, standardised catch-per-unit-effort biomass indices, a trawl survey biomass index and length compositions, acoustic and egg survey biomass estimates, length and age compositions from the commercial fisheries, and the biological parameters required for a demographic model. The model was implemented in CASAL.

The model was able to fit the steep decline and then flat trend of the CPUE indices (a pattern consistent with 'hyper-depletion'), and also prevented completely unavailable ('cryptic') mature stock biomass from occurring; in this sense the model was successful. Whilst the model could fit most of the data quite well, it could not fit all of the observational data at the same time. In particular, it could not easily fit the decline in the trawl survey biomass index for the flat stratum. Model sensitivity runs focused on investigating the fit to the trawl survey biomass index, spawn fishery length and age compositions, and modifications of productivity assumptions (natural mortality rate and recruitment).

Whilst the model was not used to inform management decisions, it did indicate an explanation for hyper-depletion and cryptic mature biomass, and the results supported a number of hypotheses; (1) that spatially distinct CPUE indices provide biased estimates of total stock biomass trends; (2) that mature biomass is not equal to spawning biomass, with smaller and younger fish more prone to skip spawning; (3) that productivity assumptions for orange roughy remain the key unknown, and (4) that representative sampling of orange roughy stocks is difficult to achieve. The latter may ultimately preclude credible complex quantitative stock assessment models being fitted.

1. INTRODUCTION

Orange roughy are the focus of an important deepwater fishery in New Zealand, and have been fished for 30 years (Ministry of Fisheries 2010). The Mid-East Coast (MEC) orange roughy stock covers an area off the east coast of the North Island from the Ritchie Bank, east of Hawke's Bay, south to Banks Peninsula (Figure 1). It consists of the orange roughy Quota Management Areas (QMAs) ORH 2A South (the part of ORH 2A south of 38° 23' S), ORH 2B (Wairarapa), and ORH 3A (Kaikoura). These areas have been treated together as a separate stock since 1995. Before that, the stock assessment area also included the northern part of ORH 2A. This area, known as the "East Cape stock", is now assessed separately (Ministry of Fisheries 2010).

This report addresses parts of objectives 2 and 4 of the Ministry of Fisheries project ORH2008/02 that deal with the Mid-East Coast orange roughy fishery: "*To update the unstandardised and standardised catch per unit effort analyses with the inclusion of data up to the end of the 2008/09 fishing year …*" and *"To update the stock assessment, including reviewing and summarising historical biological data collected by the MFish Observer Programme and other sources, and estimating biomass and sustainable yields for the MEC"*.

This report specifically describes the investigation of alternative stock assessment model structures, including the estimation of the required input data, which was completed in February–April 2011.

2. STOCK ASSESSMENT MODEL STRUCTURE

The Mid-East Coast has been assumed to contain a discrete orange roughy stock (Ministry of Fisheries 2010). A stock assessment for MEC orange roughy was attempted in 2006–07, but encountered some problems, and was not eventually accepted. The key problem appeared to be an assumption of deterministic recruitment, which was used because of a lack of convincing information to the contrary (Francis & Clark 2005; Francis 2006). Assessments of other stocks had cast doubt on the validity of deterministic productivity assumptions (e.g. Dunn et al. 2009). Stochastic recruitment was not assumed because of the low precision and potential for bias in the available age frequency estimates, a consequence of the difficulty in interpreting growth zones on otoliths (Francis 2006; Andrews et al. 2009). Some other but potentially related problems were encountered; these included apparent hyper-depletion (Harley et al. 2001), where models could not fit the initially steep and then relatively flat biomass indices, and "cryptic" spawning stock biomass, where maturity was estimated to take place well before vulnerability to the fishery (Francis 2006; Dunn 2007). It remained unclear to what extent the problems with productivity, hyper-depletion, and cryptic spawning stock biomass, were connected within the models.

One possible solution to the problems of hyper-depletion and cryptic spawning biomass could lay with an observed structure in the orange roughy stock. Juvenile orange roughy have been found in greatest abundance in relatively shallow water, extending into deeper water as they grow, with the largest fish found on and around hills and other features (Dunn 2008; Dunn et al. 2009; Dunn & Devine 2010). Fisheries for orange roughy typically target orange roughy aggregations on and around hills and features, where higher catch rates can be achieved (Anderson & Dunn 2011). A spatial structure hypothesis with separate hill and flat strata could potentially explain both hyper-depletion and cryptic spawning stock biomass, the former by allowing for local and rapid depletion of aggregations on hills, followed by extended lower catch rates supported by immigration; the latter because hill-focused fisheries could avoid catching smaller, but reproductively active, fish outside of the hills.

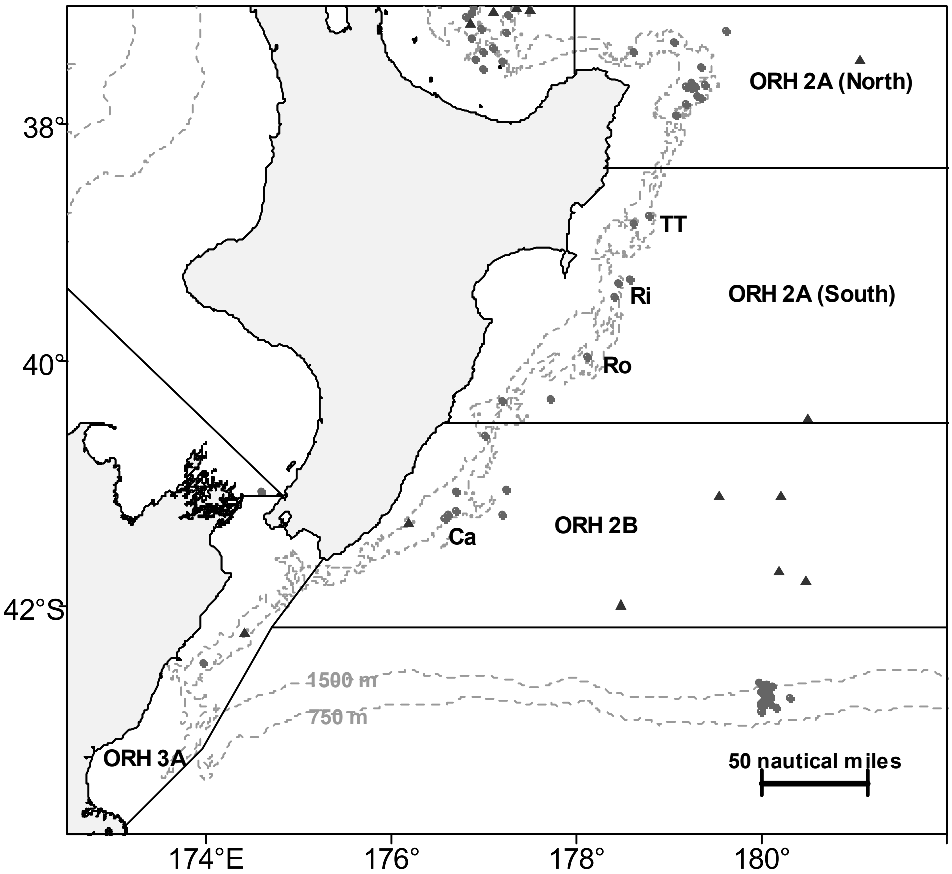

Figure 1: The Mid-East Coast fishery management sub-areas and boundaries (drawn and labelled in bold). Specific hill areas are labelled: TT, Tolaga and Tuaheni; Ri, Ritchie Bank; Ro, Rockgarden; CA, Castlepoint Hills. Other labels: ▲, knolls and seamounts (>500 m elevation); •, hills (<500 m elevation). Only features with a summit depth of less than 2000 m are shown.

The spatial model investigated in this study had one flat and one hill stratum, with fish moving from flat to hill as they grow, governed by an age-based migration ogive (Figure 2). In the model, the spawn stratum shown in Figure 2 did not actually exist, rather the spawn fishery was applied to vulnerable fish in the flat and hill strata during the spawn fishery time step, with the catch proportional to the biomass in each stratum. Because juvenile orange roughy have been found on relatively shallow flat areas, and rarely on features (Dunn et al. 2009), recruitment was assumed to take place to the flat only. In this model all mature fish were assumed to spawn, although there were two possible versions of this. The first is that mature fish live everywhere and all go to spawn; in this case the fish undergo migrations a, b, and c in Figure 2. The second is that only the fish from the hill stratum go to spawn; in this case the fish undergo only migrations a and b in Figure 2. The vulnerability of fish was assumed to be complete on the hill habitat; this seemed to be a reasonable assumption given our observations of length frequencies on hills, and it also reduced the number of parameters to be estimated and prevented cryptic mature biomass occurring in the hill stratum. In this model the only place cryptic mature biomass could occur was on the flat. For the Mid-East Coast, a regression tree analysis of mean fish length per tow identified the cut-off between hills and flat strata as being 6.05 km from the centre of known features for males, and 8.85 km for females (Dunn 2009). For all subsequent stock assessment analyses, the average of these values was used to define strata, with hills assumed to be those areas within 7.45 km (4.02 nautical miles) of the centre of known features, as recorded in the NIWA seamounts database (Rowden et al. 2008).

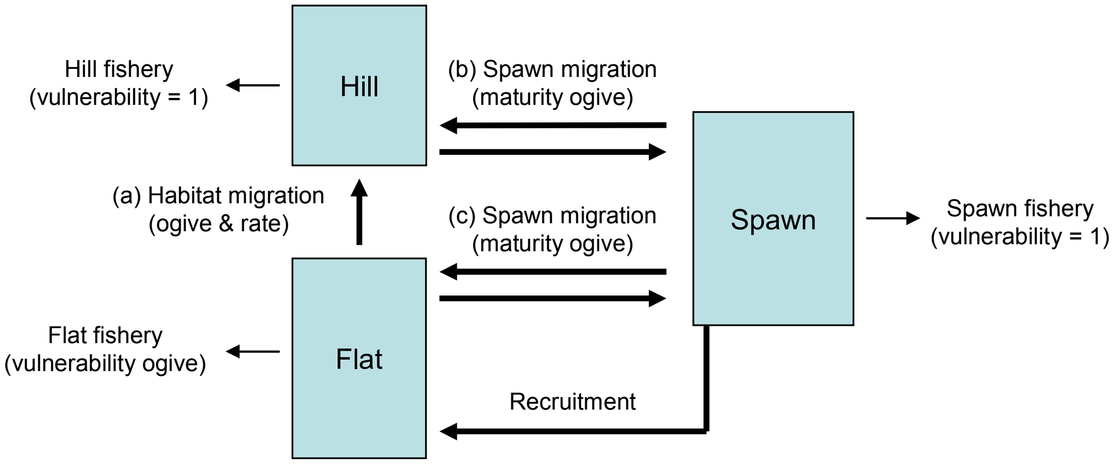

Figure 2: Schematic of the two-stratum Mid-East Coast orange roughy stock assessment model. Migrations (a) and (b) take place in both variants, but migration (c) does not take place when it is assumed that only hill fish go to spawn. Site fidelity is assumed for migrations (b) and (c). All mature fish are assumed to spawn, hence vulnerability in the spawning fishery is equal to 1. The length distribution of fish going to spawn from the hill stratum is effectively the product of the maturity ogive and the habitat migration ogive. Recruitment takes place only to the flat.

3. INPUT DATA

3.1 Catch history

There has been a history of catch overruns in this area because of lost fish and discards. In this assessment (as in previous ones), total removals were assumed to exceed reported catches by the overrun percentages given in Table 1. For each year, the catch for each model stratum (hill or flat) was estimated by multiplying the total reported catch by the proportion of estimated catch in each QMA and stratum, as estimated from tow-by-tow data, applying the relevant catch QMA over-run, and then summing across QMA to give the stratum totals (Table 2). The total catch, including over-runs, between 1981–82 and 2009–10 was 157 878 t, and during the ten years over which the fishery peaked, between 1983–84 and 1992–93, the total catch including over-runs was 112 247 t.

Table 1: Assumed catch over-runs (%) by QMA and fishing year. – no catches reported.

Fishing year	ORH2A (north and south)	ORH2B	ORH3A
1981–82	–	30	–
1982–83	–	30	30
1983–84	50	30	30
1984–85	50	30	30
1985–86	50	30	30
1986–87	40	30	30
1987–88	30	30	30
1988–89	25	25	25
1989–90	20	20	20
1990–91	15	15	15
1991–92	10	10	10
1992–93	10	10	10
1993–94	10	10	10
1994–95 and subsequently	5	5	5

Table 2: Proportion of estimated catch (t) recorded on tow-by-tow forms by fishing year and stratum (spawning, hill, or flat), and the total catch (t) by stratum for the Mid-East Coast two-stratum stock assessment model. Over-runs (OR) were added by stratum and quota management area (following Table 1).

	Proportion of TCEPR catch			Landings plus OR		
Fishing year	Spawn	Hill	Flat	Spawn	Hill	Flat
1981–82	0.04	0.12	0.84	27	85	608
1982–83	0.05	0.21	0.74	262	1 018	3 612
1983–84	0.01	0.44	0.55	125	4 198	5 298
1984–85	0.05	0.28	0.67	599	3 164	7 475
1985–86	0.13	0.38	0.48	1 560	4 076	5 121
1986–87	0.07	0.17	0.76	846	1 818	8 503
1987–88	0.24	0.23	0.53	3 022	2 842	6 740
1988–89	0.26	0.31	0.44	2 996	3 599	5 126
1989–90	0.22	0.24	0.55	2 740	2 991	6 889
1990–91	0.08	0.20	0.72	862	2 300	8 324
1991–92	0.18	0.16	0.67	1 972	1 747	7 390
1992–93	0.24	0.20	0.56	2 372	2 017	5 535
1993–94	0.24	0.34	0.42	1 733	2 475	3 011
1994–95	0.36	0.19	0.46	2 135	1 115	2 758
1995–96	0.35	0.16	0.49	691	315	979
1996–97	0.30	0.18	0.52	661	404	1 163
1997–98	0.16	0.14	0.70	368	326	1 658
1998–99	0.12	0.20	0.68	293	467	1 627
1999–00	0.14	0.14	0.72	367	370	1 906
2000–01	0.31	0.12	0.57	571	223	1 045
2001–02	0.39	0.12	0.49	614	186	755
2002–03	0.10	0.27	0.63	94	252	585
2003–04	0.06	0.14	0.79	58	134	738
2004–05	0.15	0.17	0.68	238	255	1 051
2005–06	0.28	0.16	0.57	418	240	859
2006–07	0.18	0.12	0.70	283	193	1 105
2007–08	0.23	0.06	0.70	372	103	1 110
2008–09	0.27	0.06	0.67	411	93	1 040
2009–10	0.36	0.09	0.55	556	143	865

3.2 Catch per unit effort

The collation and error-checking of catch and effort data were described in detail by Anderson & Dunn (2011). Following previous analyses (Dunn 2005; Dunn & Anderson 2008), the fishing year 1988–89 was excluded because of errors and missing data. The data were groomed by removing tows that appeared to have come fast, defined as those with a distance less than 100 m, and a catch of less than 100 kg, and a duration of less than 1 minute. Where relevant, the data from tow-by-tow and daily summary forms were combined by summarising the tow-by-tow data records into a daily-summary equivalent format. Only tows which targeted orange roughy were used in the analyses. Tows with a recorded duration of zero were changed to 0.1 hour. In order to adequately estimate categorical predictor effects in the model, a continuity rule was applied, where each level (e.g. each vessel) must have included at least 50 tows over three years, or 100 tows over two years.

The standardised catch per unit effort (CPUE) analyses were carried out by fitting a generalised linear model to CPUE, using the stepwise multiple regression technique described by Francis (2001). The units of CPUE used were log(kg per tow). Because the proportion of tows with a zero catch was trivial (1–11% per year with no clear trend), only non-zero catch was modeled, using a GLM with a normal error distribution and identity link function. The predictor variable *fishing year* was forced into the model in all analyses, and for the hill and flat indices the *fishing year:stratum* interaction was forced into the model (where stratum was hill or flat). Other variables were then tested for inclusion (Table 3). A stepwise forward procedure was used to select predictor variables, and they were entered into the model in the order which gave the maximum decrease in the Akaike Information Criterion (AIC). Predictor variables were accepted into the final model if they explained at least 1% of the deviance and their predicted effects were sensible.

Table 3: Predictor variables used included in the standardised CPUE analyses. *, predictors not available for daily summarized catch and effort data.

Variable	Type	Comment	Variable	Type	Comment
Fishing year	Categorical	Forced into the model	*Bottom depth**	3rd order polynomial	Depth of gear
Vessel	Categorical	Vessel key	*Duration*	3rd order polynomial	Tow duration
Statistical area	Categorical	MFish statistical area	*Distance**	3rd order polynomial	Tow distance in km
Month	Categorical	–	*Kw*	3rd order polynomial	Vessel engine power
Type	Categorical	Whether TCEPR or CELR form	*Tonnes*	3rd order polynomial	Vessel gross tonnage
QMA	Categorical	MFish quota management area	*Longitude**	3rd order polynomial	Tow start longitude
Number of tows	3rd order polynomial	Only for daily summarized data	*Latitude**	3rd order polynomial	Tow start latitude
Fishing day	3rd order polynomial	Day of the fishing year	*Time**	3rd order polynomial	Tow start time
*Speed**	3rd order polynomial	Tow speed			

3.2.1 Phases of the fishery

The history of the fishery was considered to determine whether the CPUE should be stratified over time. The CPUE indices were eventually split into two time periods, the first period finishing in 1996–97, on the basis of the fishery description below. This was broadly consistent with several changes in the fishery, but maintained two relatively long time series in order to estimate biomass trends.

Early development. Catches of orange roughy were first reported for the Mid-East Coast in 1981–82, primarily from the hill areas of Wairarapa and outside of the spawning season (Field 1992). By 1983–84 the fishery had expanded, and was operating throughout the year (Anderson & Dunn 2011).

Expansion and peak of the fishery. In 1985 industry initiatives led to a multi-vessel exploratory survey of the Mid-East Coast, and a substantial non-spawning fishery (Field 1992), which has persisted (Anderson & Dunn 2011). At around the same time there was an expansion of the fishery towards spawning aggregations on and around Ritchie Bank, with the first full year of fishing on Ritchie Bank being 1986 (Field 1992).

Between 1984–85 and 1987–88 there was an increase in catch rate, due to improvements in fishing power (skipper learning), although reported CPUE for this period is probably an underestimate due to the frequency of burst nets and lost fish (Field 1992). Global position system (GPS) technology was introduced to the fleet between 1987 and 1989, which further improved fishing power and was probably responsible for a peak in CPUE around this time

(Field 1992). There was a gradual shift in fishing effort during the spawning fishery from west to east, which stopped in 1989–90 (Field 1992). A large proportion of the catch and effort data are missing from 1988–89 (Field 1992).

The peak of the Mid-East Coast fishery was between 1989–90 and 1991–92, but catch rates declined rapidly through this period. In 1993–94, spawning aggregations were located and fished to the north, off East Cape, in preference to the Ritchie Bank. From 1994–95 the East Cape and Mid-East Coast fisheries were treated as separate stocks.

Reduction of catch limits. In 1995–96 there was a substantial drop in the Mid-East Coast TACC, from 6660 to 2100 t, in response to spawning biomass estimates (Zeldis et al. 1997). By 1996–97 there was relatively little fishing on the Ritchie Bank during the spawning season, and the fishery had begun to focus in other areas (Anderson & Dunn 2011); this TACC reduction effectively marks the end of the fish-down period. Previous analyses have split CPUE indices at this time, but in response to changes in data type, meaning a shift from the use of predominantly CELR to TCEPR forms (Dunn & Anderson 2008).

In the late 1990s there is also some evidence for a change in fishing behaviour. The recording of tow characteristics for different species became clearer, such that a move to more "clinical" fishing has been inferred around this time, possibly as a response to restrictive orange roughy TACCs (Dunn & Bian 2009).

Relative stability. In 2000–01 there was a further drop in the Mid-East Coast TACC, from 2100 to 1500 t, after a stock assessment estimated that the stock was substantially depleted (Francis & Field 2000). Acoustic surveys completed in 2001 and 2003 tended to support the view that the stock was depleted, as the large spawning aggregations present in the early years were no longer found, with spawning instead in smaller scattered schools in the vicinity of Ritchie Hill (Hart et al. 2003). The spawning aggregations had become smaller, harder to locate, less stable, more disrupted by fishing, and generally more dynamic in location and time (Doonan et al. 2003, 2004). Some new fishing areas were developed between 1997–98 and 2000–01, but the fishery distribution subsequently remained relatively stable (Anderson & Dunn 2011).

In 2002–03, continuing concerns about sustainability (Anderson et al. 2002) resulted in a further drop in the TACC, from 1500 to 800 t. Shortly afterwards, the stock was estimated to be rebuilding, and the TACC was returned to 1500 t in 2004–05 (Dunn 2005). Since 2003–04 other fisheries on the east coast North Island have become further restricted, including hoki (substantial TACC reductions in 2003–04, 2004–05 and 2007–08), and more recently black cardinalfish (TACC reductions in 2009–10 and 2010–11). The alfonsino fishery TACC has remained unchanged since 1996–97. TACC reductions across several deep water species in recent years may have encouraged fishers to more accurately and discretely target species in the east coast deepwater fishery (Dunn & Bian 2009).

3.2.2 Flat and Hill indices for 1983–84 to 1996–97

Data from the spawning fishery (June and July) were removed from this index, consistent with the model structure. Data from ORH3A were also removed because of suspected misreporting of catch during this period. After data grooming and applying the data selection criteria, the data set included 16 313 tow-by-tow records. Twenty vessels were included in the data set, with reasonable overlap between vessels (Table 4).

The fit of the model was reasonable (Figure 3). While most of the data fitted the model, the small departures towards the ends of the normal model quantile plot indicated the model did not describe all of the extremes of the catch rate (particularly for large catches). The final model explained 13.9% of the deviance, with the only additional predictor selected being *vessel* (Table 5).

Table 4: Number of tows by vessel and fishing year as used in the two-stratum standardised CPUE analysis for 1983–84 to 1996–97, after application of the data selection criteria. Fishing year is shown as the year-ending (i.e. 1985 is 1984–85). Note that the fishing year 1988–89 was excluded.

Vessel	1984	1985	1986	1987	1988	1990	1991	1992	1993	1994	1995	1996	1997
1	–	168	109	20	74	–	–	–	–	–	–	–	–
2	–	31	25	29	28	–	–	–	–	–	–	–	–
3	7	83	91	160	207	–	–	–	–	–	–	–	–
4	118	42	51	27	–	17	16	–	–	36	29	–	12
5	281	214	37	39	68	89	83	215	261	246	–	–	–
6	236	112	243	263	154	126	169	169	236	279	219	–	–
7	–	19	–	–	–	34	–	33	6	5	–	–	–
8	164	31	236	67	69	173	181	132	142	375	285	59	19
9	154	17	1	2	4	–	67	126	194	154	57	25	46
10	–	10	–	–	–	–	–	81	–	41	–	–	–
11	155	23	67	15	126	102	40	83	160	173	305	141	167
12	–	–	–	–	–	21	86	45	128	–	–	12	1
13	–	–	–	–	–	30	59	197	96	99	2	–	–
14	–	–	–	–	115	232	275	441	442	381	173	77	14
15	–	128	29	173	–	–	298	366	281	308	244	144	187
16	13	–	–	–	17	126	170	40	78	129	93	73	90
17	–	–	–	–	–	–	–	–	108	107	10	–	–
18	–	–	–	–	–	–	–	–	–	11	64	12	1
19	–	–	–	–	–	–	–	–	–	3	52	20	13
20	–	–	–	–	–	–	–	–	–	–	76	100	138

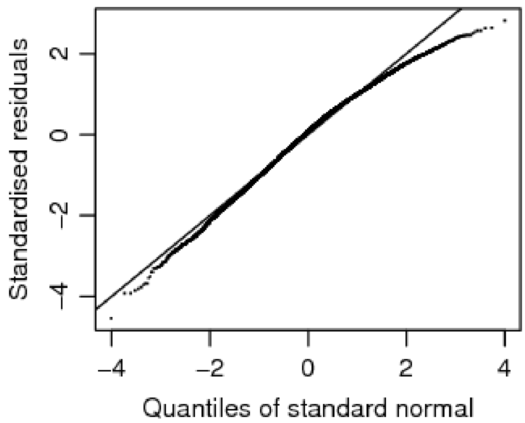

Figure 3: Normal quantile plot for the fit of the final CPUE model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1983–84 to 1996–97.

Table 5: Predictor and percentage of deviance explained for the final normal model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1983–84 to 1996–97. Df, degrees of freedom; AIC, Akaike Information Criterion; % dev. expl., % of deviance explained; Add % dev. expl., additional % deviance explained.

Predictor	Step	Df	AIC	% dev. expl.	Add % dev. expl.
Fishing year:Stratum	1	24	63 891	7.1	7.1
Vessel	2	19	62 696	13.9	6.8

The model indicated a variable catch rate for the flat stratum until about 1990–91, followed by a decline, whereas the hill stratum year effect showed a more steady decline (Figure 4). There was a roughly seven-fold difference in vessel effect (Figure 4).

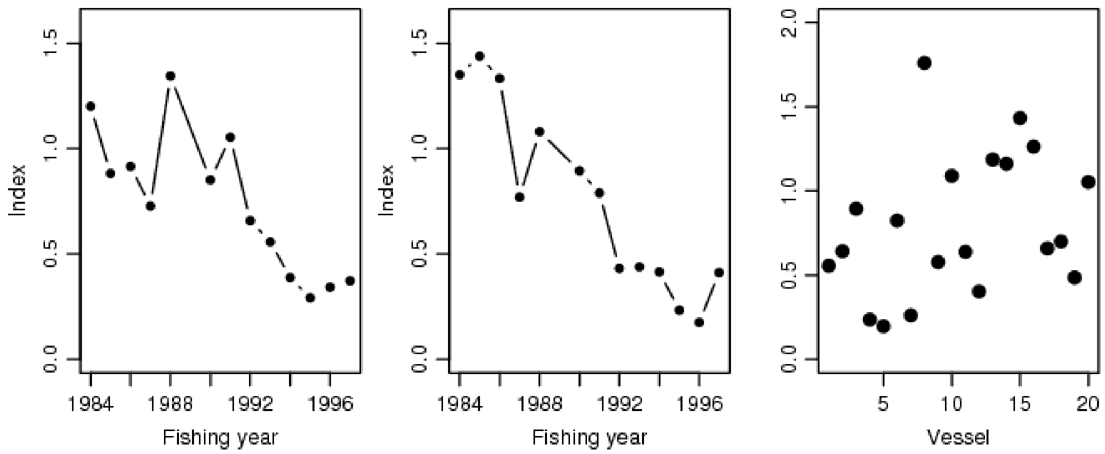

Figure 4: Model predictions by fishing year (labelled as year ending, i.e. 1984 means 1983–84) for the flat stratum (left panel), hill stratum (centre panel), and vessel, for the final CPUE model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1983–84 to 1996–97, made with all other predictors set to the median (fixed) values.

The standardisation procedure made relatively little difference to the estimated CPUE trend, although it tended to smooth out fluctuations in the earlier part of the index (before 1991–92) (Figure 5). The final index and coefficient of variation of the year effect is shown in Table 6.

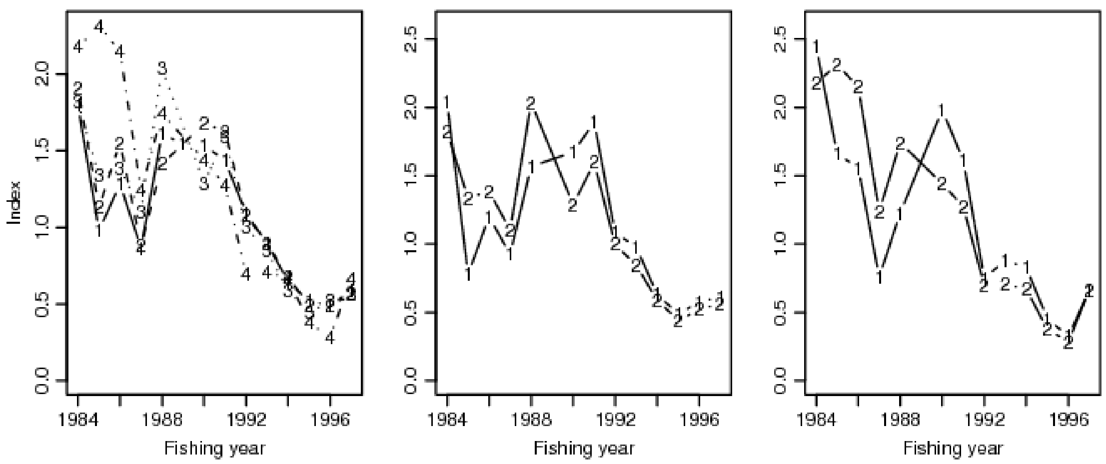

Figure 5: CPUE indices by fishing year (labelled as year ending, i.e. 1984 means 1983–84), all scaled to have a geometric mean of one. Left panel: 1, initial unstandardised CPUE; 2, subset of unstandardised CPUE used for standardised analyses; 3, standardised flat stratum index; 4, standardised hill stratum index. Centre panel; 1, standardised flat index with year predictor only; 2, standardised flat index with predictors year and vessel. Right panel; 1, standardised hill index with year predictor only; 2, standardised hill index with predictors year and vessel.

Table 6: Standardised CPUE indices and c.v.s (%) for the two-stratum analysis. FE, flat early; FL, flat late; HE, hill early; HL, hill late; SE, spawn early; SL, spawn late. The SE index uses tow-by-tow and daily summary data combined; all other indices use only tow-by-tow data.

Fishing year	FE	c.v.	FL	c.v.	HE	c.v.	HL	c.v.	SE	c.v.	SL	c.v.
1983–84	1.20	13.2	–	–	1.35	13.2	–	–	–	–	–	–
1984–85	0.88	13.4	–	–	1.44	13.4	–	–	–	–	–	–
1985–86	0.92	13.7	–	–	1.33	13.7	–	–	–	–	–	–
1986–87	0.73	13.6	–	–	0.77	13.6	–	–	–	–	–	–
1987–88	1.35	13.7	–	–	1.08	13.7	–	–	–	–	–	–
1988–89	–	–	–	–	–	–	–	–	–	–	–	–
1989–90	0.85	13.1	–	–	0.90	13.1	–	–	26.11	25.5	–	–
1990–91	1.05	12.5	–	–	0.79	12.5	–	–	18.64	24.4	–	–
1991–92	0.66	12.2	–	–	0.43	12.2	–	–	9.13	22.5	–	–
1992–93	0.56	11.7	–	–	0.44	11.7	–	–	7.64	21.8	–	–
1993–94	0.39	11.7	–	–	0.42	11.7	–	–	2.17	22.5	–	–
1994–95	0.29	12.5	–	–	0.23	12.5	–	–	1.07	23.5	–	–
1995–96	0.34	13.9	–	–	0.18	13.9	–	–	2.57	29.7	–	–
1996–97	0.37	13.7	–	–	0.41	13.7	–	–	1.63	30.9	–	–
1997–98	–	–	0.33	14.1	–	–	0.26	14.1	–	–	0.41	35.2
1998–99	–	–	0.34	13.9	–	–	0.26	13.9	–	–	0.49	19.8
1999–2000	–	–	0.33	14.1	–	–	0.22	14.1	–	–	0.39	16.8
2000–01	–	–	0.34	14.8	–	–	0.21	14.8	–	–	1.24	17.4
2001–02	–	–	0.62	16.4	–	–	0.42	16.4	–	–	2.03	21.3
2002–03	–	–	0.83	16.4	–	–	0.69	16.4	–	–	0.87	28.6
2003–04	–	–	1.03	16.0	–	–	0.68	16.0	–	–	1.09	57.6
2004–05	–	–	0.85	14.6	–	–	0.52	14.6	–	–	0.83	19.5
2005–06	–	–	0.86	15.7	–	–	0.68	15.7	–	–	2.63	18.2
2006–07	–	–	0.89	16.0	–	–	0.80	16.0	–	–	1.48	20.0
2007–08	–	–	0.82	16.0	–	–	0.49	16.0	–	–	1.17	18.5
2008–09	–	–	0.64	15.6	–	–	0.58	15.6	–	–	2.40	18.7
2009–10	–	–	0.50	16.4	–	–	0.22	16.4	–	–	2.05	17.7

3.2.3 Flat and Hill indices for 1997–98 to 2009–10

Data from the spawning fishery (June and July) were removed from this index. After data grooming and applying the data selection criteria, the data set included 7919 tow-by-tow records. Fifteen vessels were included in the data set, with reasonable overlap between vessels (Table 7).

The fit of the model was reasonable (Figure 6). While most of the data fitted the model, the small departures towards the ends of the normal model quantile plot indicated the model did not describe all of the extremes of the catch rate. The final model explained 13.9% of the deviance, with the only additional predictor selected being *vessel* (Table 8).

The model indicated an increase in the CPUE for both the flat and hill strata from 2001–02, followed by a plateau and then a decline from 2008–09 (Figure 7). There was a roughly seven-fold different in vessel effect, with two vessels having a substantially higher catch rate (Figure 7). The difference between the year trend for the hill and flat strata was very small, with the hill stratum more variable (Figure 8).

The standardisation procedure made only a minor difference to the estimated CPUE trend, notably increasing the magnitude of the CPUE increase from 2002–03 in the flat stratum (Figure 9). The final index and coefficient of variation of the year effect is shown in Table 6.

Table 7: Number of tows by vessel and fishing year as used in the two-stratum standardised CPUE analysis for 1997–98 to 2009–10, after application of the data selection criteria. Fishing year is shown as the year-ending (i.e. 2005 is 2004–05).

Vessel	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	359	164	44	–	–	–	–	–	–	–	–	–	–
2	41	31	17	5	1	–	–	–	–	–	–	–	–
3	23	149	48	–	–	–	–	–	–	–	–	–	–
4	10	14	22	–	–	–	–	–	–	–	–	–	–
5	335	347	307	287	100	–	–	–	–	–	–	–	–
6	186	186	169	84	35	22	12	8	–	–	–	–	1
7	63	46	71	21	4	9	7	12	8	7	6	–	–
8	1	1	31	49	22	7	4	–	–	–	–	–	–
9	2	62	149	96	12	121	74	195	110	–	–	–	–
10	56	127	50	30	64	48	114	85	69	100	52	23	35
11	202	254	283	139	73	74	40	75	101	143	217	286	192
12	27	6	–	–	8	23	22	56	26	29	–	11	–
13	–	–	–	–	16	16	26	46	24	–	4	–	–
14	–	1	–	–	–	–	–	–	2	23	27	3	16
15	–	19	–	–	–	–	5	19	6	19	78	117	115

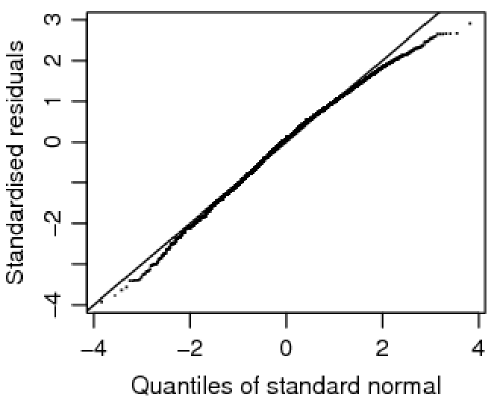

Figure 6: Normal quantile plot for the fit of the final CPUE model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1997–98 to 2009–10.

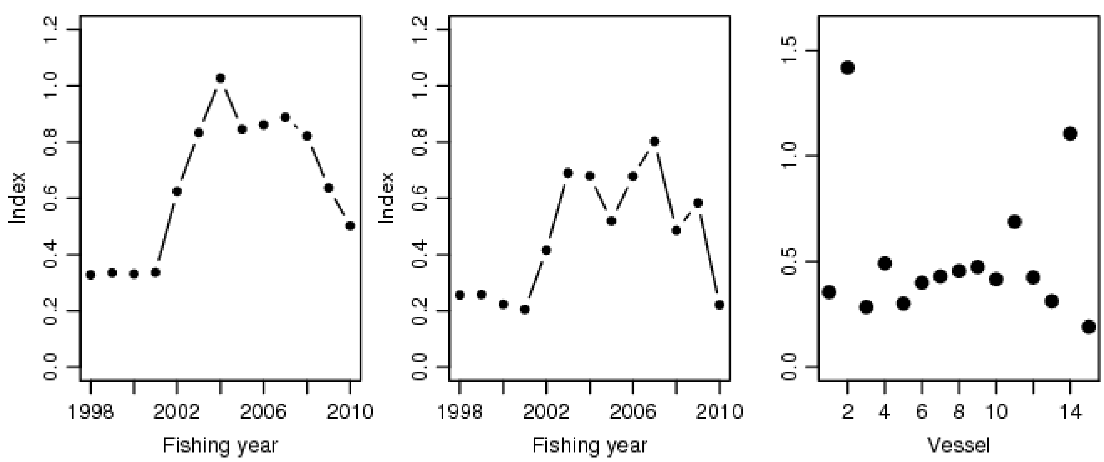

Figure 7: Model predictions by fishing year (labelled as year ending, i.e. 1998 means 1997–98) for the flat stratum (left panel), hill stratum (centre panel), and vessel, for the final CPUE model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1997–98 to 2009–10, made with all other predictors set to the median (fixed) values.

Table 8: Predictor and percentage of deviance explained for the final normal model fit to the tow-by-tow data set in the two-stratum standardised CPUE analysis for 1997–98 to 2009–10. Df, degrees of freedom; AIC, Akaike Information Criterion; % dev. expl. % of deviance explained; Add % dev. expl. additional % deviance explained.

Predictor	Step	Df	AIC	% dev. expl.	Add % dev. expl.
Fishing year:Stratum	1	24	31 627	4.3	4.3
Vessel	2	14	31 291	8.6	4.3

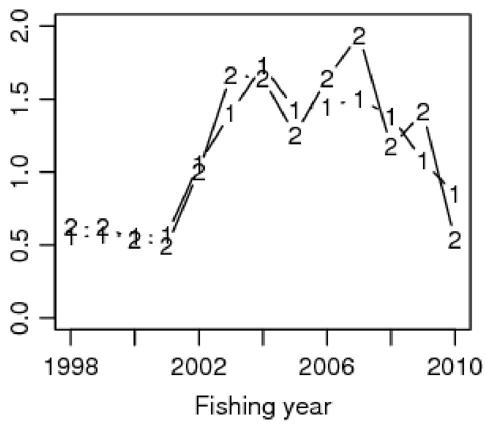

Figure 8: CPUE indices by fishing year for 1, flat, and 2, hill, scaled to have a geometric mean of one. Fishing years labelled as year ending, i.e. 1998 means 1997–98.

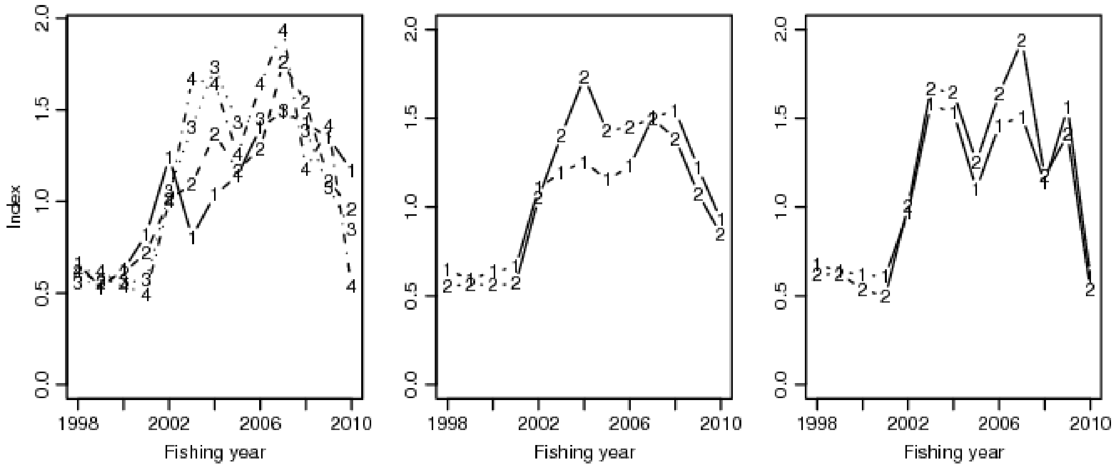

Figure 9: CPUE indices by fishing year (labelled as year ending, i.e. 1998 means 1997–98), all scaled to have a geometric mean of one. Left panel: 1, initial unstandardised CPUE; 2, subset of unstandardised CPUE used for standardised analyses; 3, standardised flat stratum index; 4, standardised hill stratum index. Centre panel; 1, standardised flat index with year predictor only; 2, standardised flat index with predictors year and vessel. Right panel; 1, standardised hill index with year predictor only; 2, standardised hill index with predictors year and vessel.

3.2.4 Spawn fishery index for 1989–90 to 1996–97

The spawn fishery included only data from June and July. Analyses of tow-by-tow catch data indicated the June and July selection was appropriate (Appendix I). Data from ORH 3A were excluded.

All tow-by-tow data were collapsed to the daily summary format, and combined with the

CELR data, and number of tows added as a potential predictor. After data grooming and applying the data selection criteria, the data set included 2690 records. Seventeen vessels were included in the data set, with reasonable overlap between vessels (Table 9).

Table 9: Number of tows by vessel and fishing year as used in the spawn standardised CPUE analysis for 1989–90 to 1996–97, after application of the data selection criteria. Fishing year is shown as the year-ending (i.e. 1990 means 1989–90).

Vessel	1990	1991	1992	1993	1994	1995	1996	1997
1	38	31	–	–	–	–	–	–
2	18	17	28	36	18	–	–	–
3	34	36	83	72	28	–	10	–
4	–	–	42	49	–	–	–	2
5	59	15	–	16	–	76	–	–
6	6	13	27	17	53	–	–	–
7	12	25	44	78	31	35	–	–
8	–	–	30	26	42	23	–	–
9	–	–	–	37	29	11	–	–
10	–	–	31	34	81	92	–	–
11	–	–	–	32	43	58	–	–
12	–	–	35	46	67	109	36	–
13	–	9	29	40	50	57	–	49
14	–	1	–	35	31	88	6	–
15	–	–	–	18	–	55	56	–
16	–	–	–	–	20	44	8	28
17	–	–	–	–	–	76	24	55

The fit of the model was reasonable (Figure 10). While most of the data fitted the model, the small departures towards the ends of the normal model quantile plot indicated the model did not describe all of the extremes of the catch rate. The final model explained 47.7% of the deviance, with the additional predictors *number of tows*, *fishing day*, and then *vessel* (Table 10).

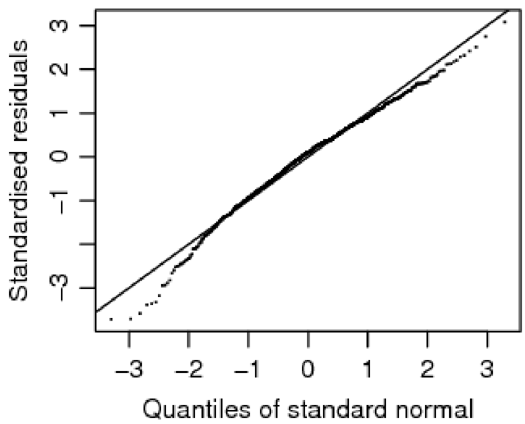

Figure 10: Normal quantile plot for the fit of the final CPUE model fit to the daily summarised data set in the spawn standardised CPUE analysis for 1989–90 to 1996–97.

The model indicated a steep decline in CPUE between 1989–90 and 1993–94 (Figure 11). The catch rate (daily catch) increased with the number of tows, and peaked at about fishing day 265, equivalent to the third week of June. There was a roughly 4-fold difference in vessel effect, with one vessel having an especially high catch rate.

Table 10: Predictor and percentage of deviance explained for the final normal model fit to the daily summarised data set in the spawn standardised CPUE analysis for 1989–90 to 1996–97. Df, degrees of freedom; AIC, Akaike Information Criterion; % dev. expl., % of deviance explained; Add % dev. expl., additional % deviance explained.

Predictor	Step	Df	AIC	% dev. expl.	Add % dev. expl.
Fishing year	1	6	3988	17.4	17.4
Number of tows	2	3	3783	32.9	15.5
Fishing day	3	3	3592	44.7	11.8
Vessel	4	16	3568	47.7	3.0

The standardisation procedure had a relatively large effect on the CPUE trend, increasing the steepness of the CPUE decline (Figure 12). This was because the mean number of tows per day increased over the time series, the mean day of the year fished was at about day 265 in the first year and then became earlier and then later after the CPUE decline had taken place, and vessels predominant at the start of the fishery had relatively low vessel effects (note that the numbering of vessels in Table 9 and Figure 11 is not the same; the former is ordered by year, whereas the latter is ordered by a vessel key). The final index and coefficient of variation of the year effect is shown in Table 6.

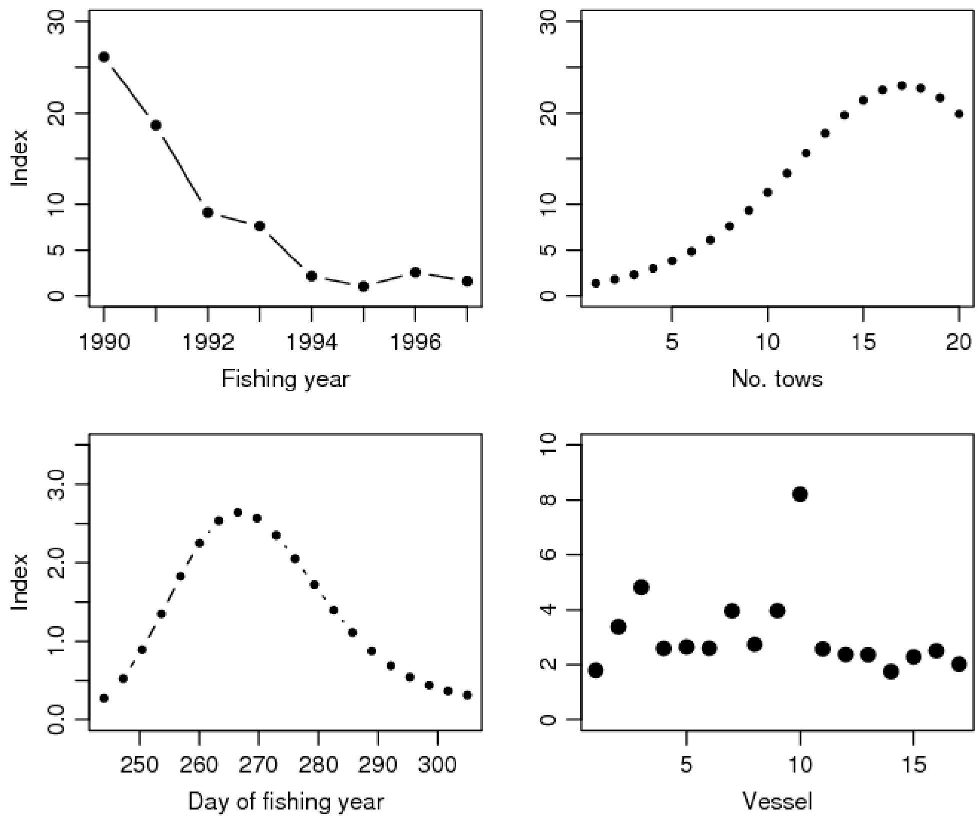

Figure 11: Model predictions by fishing year (labelled as year ending, i.e. 1991 means 1990–91) for fishing year, number of tows, day of fishing year, and vessel, for the final CPUE model fit to the daily summarised data set in the spawn standardised CPUE analysis for 1989–90 to 1996–97, made with all other predictors set to the median (fixed) values.

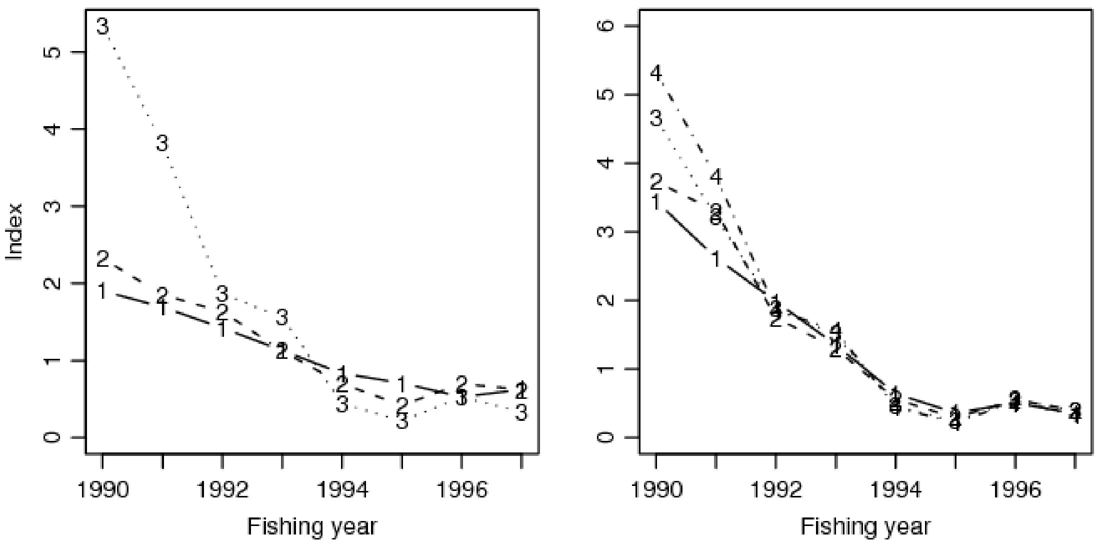

Figure 12: CPUE indices by fishing year (labelled as year ending, i.e. 1991 means 1990–1991) for the spawn index 1989–90 to 1996–97, all scaled to have a geometric mean of one. Left panel: 1, initial unstandardised CPUE; 2, subset of unstandardised CPUE used for standardised analyses; 3, standardised index. Right panel: 1, standardised index with year predictor only; 2, standardised index with predictors year and number of tows; 3, standardised index with predictors year, number of tows, and day of fishing year; 4, standardised index with predictors year, number of tows, day of fishing year, and vessel.

3.2.5 Spawn fishery index for 1997–98 to 2009–10

The spawn fishery included only data from June and July. After data grooming and applying the data selection criteria, the data set included 1200 tow-by-tow records. Six vessels were included in the data set, with reasonable overlap between vessels (Table 11).

Table 11: Number of tows by vessel and fishing year as used in the spawn standardised CPUE analysis for 1997–98 to 2009–10, after application of the data selection criteria. Fishing year is shown as the year-ending (i.e. 1998 means 1997–98).

Vessel	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1	21	82	79	62	–	–	–	–	–	–	–	–	–
2	–	11	19	32	12	12	–	–	–	–	–	–	–
3	–	47	67	16	19	2	–	18	32	–	–	–	–
4	3	14	35	15	25	–	–	–	–	9	7	16	3
5	–	–	–	23	14	–	8	9	5	34	–	–	–
6	–	1	62	22	5	22	–	43	52	43	63	61	75

The fit of the model was relatively good (Figure 13). The final model explained 19.8% of the deviance, with the additional predictors *fishing day*, *vessel*, and then tow *duration* (Table 12).

The model indicated a slow but variable (possibly episodic) increase in CPUE (Figure 14). The catch rate peaked at about fishing day 270, in the last week of June and about a week later than in the early CPUE series. There was a relatively small, roughly 3-fold, difference in vessel effect, and an increase in catch rate with tow duration. The final index and coefficient of variation of the year effect is shown in Table 6. The standardisation procedure had relatively little effect on the CPUE trend (Figure 15).

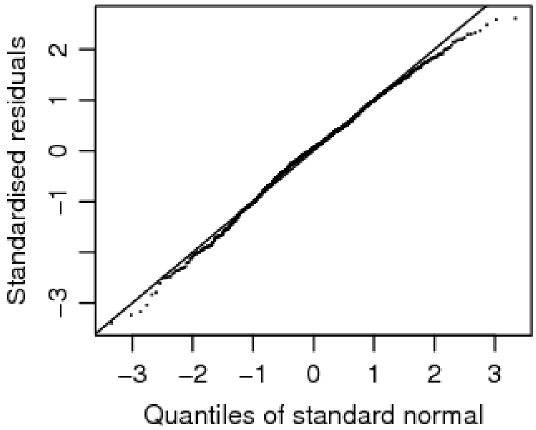

Figure 13: Normal quantile plot for the fit of the final CPUE model fit to the tow-by-tow data set in the spawn standardised CPUE analysis for 1997–98 to 2009–10.

Table 12: Predictor and percentage of deviance explained for the final normal model fit to the tow-by-tow data set in the spawn standardised CPUE analysis for 1997–98 to 2009–10. Df, degrees of freedom; AIC, Akaike Information Criterion; % dev. expl., % of deviance explained; Add % dev. expl., additional % deviance explained.

Predictor	Step	Df	AIC	% dev. expl.	Add % dev. expl.
Fishing year	1	11	4 503	12.6	12.6
Fishing day	2	3	4 442	17.4	4.8
Vessel	3	5	4 431	18.8	1.4
Duration	4	3	4 422	19.8	1.0

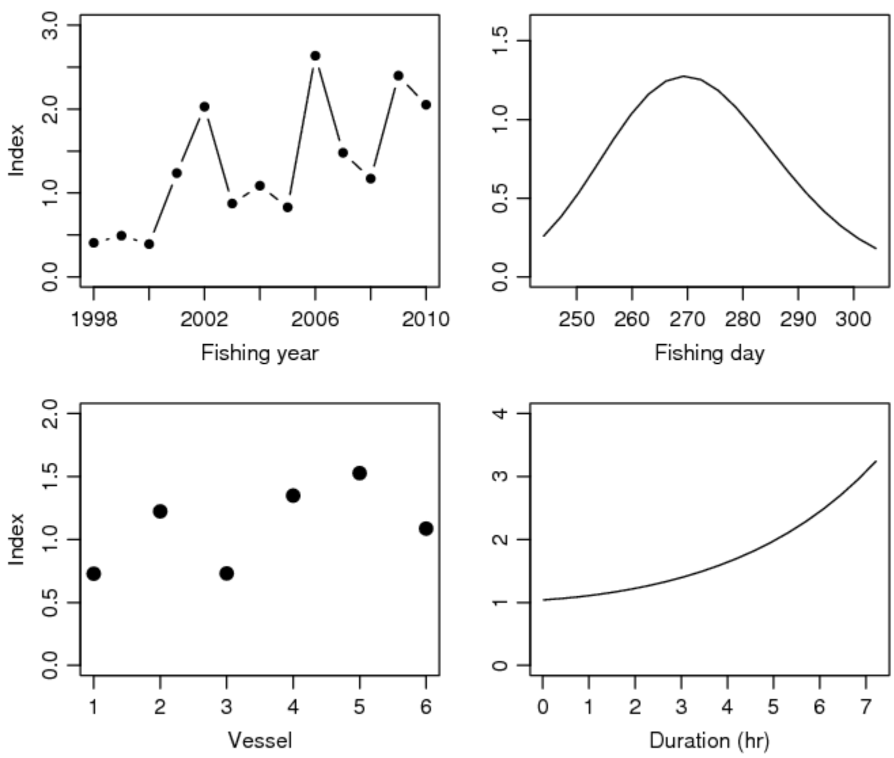

Figure 14: Model predictions by fishing year (labelled as year ending, i.e. 1998 means 1997–98) for fishing year, fishing day, vessel, and tow duration, for the final CPUE model fit to the tow-by-tow data set in the spawn standardised CPUE analysis for 1997–98 to 2009–10, made with all other predictors set to the median (fixed) values.

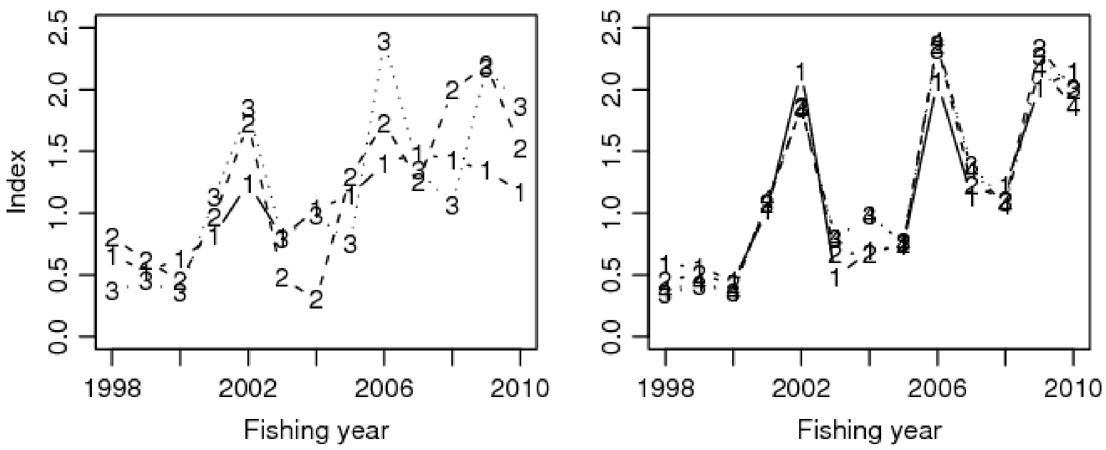

Figure 15: CPUE indices by fishing year (labelled as year ending, i.e. 1998 means 1997–1998) for the spawn index 1997–98 to 2009–10, all scaled to have a geometric mean of one. Left panel: 1, initial unstandardised CPUE; 2, subset of unstandardised CPUE used for standardised analyses; 3, standardised index. Right panel: 1, standardised index with year predictor only; 2, standardised index with predictors year and fishing day; 3, standardised index with predictors year, fishing day, and vessel; 4, standardised index with predictors year, fishing day, vessel, and tow duration.

3.2.6 Interpretation of the standardised CPUE indices

The standardised CPUE index for period 1997–98 to 2009–10 was similar for the hill and flat strata, but these were different from the spawning fishery. The increase in CPUE in the hill and flat fishery around 2001–02 could be a result of a change in fishing practice or technology, where the relevant predictors were not available to the standardisation, or it could reflect a biomass increase (e.g. recruitment). If the latter is correct, and the late spawn indices are credible, then the recruitment was not yet vulnerable to the spawning fishery. Overall, the CPUE indices suggest vulnerable biomass reached a low point between 1995–96 and 2000–01, and then started to rebuild.

The greater variability in the 1997–98 to 2009–10 hill index compared to the flat index might be reasonable given the more erratic performance of trawl gear on hills, where the seabed is rougher.

The only standardisation to have a substantial effect was for the spawn fishery, which indicated a substantial biomass decline (about 96%). In the Mid-East Coast area, spawning orange roughy occur primarily on and around Ritchie Banks, and it is assumed that fish migrate there to spawn from Kaikoura and Wairarapa (Doonan et al. 2003). The catch rate on the spawning grounds during the spawning season (taken as 20 June – 11 July; spawning normally peaks in the last week of June) dropped rapidly from 10–20 t/tow in the late 1980s, to less than 3 t/tow by the mid-1990s (Figure 16). Catch rates of less than 3 t/tow would not be consistent with fishing on substantial spawning aggregations. After 1992–93, and especially in 1994–95, fishing effort during the spawning season was spread over a much wider area, presumably in search of spawning aggregations. Around this time, most of the fishing effort moved north to the East Cape hills (not part of the Mid-East Coast stock), where new and substantial spawning aggregations had just been found. The catch and effort data therefore suggest that the spawning aggregations at Ritchie Hill were largely caught by about 1994–95, which is consistent with the large decline in the standardised CPUE for the spawn fishery. After the mid-1990s, the greatest fishing effort during the spawning period occurred in 1999–2001, but the wide area fished and low catch rates indicate no large spawning aggregation was found. Some larger catches have been taken in some recent years (e.g. 2004–

05 and 2005–06) but effort has remained relatively low. This is consistent with some rebuild of the spawning biomass.

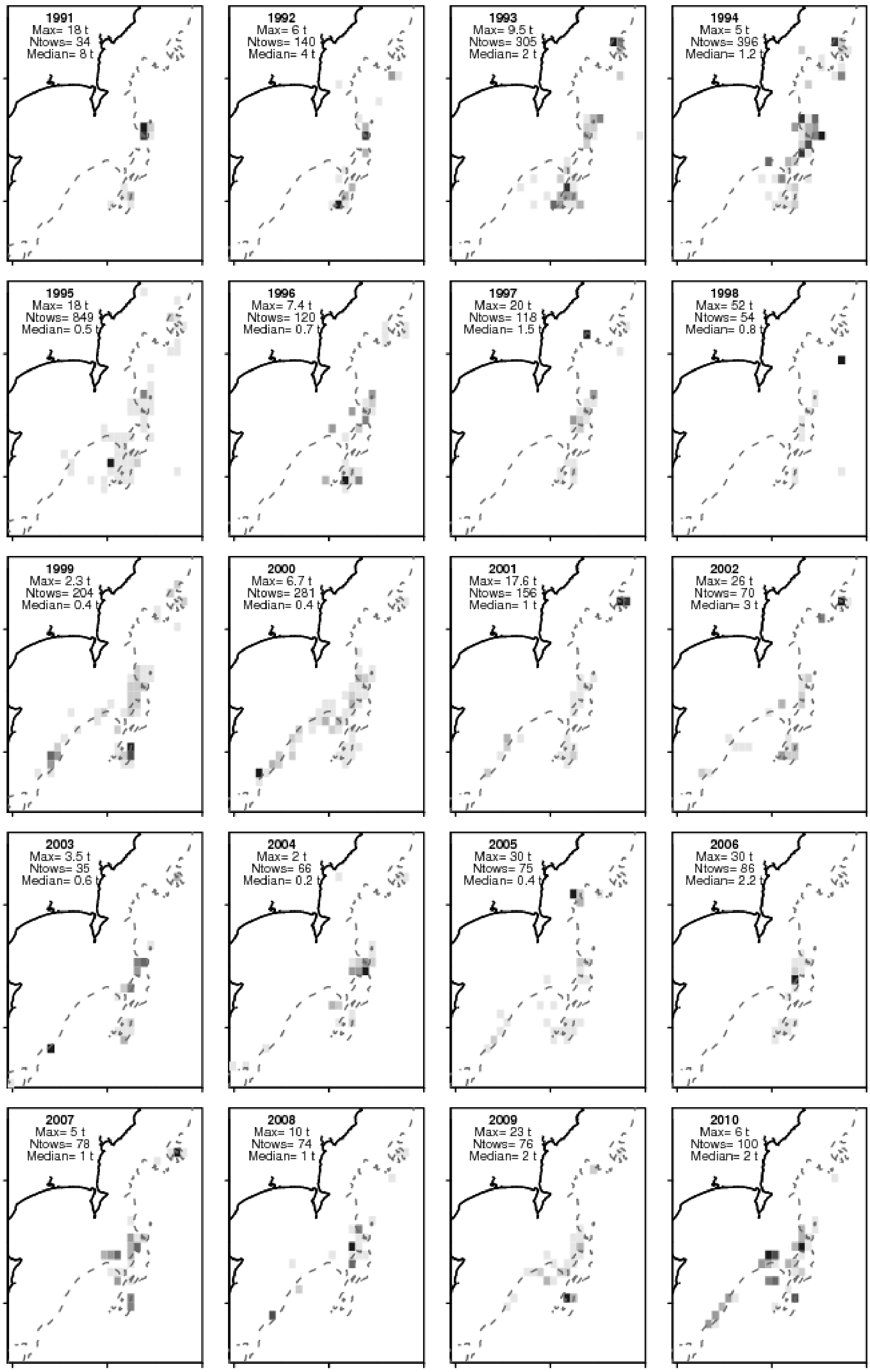

Figure 16: Image plot of the median catch rate (t/tow) of orange roughy by area cells (approx. 4' square) for 20 June – 11 July, by fishing year, for tows targeting orange roughy, using tow-by-tow data only. Each plot is labelled with the maximum of median catch rate per square (the darkest square), the number of tows, and overall median catch rate. Years labelled as year ending, i.e. 2005 means 2004–05.

3.3 Acoustic surveys

The first comprehensive acoustic survey of the Mid-East Coast spawning biomass was in June-July 2000 (Doonan et al. 2003). A survey was repeated in 2003, but this survey was shortened to reduce cost and covered only a small area where most biomass had been encountered (the "hot spots") in 2001 (Figures 17 and 18; Doonan et al. 2004). Each survey included 2–3 snapshots, which was necessary to capture changes in biomass and ensure that movement of aggregations did not affect the results. The survey was stratified random, with strata allocated based upon commercial catch information and local fishing knowledge. A rapid preliminary survey was carried out in 2001 to confirm strata. Between 2 and 5 transects were completed per stratum.

In 2001, there was a spawning plume about 2 km long (inferred from an acoustic mark appearing in two transects about 2 km apart, but the plume was not surveyed in its entirety). In 2003, two aggregations were found, each about 100 to 200 m in diameter. Few orange roughy marks were evident during the day, but small plumes did form at night, particularly in the main spawning stratum (Doonan et al. 2004).

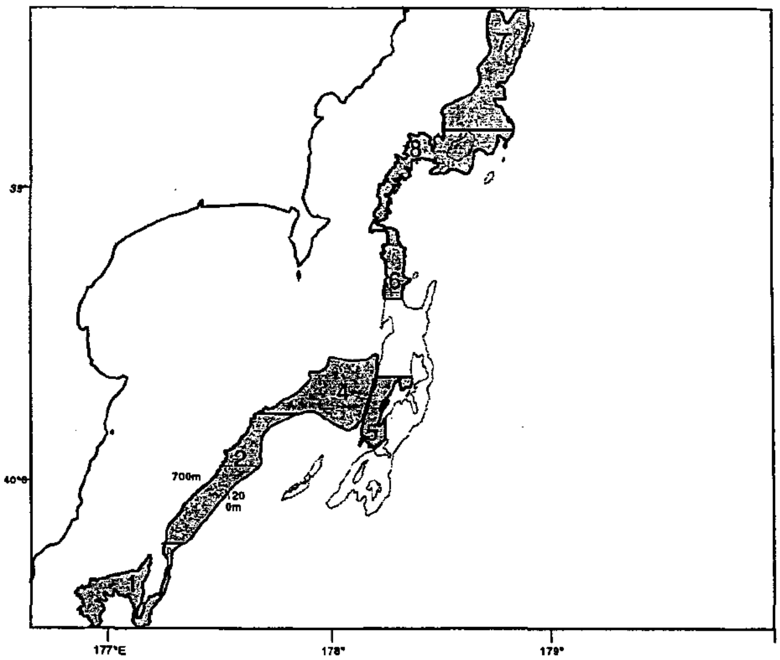

Figure 17: The background strata that were surveyed during snapshot 3 of the 2001 survey of ORH 2A South (these strata were not surveyed in 2003, see Figure 18). Reproduced from Doonan et al. (2004).

It has been assumed that not all mature orange roughy spawned each year, therefore it was necessary to scale-up estimates of spawning biomass to get mature biomass (Dunn et al. 2008). For the Mid-East Coast, the scale-up factor was estimated to be 1.7 (Table 13).

The c.v. of the 2003 acoustic biomass estimate was initially estimated to be 43% (Table 13) but was later revised, using a bootstrap procedure, to be 76% (Hicks, pers. comm.). The high uncertainty for the 2003 survey reflects the limited area surveyed, when 80% of the final biomass estimate was assumed, not observed. The estimate implied that only 21% of the mature biomass was present on the main spawning grounds in 2003.

Table 13: Acoustic biomass estimates for the Mid-East Coast during 2001 and 2003 from Doonan et al. (2003, 2004), rounded to the nearest 100 t, using the 'NIWA' target strength.

	Observed spawning biomass (t)					
Year	Main strata	Other strata	Assumed biomass from areas not surveyed	Spawning to mature raising factor	Final biomass estimate (t)	c.v. (%)
2001	8 000	6 900	–	1.7	25 300	38
2003	3 800	–	6 900	1.7	18 200	43

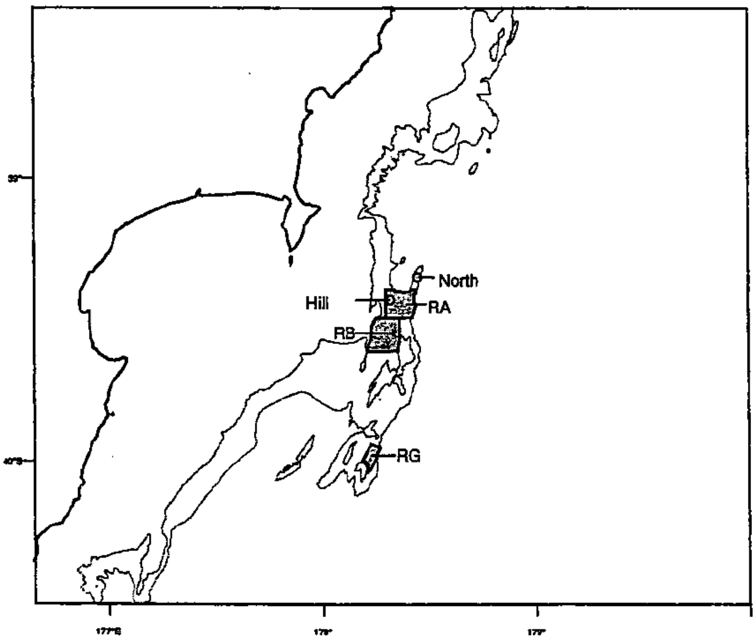

Figure 18: Locations of the main strata in the 2001 and 2003 acoustic surveys of ORH 2A South. Reproduced from Doonan et al. (2004).

In the 2007 MEC assessment, the 2001 and 2003 surveys were treated as relative biomass estimates with informed priors (Cordue, pers. comm.) (Table 14). For 2003, the biomass estimate is the observed spawning biomass (3800 t) multiplied by the scale-up factor of 1.7. The biomass in the other (unsurveyed) strata is allowed for in the ratio prior. The c.v. for mature biomass in the main survey stratum was estimated to be 0.22 (Doonan et al. 2004) whereas the c.v. for total biomass in the wide area is estimated to be 0.76 (Hicks, pers. comm.). For mature biomass in the wide area in 2003 the c.v. was assumed to be the same as in 2001, in lieu of any other estimate being available. An informed prior was placed on the 2001 proportionality constant (q_{2001}), and an informed prior was also developed for the ratio q_{2001}/q_{2003}. All priors on q were lognormal with the best estimate equated to the median of the prior distribution (Table 15).

Table 14: Acoustic estimates of mature orange roughy biomass (and their c.v.s) used in the stock assessment. The estimates (and prior) assume NIWA target strengths.

Year	Months	Estimated mature biomass (t)	c.v.	Reference
2001	June – July	25 300	0.38	Doonan et al. 2003
2003	June	6 460	0.38	Doonan et al. 2004

Table 15: Informed priors for the acoustic biomass estimates (Cordue, pers. comm.). The parameters, μ and cv, defining the lognormal prior are in natural space.

Parameter	Prior
Catchability 2001 (q2001)	Lognormal (μ=0.907, cv=0.620)
Catchability 2003 (q2003)	Uniform
q2001/q2003	Lognormal (μ=1.909, cv=0.233)

3.4 Egg production surveys

Egg production surveys of the Ritchie Bank spawning grounds were completed in 1993 and 1995 (Zeldis et al. 1997) (Table 16). The egg production method of biomass estimation was found to be problematic. In 1995, additional spawning was found to the north of the survey area, and some eggs were also observed advecting into the survey area from the southwest. In addition, egg mortality rates estimated from the abundance of egg stages were negative in 1995, and as a result the 1993 egg mortality estimates were applied in 1995. This is likely to be a result of high spatial and temporal patchiness in egg distribution. Analysis of the 1993 survey also indicated turnover of female fish, with spent females leaving the area before overall spawning was finished (as the method assumes a closed population it was necessary to make corrections for this in the egg production biomass estimate). The estimated spawning biomass was substantially lower in 1995 compared to 1993 (Table 16), but because the 1995 survey had a short duration, problems with egg distribution and abundance (which has been attributed to unexpected hydrological conditions), and had little influence in stock assessment models (Francis & Field 2000), it has historically been excluded from use in stock assessment (Anderson et al. 2002, Dunn 2005). The 1993 egg survey is included in the stock assessments as an absolute estimate of spawning biomass (with a proportionality constant equal to 1). No informed prior on the proportionality constant has been developed, largely because the egg survey has historically had little leverage in stock assessment models.

Table 16: Egg production survey spawning biomass estimates (with c.v.s) for the Mid-East Coast orange roughy stock. * Survey has not been used in stock assessments.

Year	Biomass (t)	c.v.
1993	22 000	49
1995*	7 000	50

3.5 Research trawl surveys

Research trawl surveys of the Mid-East Coast and East Cape stocks (Cape Runaway to Banks Peninsula) were completed by RV *Tangaroa* in March-April 1992–94 (Grimes 1994, 1996a,b), and then a comparable survey was completed for only the Mid-East Coast in 2010 (Doonan & Dunn 2011). In the 1992–94 and 2010 surveys, a similar area was surveyed each year initially using stratified random tow positions, with a 2-phase design. Three hill strata were added to the survey design during the 1992 survey in the vicinity of Rockgarden, and a further two hill strata were added in 1993, one encompassing Tolaga hill and the other a small area north of the Castlepoint Hills. For the spatially stratified model it was necessary to split the trawl survey data into hill and flat strata and recalculate the biomass estimates. The 1992 survey was excluded because not all of the hill areas were fished in that year. For the 1993, 1994 and 2010 surveys, the hill strata were assumed to be the survey commercial hill strata (survey strata 1–5), plus an additional stratum that included tows on the Castlepoint Hills (previously a part of stratum 23). The Castlepoint stratum had an estimated area of 158 km^2, reducing the area of stratum 23 by the same amount. Note that the definition of the hill and flat strata is not exactly the same as used in the CPUE analyses. The trawl survey biomass estimates are treated as relative biomass estimates in the model (Table 17). Length frequencies from the surveys are included to estimate survey vulnerability (Table 18).

Table 17: Mid-East Coast orange roughy trawl survey biomass estimates (with c.v.s). The stock assessment uses the biomass estimate for total orange roughy, with a selectivity estimated from the accompanying length frequencies (Table 18).

		Flat		Hill	
	Year	Biomass (t)	cv (%)	Biomass (t)	cv (%)
Total	1993	14 889	27.9	291	40.2
	1994	11 543	15.3	1 282	59.2
	2010	6 296	20.0	791	79.0
Adult (≥32 cm SL)	1993	4 535	18.9	268	42.3
	1994	4 100	19.3	1 128	59.7
	2010	3 030	24.0	690	87.0
Juvenile	1993	10 354	34.2	23	29.2
	1994	7 443	15.0	153	56.6
	2010	3 265	21.0	101	50.0

Table 18: Mid-East Coast orange roughy trawl survey overall (total) length frequency distributions (proportions at length) by year and stratum.

	Hill			Flat		
Standard length (cm)	1993	1994	2010	1993	1994	2010
12	0	0	5.9E-04	1.2E-04	0	2.3E-04
13	0	0	5.0E-04	1.5E-04	1.2E-04	7.2E-04
14	0	0	5.9E-04	4.3E-04	8.7E-04	1.5E-03
15	5.9E-11	0	2.0E-03	1.3E-03	8.7E-04	6.4E-03
16	2.0E-11	9.2E-12	2.9E-03	3.1E-03	2.5E-03	1.2E-02
17	1.4E-10	2.5E-12	7.8E-04	7.7E-03	4.3E-03	1.3E-02
18	9.7E-04	2.9E-11	3.1E-04	1.9E-02	9.7E-03	1.3E-02
19	5.3E-04	6.0E-04	1.9E-04	2.8E-02	2.5E-02	9.4E-03
20	4.9E-10	3.5E-04	3.8E-04	3.4E-02	4.1E-02	1.1E-02
21	5.7E-03	5.6E-04	6.9E-04	4.4E-02	4.5E-02	1.8E-02
22	8.5E-10	4.5E-04	2.9E-03	5.4E-02	5.3E-02	2.1E-02
23	6.2E-03	1.2E-03	2.9E-03	7.0E-02	5.6E-02	2.6E-02
24	2.9E-03	6.0E-04	5.8E-03	7.6E-02	5.8E-02	3.6E-02
25	3.3E-03	9.1E-04	3.3E-03	8.5E-02	6.7E-02	4.2E-02
26	6.4E-03	8.5E-04	1.4E-02	8.1E-02	6.7E-02	4.7E-02
27	4.4E-03	2.9E-03	9.1E-03	8.3E-02	7.3E-02	6.4E-02
28	9.5E-03	1.4E-02	2.9E-02	7.4E-02	7.6E-02	7.4E-02
29	1.7E-02	3.1E-02	3.0E-02	7.4E-02	8.0E-02	8.2E-02
30	3.2E-02	5.0E-02	3.8E-02	6.1E-02	7.1E-02	1.0E-01
31	4.6E-02	7.4E-02	6.9E-02	4.8E-02	6.7E-02	9.4E-02
32	7.8E-02	1.1E-01	6.5E-02	3.3E-02	5.0E-02	8.7E-02
33	1.1E-01	1.2E-01	1.3E-01	2.9E-02	4.2E-02	7.9E-02
34	1.1E-01	1.2E-01	1.7E-01	2.8E-02	3.4E-02	5.4E-02
35	1.2E-01	1.5E-01	1.0E-01	2.0E-02	2.4E-02	4.5E-02
36	8.7E-02	1.2E-01	1.1E-01	1.6E-02	1.9E-02	3.2E-02
37	8.7E-02	8.5E-02	8.0E-02	1.2E-02	1.1E-02	1.5E-02
38	9.1E-02	4.4E-02	5.9E-02	7.0E-03	1.0E-02	7.4E-03
39	5.9E-02	3.3E-02	3.6E-02	4.7E-03	7.1E-03	3.5E-03
40	5.5E-02	1.4E-02	3.2E-02	4.1E-03	3.0E-03	1.6E-03
41	3.9E-02	8.8E-03	6.8E-03	2.2E-03	8.4E-04	1.6E-04
42	1.5E-02	8.9E-03	0	9.4E-04	4.5E-04	4.0E-04
43	1.3E-02	2.1E-03	0	4.7E-04	7.4E-05	1.6E-04
44	1.8E-03	2.4E-04	0	1.0E-04	1.2E-04	0
45	0	0	0	1.0E-04	3.8E-05	0

The seabed of the Mid-East Coast is often rough, which makes trawling more difficult. As a result, the trawl net used in the research surveys (and commercial fisheries) has heavy ground gear and cut-away lower wings, making the net relatively inefficient, at least compared to the survey nets used on flat ground surveys, and catchability might therefore be expected to be relatively low. Further, in some strata much of the ground is too rough to trawl, leading to uncertainty about how well the survey describes the overall biomass.

3.6 Biological parameters

The biological parameters previously assumed for Mid-East Coast orange roughy are shown in Table 19.

Table 19: Biological parameters assumed for the Mid-East Coast orange roughy stock assessment.

Age structure		**Von Bertalanffy growth**	
Minimum age	1	L_∞	37.63 yr^{-1}
Maximum age (plus group)	80+	K	0.065 yr
Recruitment		t_0	-0.5
Form	Beverton & Holt	**c.v. of mean length at age**	
Sigma r	1.1	Age 1	16%
Steepness	0.75	Age 80	5%
Age at maturity		**Length-weight (cm to tonnes)**	
a_{50}	25.73 yr	A	9.21e-8
a_{to95}	7.11 yr	B	2.71
Mortality			
Natural mortality	0.045 yr^{-1}		

In the 2007 stock assessment, the von Bertalanffy growth parameters were revised to align correctly with the length bins of the length frequency distributions, where measured lengths floored to the nearest full cm below + 0.5 cm were used to fit the growth curve (Hicks 2007a). The only parameter to change from the previous assessment was L_∞, which was revised from 37.19 to 37.63 (Table 19). The c.v. of length around the mean length at age was assumed to vary linearly with length (Table 19; Hicks 2007b), and although these were considered especially uncertain (Hicks 2007c), they were similar to values estimated for Chatham Rise orange roughy (c.v. age 1 = 20%; c.v. age 80 = 6%; Dunn 2007).

The 2005 stock assessment used an estimated mean age of first maturity (a_{50}) of 31.31 years, with the age from a_{50} to 95% mature (a_{to95}) of 7.07 years (Dunn 2005). A new maturity ogive was estimated in 2007, which was the mean of three Central Ageing Facility (CAF) estimates, averaged with a NIWA estimate (Horn et al. 1998), thereby giving equal weights to CAF and NIWA (Table 20). The CAF estimate of a_{to95} was used because an a_{to95} was not reported for the NIWA estimate. The estimate of 28.6 yr (Table 20) was accepted by the MFish Deepwater Working Group in 2007, but in 2011 the working group agreed to evaluate all three maturity estimates as sensitivity runs (i.e. NIWA, CAF, and combined), with the base case being the NIWA estimate.

Table 20: Summary of the age to transition zone for orange roughy otolith batches read by CAF and NIWA. The transition zone is assumed to mark the onset of sexual maturity. Reproduced from Hicks (2007c).

Source	Source	*n*	a_{50}	SE
CAF	Commercial landings, June-July 1989	105	32.49	0.51
CAF	Commercial landings, June-July 1990	131	30.85	0.40
CAF	Commercial landings, June-July 1991	129	31.11	0.41
NIWA	Research survey, October 1990	33	25.73	0.44

The form and parameters of the stock-recruit relationship for orange roughy are unknown. Stock assessments in Australia have estimated steepness to be 0.75, and variability (sigma r) to be 0.58 (Wayte 2006).

The natural mortality (M) estimate used in recent New Zealand assessments was 0.045 yr^{-1}, which was derived from an ageing study on the Chatham Rise (Table 21). A low M of less than 0.1 yr^{-1} is consistent with a high longevity (Andrews et al. 2009). However, M remains uncertain, and the recently assumed value is the highest of the published estimates (Table 21). There seem to be very few other estimates of M for high longevity fishes, but total mortality rates as low as 0.03 yr^{-1} have been estimated for rockfish, which have a longevity of about 100 years (Yamanaka & Logan 2010).

Table 21: Published estimates of natural mortality (M) in orange roughy. For Doonan (1994) and Doonan & Tracey (1997), the numbers in parentheses are the 95% confidence intervals of the M estimate. The Bay of Plenty and Chatham Rise estimates were made soon after the fisheries started (in 1993–94 and 1979–80 respectively; Doonan 1994; Doonan & Tracey 1997), and so should be unbiased by fishing mortality and recruitment.

Location	Year range	*n* aged	Method	M	Source
Cascade Plateau, Australia	1999, 2004	1 356	Stock assessment model	0.020	Wayte & Bax (2006)
Eastern Zone, Australia	1992, 1995, 1999, 2001, 2004	5 096	Stock assessment model	0.042	Wayte (2006)
Chatham Rise, New Zealand	1984	432	Chapman-Robson	0.045 (0.030–0.060)	Doonan (1994)
Bay of Plenty, New Zealand	1995 – 1996	362	Chapman-Robson	0.037 (0.025–0.062)	Doonan & Tracey (1997)

3.7 Commercial length frequency data

Length frequency data for orange roughy are described in detail by Anderson (2011), and are predominantly collected by the Ministry of Fisheries Observer Programme. Most sampled tows were from the flat fishery, with samples from the spawn fishery largely from 1994–95 (Table 22).

An attempt was made to keep samples separate for each year, but some years were aggregated to ensure that each length frequency contained at least 200 measured fish (Table 23): aggregated years were for the flat stratum 1993–94 and 1994–95 (labelled as 1993–94), and 2003–04 and 2004–05 (labelled as 2004–05); for the hill stratum 1992–93 and 1993–94 (labelled as 1993–94), 2000–01 and 2002–03 (labelled as 2001–02), and 2006–07 and 2007–08 (labelled as 2006–07); for the spawn fishery 1992–93 and 1993–94 (labelled as 1993–94), 1995–96 and 1996–97 (labelled as 1996–97), and 2006–07 and 2007–08 (labelled as 2006–07).

The available data also included length frequency samples of landings from the spawn fishery in 1989–91 and 2002. These length samples were collected alongside otoliths that were used to estimate age frequencies (Section 3.8). When the age data were excluded from the model, these length samples were included, but where the age frequencies were used these length data were excluded (i.e. to prevent the length data being effectively used twice).

The overall length frequency for each fishery and time period was calculated as the mean of the catch-weighted total numbers at length for males and females (thereby scaling the length frequencies to a 50:50 sex ratio). The estimated length frequencies are shown in Figures 19, 21, and 23, and in Appendix II. The multinomial effective sample sizes were estimated from the intercept of regressions of log(proportion) and log(c.v.) (Figures 20, 22, and 24). Consistent with the assumed stock structure, the mean length per tow was greater on hills than on the flat, but it was also greater again in the spawn fishery (Figure 27). The latter, as we will see in section 5, was not consistent with the initial assumed stock structure. A relatively high number of tows with a relatively small mean length were sampled for the hill fishery in 1994 (Figure 25).

Table 22: Number of tows sampled for orange roughy length frequencies by fishery, by MFish observers aboard commercial fishing vessels on the Mid-East Coast.

Fishing year	Flat	Hill	Spawn
1989–90	17	21	9
1990–91	8	4	–
1991–92	–	–	–
1992–93	–	1	2
1993–94	26	7	3
1994–95	1	2	60
1995–96	–	–	2
1996–97	15	3	4
1997–98	4	5	–
1998–99	26	17	–
1999–2000	33	18	–
2000–01	14	8	–
2001–02	4	–	–
2002–03	8	2	–
2003–04	1	–	–
2004–05	2	–	–
2005–06	–	–	–
2006–07	17	1	13
2007–08	44	7	1
2008–09	19	–	–
2009–10	9	7	–

Table 23: Number of orange roughy measured for length by fishery (length range 15–55 cm SL), by MFish observers aboard commercial fishing vessels on the Mid-East Coast.

Fishing year	Flat	Hill	Spawn
1989–90	1 409	1 668	732
1990–91	703	358	–
1991–92	–	–	–
1992–93	–	80	170
1993–94	2 114	596	306
1994–95	79	201	4 826
1995–96	–	–	90
1996–97	1 319	274	373
1997–98	338	418	–
1998–99	2 085	1 504	–
1999–2000	2 370	1 088	–
2000–01	1 095	628	–
2001–02	301	–	–
2002–03	657	157	–
2003–04	100	–	–
2004–05	138	–	–
2005–06	–	–	–
2006–07	1 699	100	1 222
2007–08	3 390	384	100
2008–09	954	–	–
2009–10	648	597	–

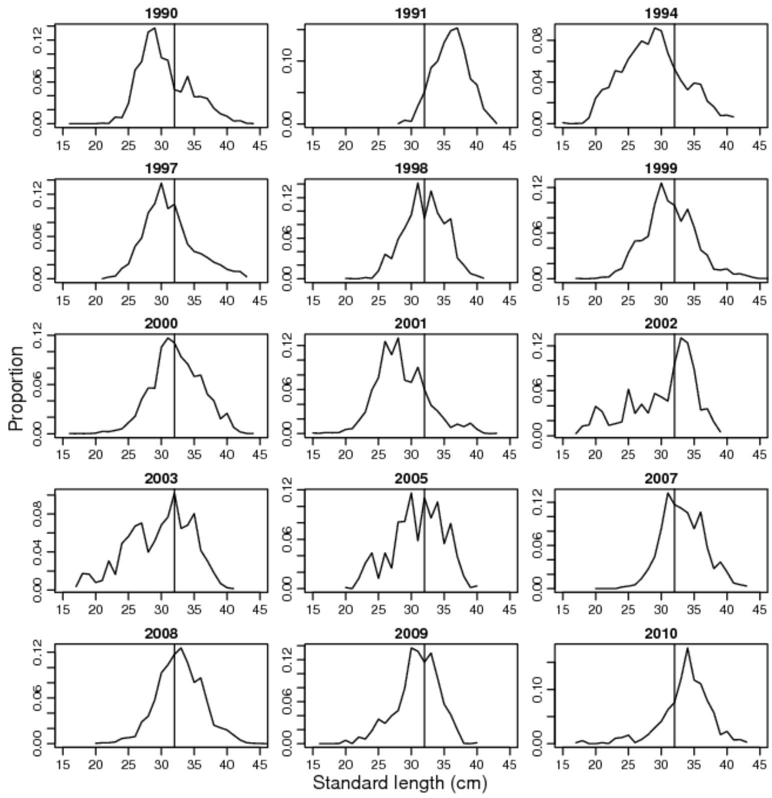

Figure 19: Orange roughy estimated length frequency distributions (catch weighted) for the flat stratum of the Mid-East Coast, by fishing year (labelled as year ending). Vertical line is at 32 cm SL for reference.

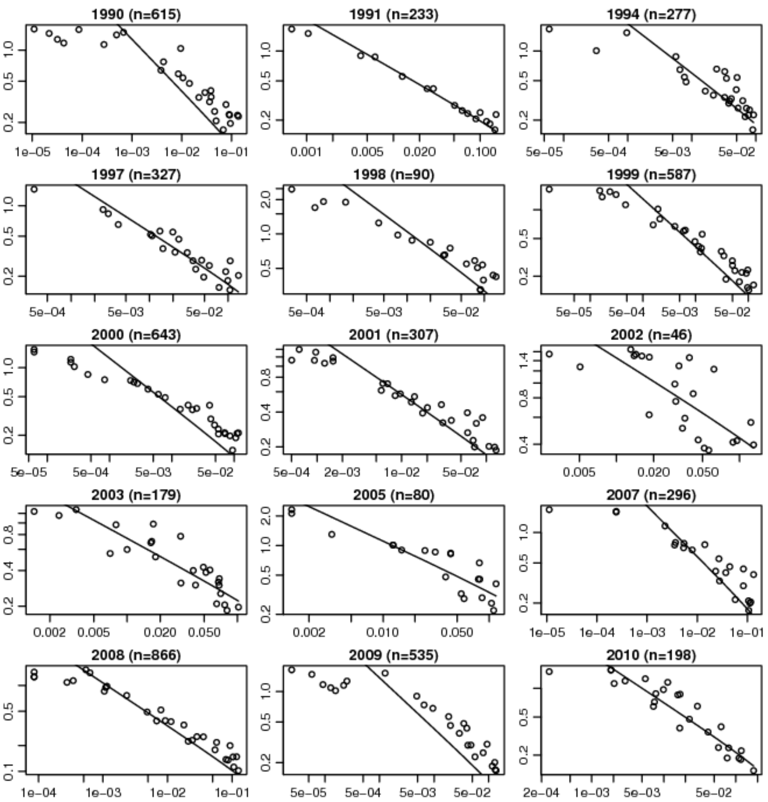

Figure 20: Log(proportion) (x-axis) and log(c.v.) for the orange roughy length frequency distributions by fishing year (labelled as year ending) from the flat stratum of the Mid-East Coast, from which multinomial effective samples sizes were estimated (shown as *n*, in parentheses).

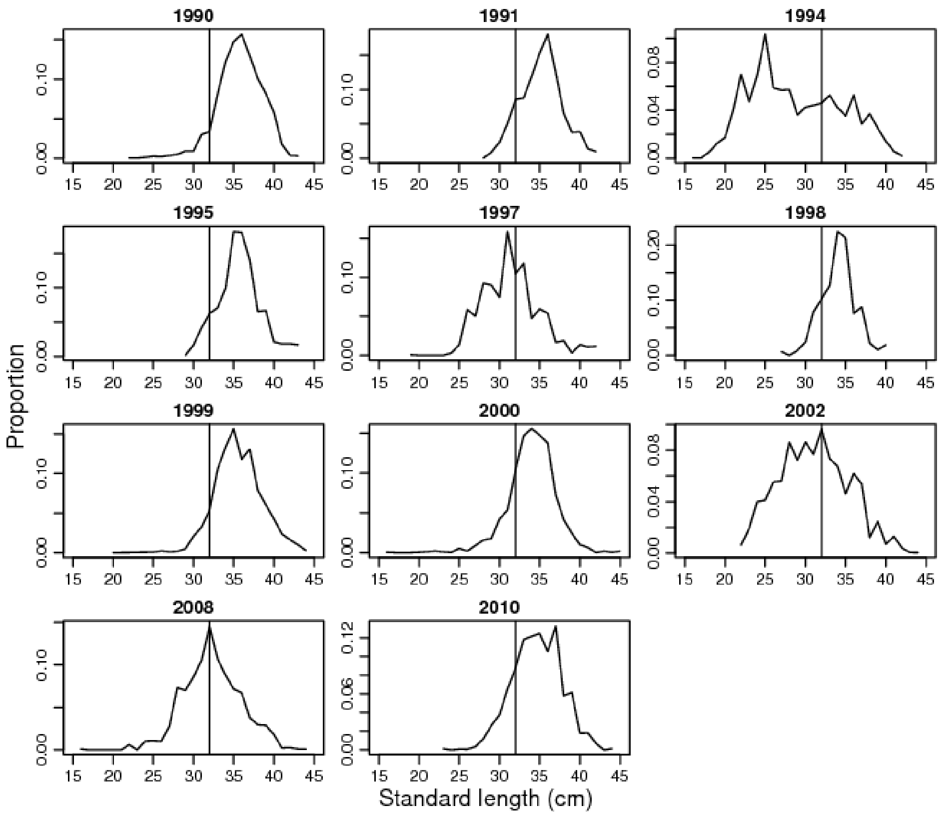

Figure 21: Orange roughy estimated length frequency distributions (catch weighted) for the hill stratum of the Mid-East Coast, by fishing year (labelled as year ending). Vertical line is at 32 cm SL for reference.

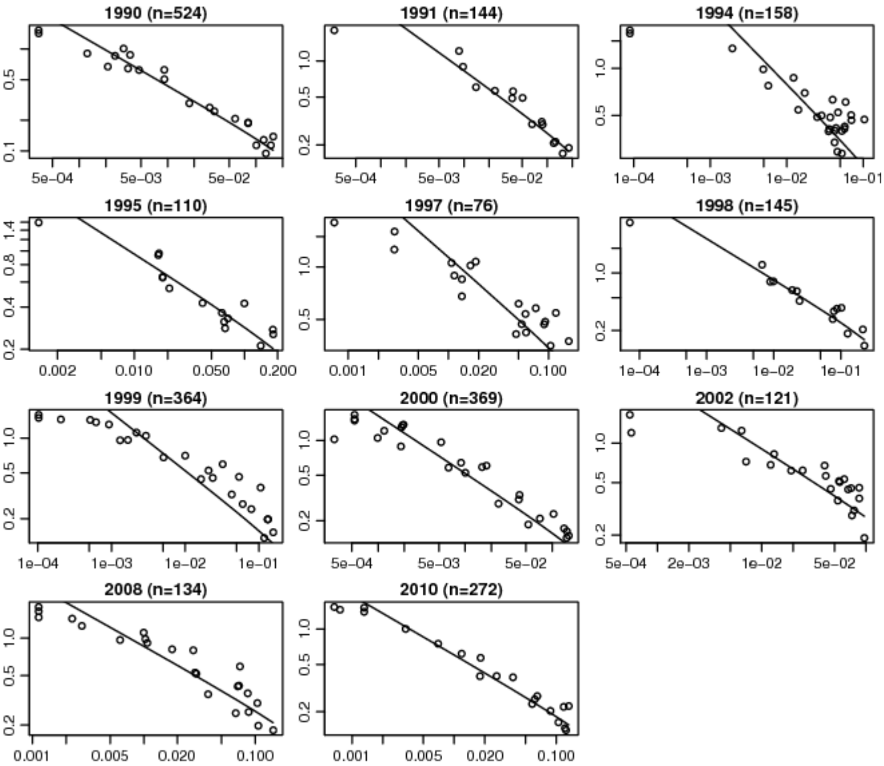

Figure 22: Log(proportion) (x-axis) and log(c.v.) for the orange roughy length frequency distributions by fishing year (labelled as year ending) from the hill stratum of the Mid-East Coast, from which multinomial effective samples sizes were estimated (shown as *n*, in parentheses).

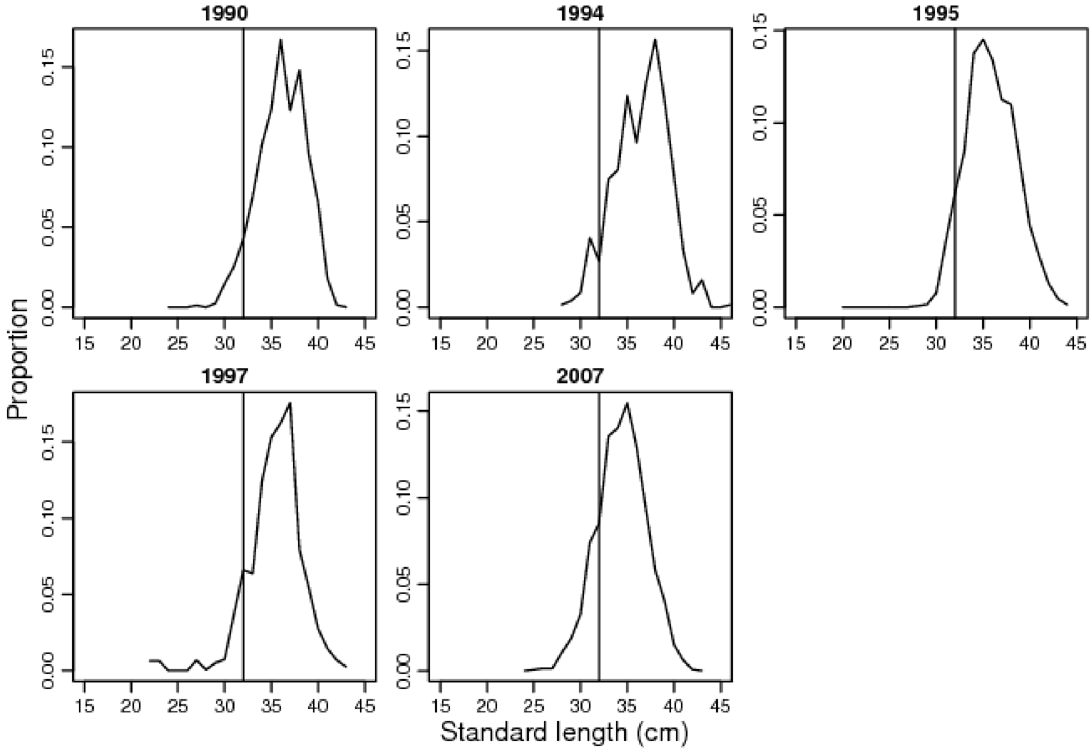

Figure 23: Orange roughy estimated length frequency distributions (catch weighted) for the spawn fishery of the Mid-East Coast, by fishing year (labelled as year ending). Vertical line is at 32 cm SL for reference.

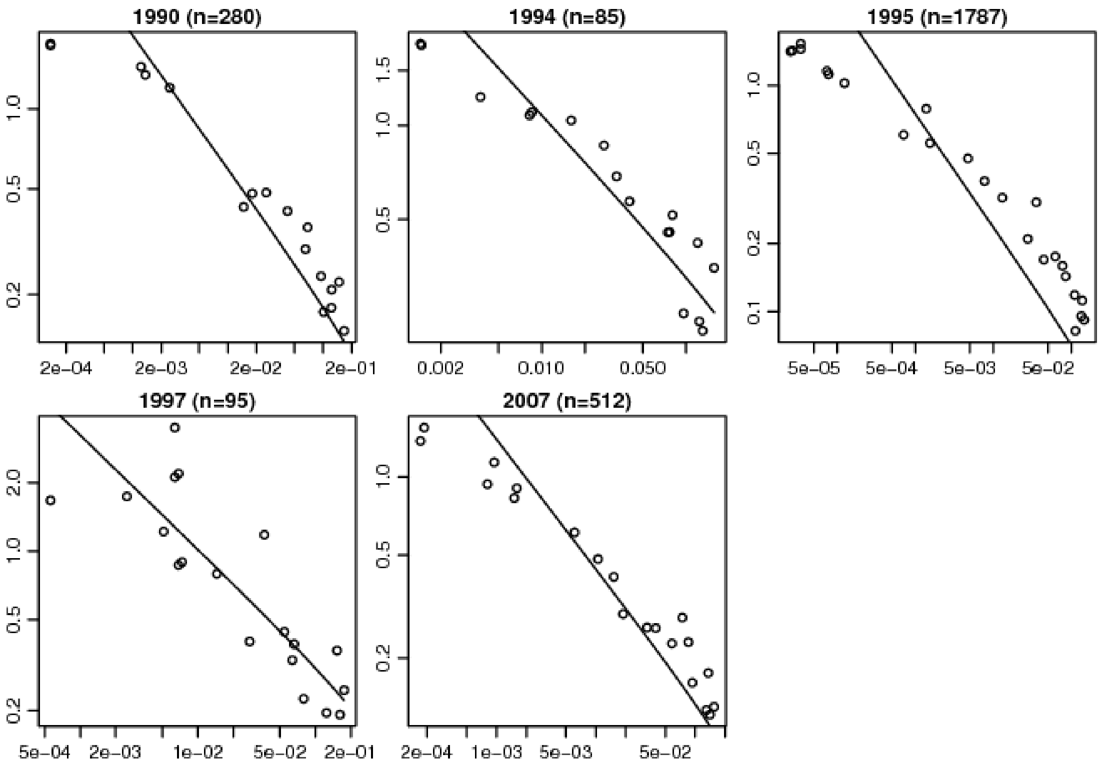

Figure 24: Log(proportion) (x-axis) and log(c.v.) for the orange roughy length frequency distributions by fishing year (labelled as year ending) from the spawn fishery of the Mid-East Coast, from which multinomial effective samples sizes were estimated (shown as *n*, in parentheses).

The tows having lower mean length were from the Kaikoura region, which was more often sampled in 1994 (Figure 26). Smaller orange roughy are known to be more frequent in the southern area, and some previous stock assessments have split the stock into north and south strata (see Branch 2002; Dunn & Anderson 2008). In the present model this additional north/south stratification, whilst justifiable, was not incorporated because it would have introduced further complexity, requiring migrations not only from flat to hill, but from south to north (including potential permutations of these strata). This complexity, even if migrations were estimable, was considered beyond the scope of this study. The 1994 length frequency for the hill had relatively low weight however (see Figure 22), so had relatively little leverage in the model.

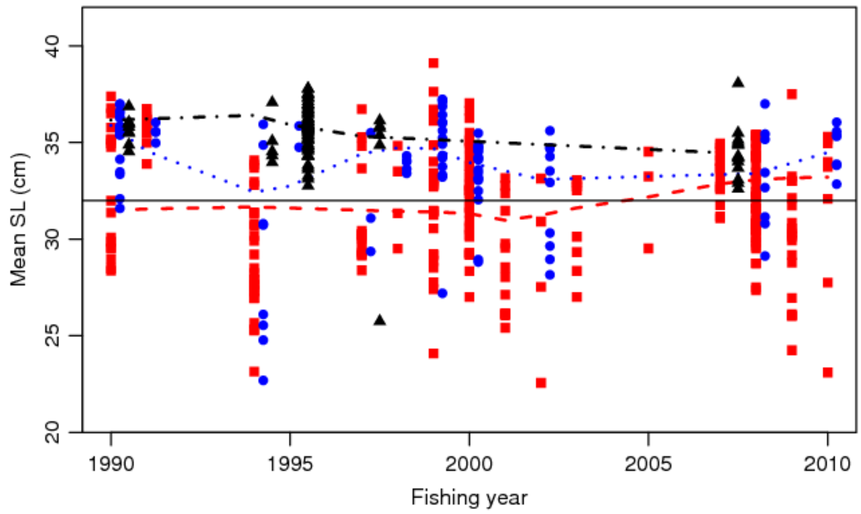

Figure 25: Mean orange roughy standard length (SL) per tow (points) from MFish observer samples of commercial catches for the Mid-East Coast flat stratum (squares), hill stratum (circles), and spawn (triangles), by fishing year (labelled as year ending). Fitted loess lines (weighted by catch weight) indicate the trend, for the flat stratum (dashed line), hill stratum (dotted line), and spawn (dot and dash line). The horizontal line is for reference and at 32 cm.

Because of the variability in the shape of the estimated length frequency distributions, a model assuming constant recruitment and vulnerability simply cannot fit them all. High variability in length frequencies has been previously observed for orange roughy (e.g. Anderson & Dunn 2008), and it has been argued that the length data should receive relatively little weight in stock assessment models (Francis 2006).

3.8 Age frequency data

The proportion of older fish in the sampled catch has declined substantially; the proportion of fish older than 60 years declined from about 48% in 1990 to 12% in 2002 (Figure 27). This change in age frequency seems large, and unlikely to be attributed solely to ageing bias (Francis 2006).

Because of concerns about the veracity of the age frequency data, for most model runs these data were excluded, and used instead as a diagnostic, by comparing the model predicted age frequencies with the observed frequencies. The age frequency data were only fitted in the model when recruitment variability was estimated.

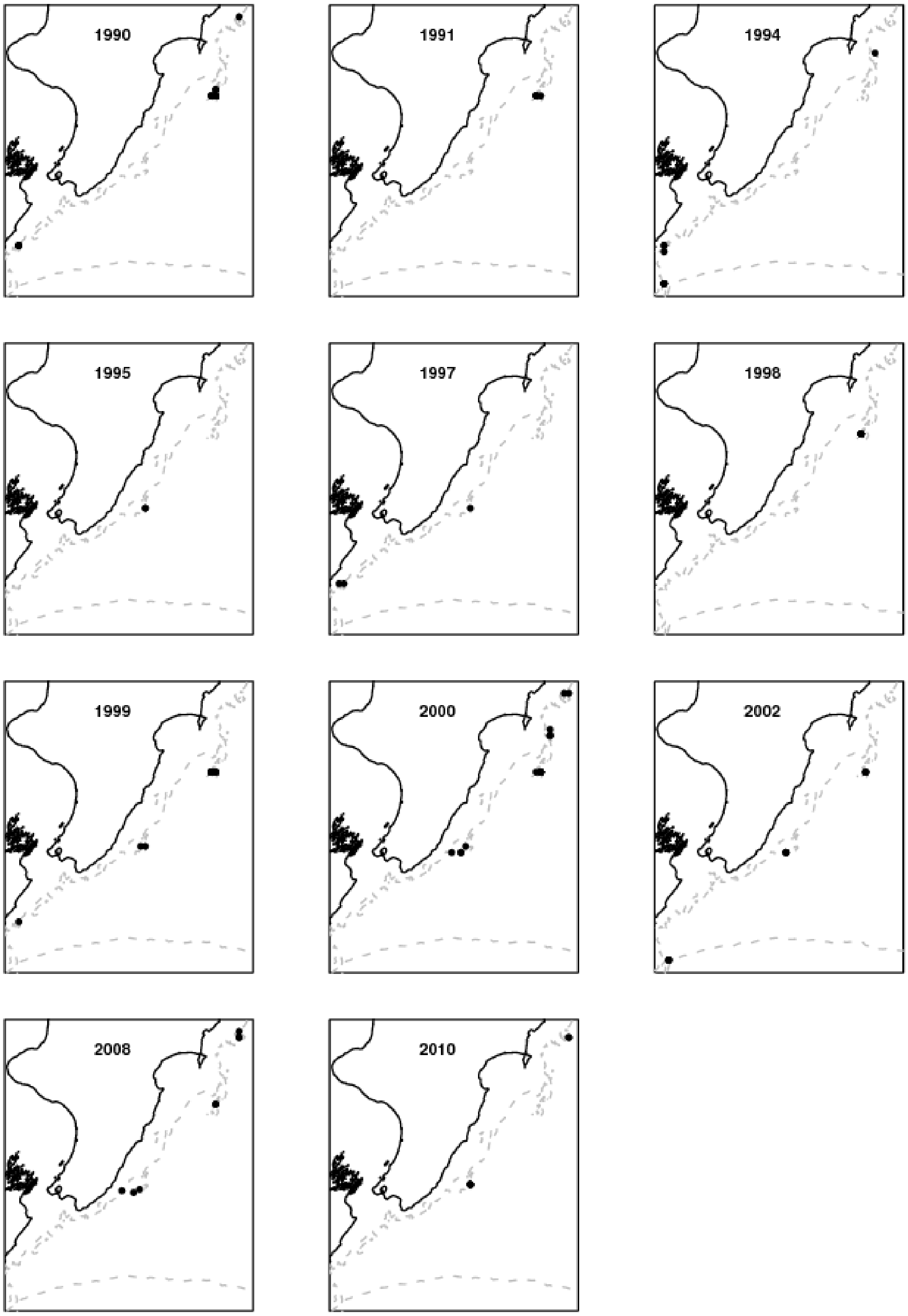

Figure 26: Location of MFish observer length frequency samples of orange roughy (dots) for the hill stratum of the Mid-East Coast by fishing year (labelled as year ending).

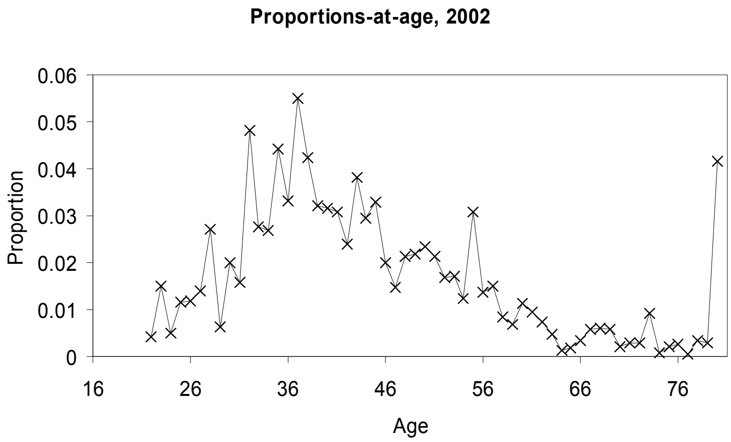

Figure 27: Proportion of orange roughy at age estimated from Mid-East Coast otolith samples from the spawning fishery, aggregated for 1989–91, and for 2002, with a plus group at age 80 (reproduced from Dunn 2005).

4. MODEL ASSUMPTIONS

The observational data were incorporated into a Bayesian stock assessment, performed using the stock assessment program CASAL (Bull et al. 2005). The stock was partitioned by age, maturity (immature or mature), and stratum (hill or flat), with a single maturation episode, and age groups 1–80 years, with a plus group at 80+. The stock was not partitioned by sex.

The hill fishery was applied to the hill stratum, the flat fishery to the flat stratum, and the spawn fishery to both hill and flat strata. In each year, the catch from the spawn fishery was allocated to flat and hill in proportion to the estimated vulnerable biomass in each.

The hill and flat fisheries took place in time step one, and the spawn fishery (and spawning) in time step two. In initial model runs, the proportion of mature fish spawning was assumed to be one, although in reality it is known that not all orange roughy spawn every year (see Dunn et al. 2008). However, an age component to the non-spawning proportion was effectively investigated through comparison of the mature biomass estimated on the flat and hill (derived from the maturity at age ogive), and the biomass estimated to be in the spawning fishery (see section 5). Recruitment took place in time step one and in the flat stratum only.

The one-way migration from the flat to the hill took place each year in time step one, and was modelled as a rate, which was a function of age according to a capped logistic ogive.

Initial model runs assumed deterministic recruitment. Where estimated, recruitment was assumed to be Beverton-Holt (see Table 19). Maturity at age, natural mortality, growth, variability around mean length at age, and the length-weight conversion, were assumed to be constant (see Table 19). Other model settings, such as the order of processes within time steps, used CASAL defaults (Bull et al. 2005)

Lognormal errors, with known (sampling error) c.v.s were assumed for the CPUE, trawl survey, and acoustic survey indices. An additional process error variance of 0.2 was added to the c.v.s from the CPUE indices and the trawl survey estimates (following Dunn 2005).

When age frequencies were included, an ageing error misclassification matrix was applied (see Dunn 2005), and the length frequency data from fish used in the estimation of the age frequencies were excluded. When recruitment deviates were estimated, vector smoothing and vector average penalties were included.

Because this was an exploratory model, and not used for formal stock assessment purposes, the model was not balanced nor were alternative observation weightings investigated. However, the estimated multinomial effective sample sizes for composition data (length frequencies) were capped at 500, to prevent any single sample dominating the fit.

A penalty function was included to discourage the model from allowing the stock biomass to drop below a level at which the historical catch could not have been taken. Maximum posterior density (MPD) estimates were found for the free parameters in the model; no MCMC runs were completed. Sensitivity runs were focused on the assumed model structure, e.g. all fish or only those from hill habitats were assumed to spawn, and the assumed ages at maturity or natural mortality rate were varied.

5. MODEL RESULTS

The likelihood and parameter estimates, derived quantities, and fits to data, are shown for selected runs in Appendices III–XIII. The two different models (see section 2) are hereafter referred to as model ABC; where all migrations (a), (b), and (c) in Figure 2 are undertaken (such that mature fish from all strata are assumed to spawn), and model AB; where only migrations (a) and (b) are undertaken (such that only mature fish from the hill are assumed to spawn).

5.1 First model runs (“base runs”)

The first run of the model ABC produced rather poor fits to the observed data (Appendix III). The model predicted more small fish in the spawn fishery than were observed, and therefore indicated that the assumed age of vulnerability was too low, which in this run was not estimated but set to the maturity ogive. The age frequency data, although not fitted, also suggested the estimated age of vulnerability for the spawn fishery was too low. Most of the initial biomass was estimated to occur in the hill stratum, which in the model was not depleted as fast as indicated by the hill CPUE index; the fits to all of the CPUE indices were visually quite poor. A predicted biomass rebuild, after the reduction in catches in the mid-1990s, conflicted with the decline in the trawl survey biomass index. Vulnerability in the flat fishery was estimated to take place close to the assumed maturity ogive, such that a small amount of cryptic mature biomass was estimated.

The first run of the model AB fared no better (Appendix IV). Unlike the base run of model ABC, this model incurred catch penalties, indicating the estimated biomass was too small to provide the catch. The fit to the left hand side (LHS) of the spawn fishery length frequencies was again poor. The fit to the hill CPUE index was better, but the fits to the spawn and flat

CPUE indices remained poor. As in the ABC model, the fit to the trawl survey biomass index was poor, and most initial biomass was in the hill stratum. There was no cryptic mature biomass estimated in this model run.

5.2 Fitting the spawn fishery length composition

There were two potentially straightforward solutions to the lack of fit of the model to the spawn fishery length frequency distributions. The first was to change (increase) the assumed age at maturity, so that the size at which fish entered the spawn fishery increased. The second was to estimate a separate vulnerability ogive for the spawn fishery. The latter could introduce a difference between the assumed mature biomass, which was determined by the maturity ogive, and the estimated spawning biomass, which was determined by the spawn fishery ogive.

Changing the assumed maturity ogive from the NIWA estimate to the higher CAF estimate (see section 3.6) in the model ABC removed the cryptic biomass, but still produced a poor fit to the LHS of the spawn fishery length frequency distribution (Appendix V). This indicated that the mean age of vulnerability to the spawn fishery, as indicated by length frequency distributions via the assumed growth model, was above the available range of maturity at age estimates, as estimated from counts to the transition zone on otoliths. The fits to observed data were otherwise similar to the base model ABC run.

Estimating a vulnerability ogive for the spawn fishery in model ABC resulted in a much better fit to the LHS of the spawn fishery length frequency distribution, with an estimated A50 for this fishery of 41 years (Appendix VI). The fit to the CPUE indices were also greatly improved, although the estimated decline in the spawn fishery biomass was still not as steep as observed. Contrary to the previous runs, there was now more initial biomass on the flat than the hill. This distribution of mature biomass has also been estimated in trawl surveys (Doonan & Dunn 2011). The fit to the trawl survey biomass index remained poor. The estimates of spawning biomass for 2001 and 2003 (both about 2000 t) were well below the observed estimates. This model run resulted in the maturity ogive occurring before the spawn fishery ogive, which suggests mature biomass was not equal to spawning biomass. This could be interpreted as indicating either an age structured cryptic spawning biomass, or an age structured non-spawning proportion. The level of cryptic or non-spawning biomass will depend on the assumed maturity ogive, and was reduced with the CAF maturity estimate. The age of vulnerability to the spawn fishery was estimated to be higher than indicated by the age observations, which could indicate that the length frequency data were biased (this seems unlikely given the nature and coverage of these data), the growth curve was biased (possible), or the ageing was biased (also possible, see Francis 2006).

Estimating a vulnerability ogive for the spawn fishery in model AB produced a similar fit, although the fit to the hill length frequency distributions was not as good (Appendix VII). Contrary to the ABC model, this run estimated more initial biomass in the hill strata than the flat.

In both runs estimating a vulnerability ogive for the spawn fishery, the correspondence to the observed age frequency data was poor, in particular to the LHS (vulnerability). This could be a result of ageing bias or error, for example the "smearing" of ages through ageing imprecision (see e.g. Figure A7.8, distribution for 2002, where this seems quite plausible), or it could indicate a model misspecification.

5.3 Fitting the spawn fishery age composition

The age composition observations were not fitted in initial model runs, but were used in later runs as a diagnostic. When these data were fitted, with the relevant length data excluded, there was an improved fit to the 2002 age frequency composition, but the vulnerability estimated for the 1990 age composition was still to the right of the observations (Appendix VIII). The visual fits to other data weren't much improved compared to previous runs.

The model fit, assuming constant vulnerability, highlighted the difference in the LHS of the 1990 and 2002 age compositions; this could be sampling error, or perhaps indicate a real change in vulnerability. Each age composition assumed a multinomial error distribution with an effective sample size of 500. The multinomial is relatively robust to outliers, and therefore fitted the 'general shape' of the age composition. The fit to the age composition plus-group (effectively an outlier) would probably have been improved by changing the error assumption (e.g. to a lognormal), but was not evaluated here.

5.4 Fitting the trawl survey biomass index

The trawl survey biomass index, with the new observation for 2010, was considered a key input to the orange roughy MEC stock assessment. The model runs considered above all predicted biomass rebuilds that conflicted with this data set, which indicated a decline. Two options for fitting the trawl survey biomass decline were (1) assuming mean productivity was incorrect (i.e. lower than assumed), or (2) allowing stochastic recruitment. To achieve the latter, annual recruitment deviates were estimated for the years 1910–2005 inclusive, and the maturity ogive was set equal to the estimated spawn fishery vulnerability ogive.

When estimating recruitment residuals, it was necessary to fix the following parameters to avoid them going to bounds; the vulnerability ogive for the flat fishery, the vulnerability ogive for the flat trawl survey, and the A50 and A95 of the migration ogive (the cap parameter was free).

5.4.1 Changing M

Including the age composition data and estimating natural mortality (M) made little difference to the model fit (Appendix IX), and estimated an M very close to the assumed M. The reasonable fit to the RHS of the age compositions, including in this run to the plus groups, indicated that the age compositions were consistent with the assumed M of 0.045 in this model.

Because the trawl survey biomass index declines, a possible solution is to assume a lower M. A model run assuming an M of 0.025 (the lower 95% confidence interval of New Zealand orange roughy M estimates) did not provide a plausible solution; the fit to almost all of the observation data was relatively poor, and the trawl survey vulnerable biomass did not decline (Appendix X).

5.4.2 Estimating recruitment residuals

Estimating stochastic recruitment residuals improved the fit to almost all of the observational data, in particular to the CPUE indices and length compositions (Appendix XI). This run estimated more fish in the plus group than were observed, and a cyclical pattern in recruitment with a general increase between 1910 and 1980. Although the likelihood indicated the fit to the trawl biomass indices was improved, the fit was still not good, with the predicted biomass on the flat increasing whereas the observations decreased.

The CV of the trawl survey biomass indices was then reduced to 5%, to see if increasing the weight on these observations would improve the fit (Appendix XII). The fit to the trawl survey biomass index was improved, but still did not capture the observed decline. This model run produced worse fits to almost all of the other data, most noticeably to the early hill CPUE index and the composition data.

A number of other model runs were attempted in order to try to fit the decline in the trawl survey biomass index. These included: estimating recruitment whilst also allowing mean recruitment to vary outside of that expected from B_0 (by estimating R_{mean} and B_{mean}); estimating or lowering M; up-weighting the trawl survey biomass indices by lowering their c.v.s and process error or by excluding or down-weighting various combinations of other observation data sets; and allowing greater freedom in recruitment patterns by estimating recruitment residuals without including the age composition observations and/or by reducing the smoothing and vector average penalties. Many of these runs required fixing several parameters (for example those determining migration or vulnerabilities), to prevent parameters (B_0 in particular) running to bounds, and various combinations of fixed parameters were tried. No reasonable model run was found that could fit all observational data whilst estimating recruitment.

This is not to say that the decline in the trawl survey biomass index could not be fitted. This was achieved, for example, by estimating a very large YCS in the past, followed by recruitment failure (Appendix XIII). This run fitted the trawl survey index and CPUE relatively well, capturing the decline in the trawl survey biomass index, but conflicted strongly with the observed length compositions and, although not fitted in this model run, with the observed age compositions.

6. DISCUSSION

This model was developed to investigate spatial structure hypotheses for orange roughy stock assessment, as an attempt to explain previous model predictions of hyper-depletion and cryptic biomass. Some progress was made, but problems were encountered (as in previous assessments) with the productivity assumptions, which were not the intended focus of this study.

6.1 Positive features

- The model runs showed that the commonly observed steep decline and then flat trend of many orange roughy CPUE indices (the 'hyper-depletion' trend) could be explained, and fitted, by a model assuming spatial structure and migrations. Hyper-depletion in the model was caused by spatial structure, rather than modelled using an exponent on the biomass (i.e. the *h* in CPUE = qB^h; Dunn 2005). If the spatial structure is accepted, then unbiased monitoring of total stock biomass would require biomass indices or estimates from both flat and hill strata.

- In this model a truly unavailable ('cryptic") spawning stock biomass could, by definition, not occur in the hill stratum and during the spawning fishery. Cryptic spawning biomass could effectively occur if fishing was focused only on hills, and the assumptions of model ABC were correct. Nevertheless, there was still a conflict between the assumed maturity ogive and the vulnerability estimated for the spawning fishery (i.e. the 'spawning' ogive). This conflict was not just a model artefact, but was apparent in the data. The mean age at maturity was assumed to be 25.73 years, equivalent to a 30 cm fish, but the mid-point of the LHS of the spawn fishery length composition (considered well-sampled) was at about 32 cm. This does not mean that the estimated vulnerability ogive was not influenced by fits to other data sets and other model assumptions (Dunn 2009), but it does at least cast doubt on the assumption that all mature fish spawn with equal frequency, which leads to some interesting hypotheses for spawning behaviour (see below).

- Some model runs got close to providing a reasonably good fit to almost all observational data; as such the model assumptions showed promise. The most notable poor fit was to the trawl survey biomass index on the flat. As a result of this poor fit, further development of the model was not completed. The trawl survey biomass index was the most recent fishery-independent observation, and as such considered to be a key observation with high *a priori* weighting in the assessment.

6.2 Problems

- The main problem was that the trawl survey flat biomass decline could not be fitted together with all of the other data. It was not clear whether the model was at fault (except in the general sense that all models are 'wrong'), or whether the problem lay with the trawl survey biomass index or with other observational data. The two-stratum spatial structure (hill and flat, with a spawn fishery) did not resolve the problems with productivity. In other words, the productivity problem did not appear to be an artefact caused by spatial structure; which was the subject of investigation of this study.

- If deterministic recruitment was assumed, then the trawl survey biomass index made no sense. For example, if the B_0 was equal to only half of the total catch over the first ten years of the fishery (about 55 000 t), then the average recruitment should have been at least M (4.5%) × B_0, or about 2500 t. As the catches since the mid-1990s were less than this (below 1600 t since 2001–02), the stock should have been steadily rebuilding, not declining as indicated by the trawl survey. An obvious explanation is stochastic recruitment, but the YCS pattern required to fit this decline was very inconsistent with the observed age composition.

- The trawl survey estimated that the biomass on MEC hills was relatively low compared to flats (approximately 5% of biomass on the hills; Doonan & Dunn 2011). But general thinking on orange roughy suggests that they are 'feature orientated' and hills should support a substantial, and possibly greater, biomass. In run 3 (model ABC; Appendix VI), by 1994 the biomass on hills was depleted such that there was more biomass on the flat than on the hills. This did not (and could not) occur with the model AB, where spawning biomass had to be on the hills, and where biomass on hills in 1994 was still much larger than on the flat (Appendix VII). The ratio between orange roughy biomass on hills and flats may not be straightforward, and could vary by stock depending on the nature of the habitat.

- The model fits to the acoustic biomass observations were generally not good. For example, run 3 (Appendix VI) predicted the biomass available to the acoustic survey to be about 2000 t, compared to the observed biomass of about 15 000 t. This indicated that the stock was either estimated to be too small and/or too depleted, or that the observations or assumptions of the acoustic surveys were wrong. It seems most likely to be the former.

- The age composition data could not be fitted well. Age data are known to be dubious for orange roughy, and have been excluded from previous assessments because of concerns about bias (Francis 2006). The best fit using these data was run 4 (Appendix VI), which assumed model AB.

- The various model runs sometimes estimated more initial biomass to be on the hills, and sometimes on the flat. The variability in where most biomass started out was determined primarily by the migration ogive. Unfortunately CASAL couldn't limit (cap) the biomass in any one stratum, which we might consider a reasonable assumption for spatially limited areas, specifically the hills. There could also be density dependent effects on migration, which could have been investigated using CASAL, but were considered too complex for this study.

6.3 Other conclusions and hypotheses

Previous models have rarely been able to fit CPUE indices from hills or hill complexes (e.g. Dunn 2007). The present study demonstrated an explanation for observed hill CPUE trends, and in doing so indicated that CPUE may well provide biased estimates of stock biomass trends. This conclusion is perhaps no surprise, but has not prevented hill CPUE indices being regularly used in stock assessments.

Mature orange roughy are known to skip spawning (see Dunn et al. 2008). The difference in the model estimated maturity and spawning ogives suggests that there could be an age component to skipping spawning (young fish skip more often), which could in principle introduce depensation at low stock size. This is because as the stock age structure is depleted, the proportion of mature biomass that spawns decreases. In order to guard against recruitment overfishing, it would be safer to assess and manage spawning biomass rather than mature biomass.

There was a great deal of variability in the length compositions, which the model was unable to fit with constant vulnerability and productivity assumptions. It seems unlikely that fish are measured with substantial error. The observed variability might therefore be caused by small-scale spatial structure in addition to ontogenetic movements and size-assortative shoaling, which could be related to habitat; or (if not) to movements within the stock. Either way, it seems that obtaining representative (consistent) samples for MEC orange roughy has been difficult. Of note here is the difference between the length compositions on the flat sampled by the trawl survey compared to those sampled by the commercial fishery. The gear types used by both are similar, with similar sized cod-end meshes, so the greater proportion of smaller fish (less than 25 cm SL) sampled by the research vessel was presumably either because the allocation of tows to model strata ('flat' or 'hill') was biased, or because there was further small-scale spatial and ontogenetic structure. It could be that the commercial fishers targeted areas where larger orange roughy were predominant (given that discarding on observed tows should be negligible). Whether this potential additional structure is true and important for stock assessment is unknown.

Other orange roughy stock assessments have predicted biomass rebuilds that have not been supported by observed data. Stock assessment model sensitivity runs have addressed this by assuming lower mean productivity (lower M), or by allowing stochastic recruitment. Other explanations might include (1) under-reporting of catches after TACCs were reduced; (2) an increase in incidental or natural mortality, e.g. escapees from trawl nets might be substantial in number, and either later die from injuries, or be behaviourally impaired and then predated; (3) the estimate of B_0 was too high, because there was an orange roughy vulnerable biomass expansion that coincided with the start of the fishery. For example, if sperm whales were important predators of orange roughy, then whaling during the early 20^{th} century might have produced a population boom in orange roughy that arrived in the fishery later in the 20^{th} century. Whether any of these alternatives are actually credible explanations is unknown.

7. ACKNOWLEDGMENTS

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APPENDIX I

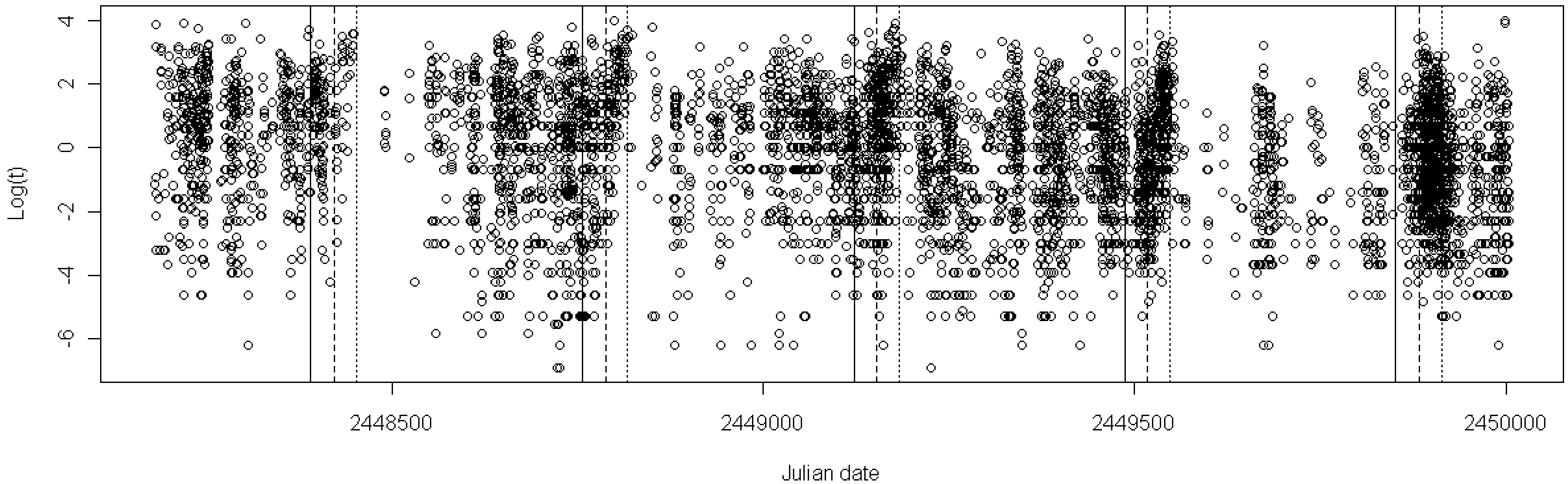


Figure A1.1: Orange roughy catch per tow (log of tonnes) for the ORH 2A South subarea of the Mid-East Coast by Julian date between 1 October 1990 and 30 September 1995. Each set of vertical lines indicates 1 May (solid lines), 1 June (dashed lines), and 1 July (dotted lines).

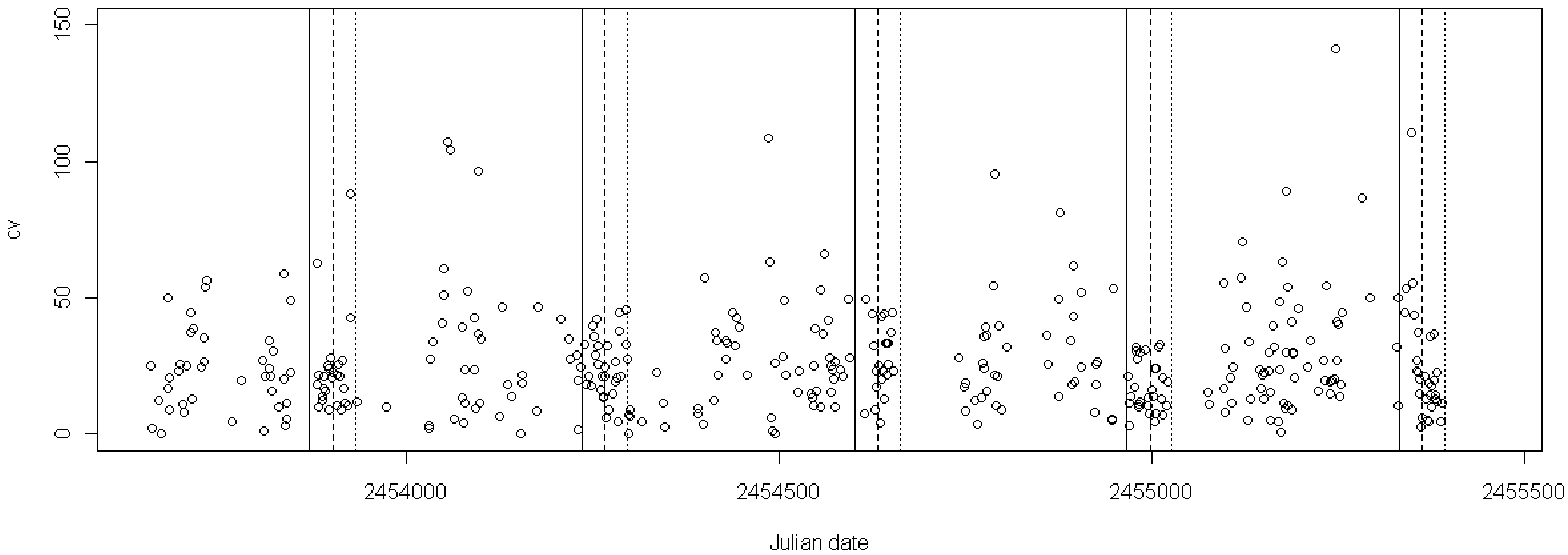


Figure A1.2: Coefficient of variation (CV) of orange roughy catch per tow (log of kg) by Julian day, for the ORH 2A South subarea of the Mid-East Coast by Julian date between 1 October 1990 and 30 September 1995. Each set of vertical lines indicates 1 May (solid lines), 1 June (dashed lines), and 1 July (dotted lines).

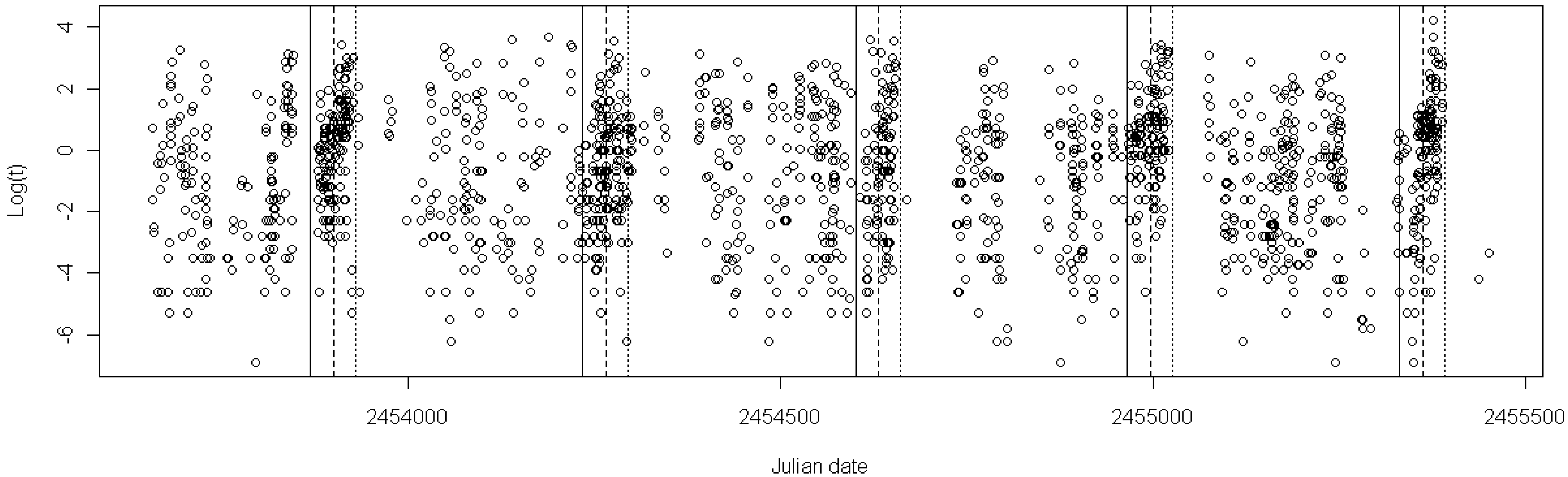


Figure A1.3: Orange roughy catch per tow (log of tonnes) for the ORH 2A South subarea of the Mid-East Coast by Julian date between 1 October 2005 and 30 September 2010. Each set of vertical lines indicates 1 May (solid lines), 1 June (dashed lines), and 1 July (dotted lines).

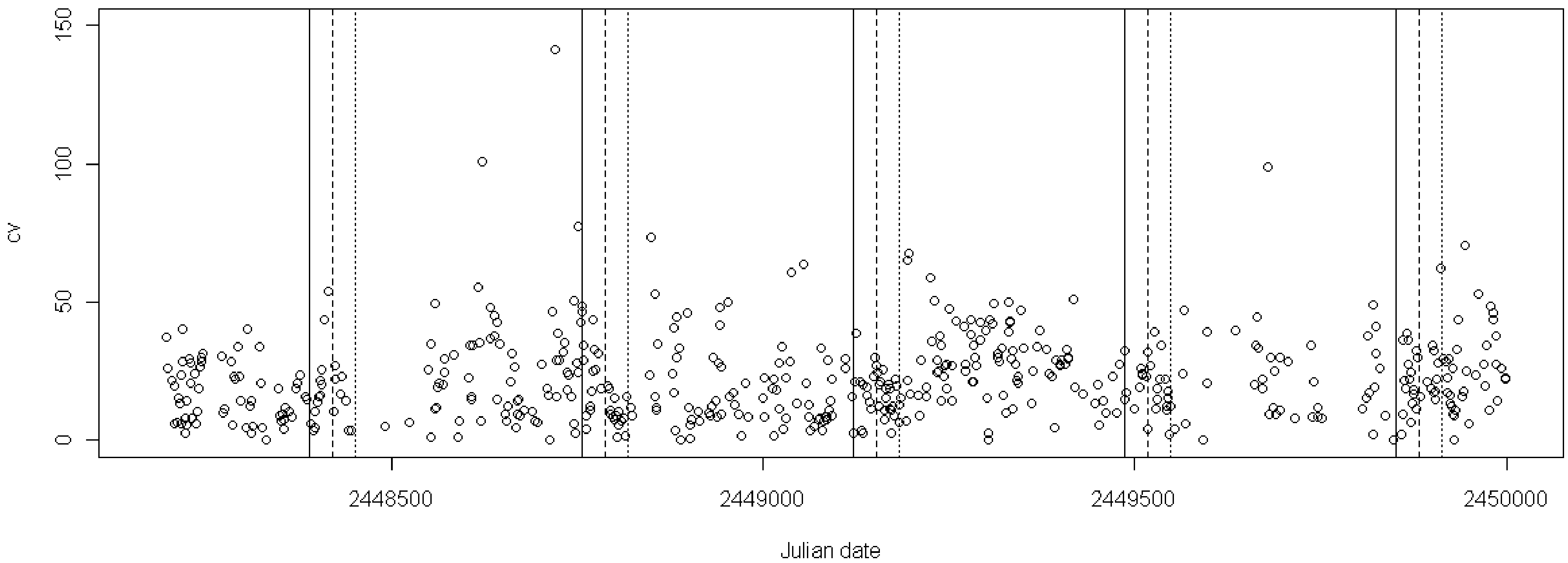


Figure A1.4: Coefficient of variation (CV) of orange roughy catch per tow (log of kg) by Julian day, for the ORH 2A South subarea of the Mid-East Coast by Julian date between 1 October 2005 and 30 September 2010. Each set of vertical lines indicates 1 May (solid lines), 1 June (dashed lines), and 1 July (dotted lines).

APPENDIX II

Estimated Length frequency compositions (proportions at length) by fishery and fishing year (labelled as year-ending) from commercial samples.

Flat

SL (cm)	1990	1991	1994	1997	1998	1999	2000	2001	2002	2003	2005	2007	2008	2009	2010
15	0	0	0.001	0	0	0	0	0.0009	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0.0002	0.0006	0	0	0	0	0	0	0
17	0	0	0.0001	0	0	0.0003	0.0001	0.0015	0.0028	0.0035	0	0	0	0.0001	0.0018
18	0	0	0.0003	0	0	0	0.0001	0.0012	0.013	0.0173	0	0	0	0.0001	0.0055
19	0	0	0.0056	0	0	0	0.0002	0.0015	0.0143	0.0167	0	0	0	0.0002	0
20	0	0	0.0244	0	0.0003	0.0005	0.0008	0.0057	0.0391	0.0079	0.0014	0.0002	0.0005	0.0048	0
21	0.0007	0	0.0326	0.0003	0	0.0019	0.0028	0.0068	0.0322	0.01	0	0.0002	0.0011	0.0002	0.0018
22	0.0003	0	0.0347	0.0026	0	0.0021	0.0025	0.0177	0.0139	0.0306	0.0124	0	0.0011	0.0095	0.0003
23	0.0095	0	0.0508	0.004	0.0016	0.0097	0.0041	0.0295	0.0161	0.0164	0.031	0	0.0023	0.0066	0.0099
24	0.0085	0	0.0494	0.0148	0.0006	0.0134	0.006	0.0597	0.0185	0.0492	0.0434	0.0023	0.0068	0.0185	0.0113
25	0.0292	0	0.0622	0.0211	0.0116	0.0344	0.0136	0.0762	0.062	0.0564	0.0124	0.0035	0.0079	0.0351	0.0157
26	0.077	0	0.0709	0.0462	0.0361	0.0498	0.0212	0.1255	0.0298	0.0673	0.0434	0.0053	0.0092	0.0291	0.002
27	0.089	0	0.0794	0.0578	0.0297	0.0501	0.042	0.1074	0.042	0.0705	0.0248	0.0142	0.0285	0.0399	0.0078
28	0.1314	0.0007	0.0763	0.0935	0.0587	0.0558	0.0558	0.1303	0.0303	0.0398	0.081	0.0271	0.036	0.0474	0.0168
29	0.1374	0.0061	0.0919	0.1066	0.0751	0.0978	0.0555	0.0727	0.0563	0.0518	0.0817	0.0445	0.0576	0.0795	0.0293
30	0.0946	0.0042	0.0892	0.1359	0.0946	0.1261	0.1054	0.0699	0.0517	0.0685	0.1163	0.0834	0.093	0.137	0.0411
31	0.091	0.0289	0.0678	0.0995	0.1418	0.1024	0.1168	0.0904	0.0462	0.0767	0.0581	0.1329	0.1035	0.1323	0.0626
32	0.0488	0.0508	0.0526	0.1057	0.0891	0.0967	0.1108	0.0602	0.0952	0.1022	0.1105	0.1167	0.1174	0.1167	0.076
33	0.0456	0.0892	0.0413	0.0769	0.1299	0.0756	0.0938	0.0386	0.1303	0.0648	0.0858	0.1119	0.1257	0.1297	0.1193
34	0.068	0.0998	0.0325	0.0491	0.0973	0.0915	0.0851	0.0307	0.1238	0.0682	0.1054	0.1054	0.1062	0.0938	0.1767
35	0.0384	0.1294	0.0391	0.0388	0.0814	0.0678	0.0698	0.0201	0.0886	0.0805	0.0546	0.0832	0.0804	0.0564	0.1174
36	0.0388	0.148	0.0377	0.0358	0.0887	0.0378	0.0715	0.0084	0.0344	0.0417	0.0793	0.1064	0.0864	0.0416	0.1106
37	0.0361	0.1524	0.0217	0.0302	0.0308	0.0309	0.0482	0.013	0.036	0.0308	0.0389	0.0572	0.0544	0.02	0.0796
38	0.022	0.1185	0.0162	0.0236	0.02	0.0124	0.0401	0.0096	0.0184	0.0181	0.015	0.0278	0.0242	0.0003	0.0574
39	0.0142	0.0718	0.0077	0.0198	0.0076	0.0114	0.0182	0.0142	0.0051	0.007	0.0014	0.0371	0.0209	0.0001	0.0167
40	0.0106	0.062	0.0081	0.0136	0.0043	0.0129	0.0249	0.006	0	0.0024	0.0033	0.0233	0.0179	0.0013	0.0227
41	0.0038	0.0244	0.0065	0.0108	0.0008	0.0059	0.0078	0.001	0	0.0014	0	0.0079	0.0113	0	0.0072

Flat (cont.)

42	0.0043	0.0127	0	0.0103	0	0.0064	0.0022	0	0	0	0	0.0055	0.0048	0	0.0074
43	0.0005	0.001	0	0.003	0	0.0041	0.0004	0.0005	0	0	0	0.0037	0.0012	0	0.0029
44	0.0001	0	0	0	0	0.0016	0.0003	0	0	0	0	0	0.0006	0	0
45	0	0	0	0	0	0.0002	0	0	0	0	0	0	0.0003	0	0
46	0	0	0	0	0	0.0002	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0.0002	0	0	0	0	0	0	0.0003	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0	0

Hill

SL (cm)	1990	1991	1994	1995	1997	1998	1999	2000	2002	2008	2010
16	0	0	0.0001	0	0	0	0	0.0005	0	0.0011	0
17	0	0	0.0001	0	0	0	0	0	0	0	0
18	0	0	0.0049	0	0	0	0	0	0	0	0
19	0	0	0.0123	0	0.0007	0	0	0	0	0	0
20	0	0	0.0172	0	0	0	0.0001	0.0005	0	0	0
21	0	0	0.0398	0	0	0	0.0001	0.0012	0	0	0
22	0.0003	0	0.07	0	0	0	0.0002	0.002	0.0064	0.0061	0
23	0.0003	0	0.0469	0	0	0	0.0005	0.001	0.0192	0	0.0013
24	0.0012	0	0.0694	0	0.0029	0	0.0006	0.0003	0.0401	0.0103	0
25	0.0026	0	0.1035	0	0.0136	0	0.0009	0.0053	0.0411	0.0107	0.0008
26	0.0021	0	0.0588	0	0.0588	0	0.0022	0.0018	0.0552	0.01	0.0007
27	0.0036	0	0.0568	0	0.0502	0.0067	0.0013	0.009	0.056	0.0278	0.0034
28	0.0048	0.0003	0.0572	0	0.0925	0.0001	0.0017	0.0157	0.086	0.0731	0.0118
29	0.0092	0.0087	0.036	0.0014	0.0903	0.0089	0.0051	0.0176	0.072	0.0699	0.0261

Hill (cont.)

30	0.0092	0.0234	0.0425	0.0165	0.0744	0.0243	0.0208	0.0422	0.0862	0.0859	0.0376
31	0.03	0.0504	0.044	0.0415	0.159	0.079	0.0323	0.0533	0.0768	0.1048	0.0651
32	0.0338	0.0856	0.0459	0.0623	0.1046	0.1022	0.0538	0.1038	0.0965	0.1455	0.0876
33	0.0815	0.0878	0.0524	0.0707	0.1181	0.1265	0.1056	0.1467	0.0734	0.1069	0.1181
34	0.1224	0.1192	0.0421	0.0995	0.0474	0.2246	0.1338	0.1554	0.0674	0.0876	0.1215
35	0.1474	0.153	0.0352	0.1819	0.0595	0.213	0.1567	0.1476	0.0459	0.0716	0.1246
36	0.1569	0.1809	0.0526	0.1806	0.0539	0.0759	0.1181	0.1372	0.0618	0.067	0.1051
37	0.1294	0.1251	0.0285	0.1402	0.0166	0.0878	0.131	0.0724	0.0537	0.0378	0.1325
38	0.1009	0.0655	0.037	0.0652	0.0187	0.0222	0.079	0.0414	0.0122	0.0296	0.058
39	0.0816	0.0378	0.025	0.0666	0.0029	0.0099	0.0604	0.0242	0.0247	0.0289	0.0615
40	0.0581	0.0387	0.0141	0.0208	0.0136	0.0189	0.0428	0.0101	0.0071	0.018	0.0179
41	0.0176	0.0139	0.0057	0.0181	0.0107	0	0.0237	0.0065	0.0131	0.0023	0.0181
42	0.0038	0.0097	0.0019	0.0181	0.0115	0	0.0164	0	0.0041	0.0028	0.007
43	0.0032	0		0.0167	0	0	0.01	0.0019	0.0006	0.0011	0
44	0	0	0	0	0	0	0.0029	0.0005	0.0005	0.0011	0.0013
45	0	0	0	0	0	0	0	0.0019	0	0	0

Spawn

SL (cm)	1990	1994	1995	1997	2007
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0.0064	0
23	0	0	0	0.0064	0
24	0.0001	0	0	0	0.0002
25	0	0	0.0001	0	0.0008
26	0	0	0.0001	0	0.0016
27	0.0012	0	0.0001	0.0069	0.0015
28	0	0.0015	0.0007	0.0006	0.0105
29	0.0024	0.0038	0.0015	0.0051	0.0188
30	0.0147	0.0085	0.0077	0.0074	0.0327
31	0.0254	0.0406	0.0355	0.0368	0.0741

Spawn (cont.)

32	0.0425	0.027	0.0621	0.0659	0.0854
33	0.0691	0.0749	0.0845	0.0638	0.1355
34	0.1018	0.0805	0.1376	0.1244	0.1404
35	0.1236	0.1238	0.1453	0.1531	0.1548
36	0.1672	0.0962	0.1342	0.1623	0.1294
37	0.123	0.1307	0.1126	0.1757	0.0935
38	0.1482	0.1566	0.1101	0.0794	0.0582
39	0.0956	0.1204	0.0768	0.0545	0.0401
40	0.0655	0.0769	0.0442	0.0276	0.0152
41	0.0181	0.033	0.0276	0.0145	0.0061
42	0.0014	0.0082	0.013	0.0069	0.0009
43	0.0001	0.016	0.0047	0.0025	0.0002
44	0	0	0.0014	0	0
45	0	0	0	0	0
46	0	0.0014	0	0	0

Appendix III

Table A3.1: Model ABC base run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	240 660
B2011	158 172
B2011/B0	0.66
Flat B0	46 199
Flat B2011	36 056
Flat B2011/B0	0.78
Hill B0	203 018
Hill B2011	129 152
Hill B2011/B0	0.64
Spawn B0	240 622
Spawn B2011	158 179
Spawn B2011/B0	0.66

Likelihood components	
Total	3 556.41
Egg survey	7.20
FlatCPUE_early	-2.29
FlatCPUE_late	-8.52
HillCPUE_early	11.69
HillCPUE_late	7.10
SpawnCPUE_early	34.40
SpawnCPUE_late	10.95
Acoustic_2001	-0.97
Acoustic_2003	-0.27
Trawl_flat	1.03
Trawl_hill	1.16
Trawl_LF_flat	223.88
Trawl_LF_hill	284.98
Fishery_LF_flat	1 268.18
Fishery_LF_hill	899.48
Fishery_LF_spawn	874.55
Acoustic q ratio	-2.11
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.28
Prior q_FlatCPUE_late	-10.76
Prior q_HillCPUE_early	-12.43
Prior q_HillCPUE_late	-12.59
Prior q_SpawnCPUE_early	-10.26
Prior q_SpawnCPUE_late	-11.78
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	1.66
Prior on B0	12.39
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0

Vulnerability	
Flat A50	26.33
Flat Ato95	3.81
Hill A50	1*
Hill Ato95	1*
Spawn A50	25.73*
Spawn Ato95	7.11*
Survey Flat A50	17.79
Survey Flat Ato95	6.94
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	25.66
Migration Ato95	7.59
Migration cap	0.12

q's	
FlatCPUE_early	3.45e-05
FlatCPUE_late	2.12e-05
HillCPUE_early	3.99e-06
HillCPUE_late	3.39e-05
SpawnCPUE_early	3.51e-05
SpawnCPUE_late	7.61e-06
Acoustic_2003	0.07
Acoustic_2001	0.17
Trawl_hill	0.01
Trawl_flat	0.17

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

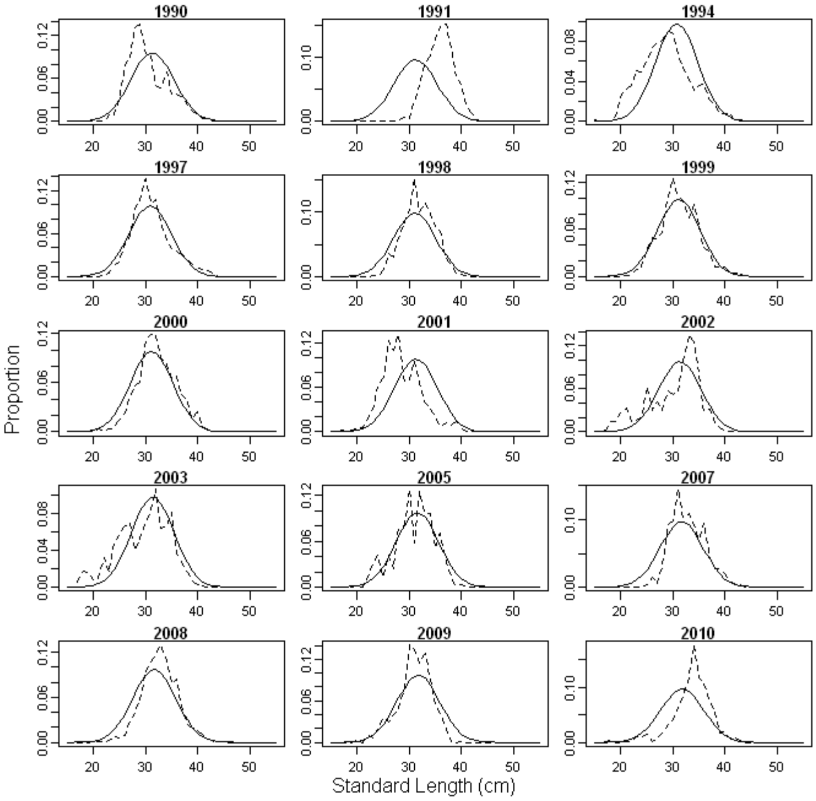


Figure A3.1: Model ABC base run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

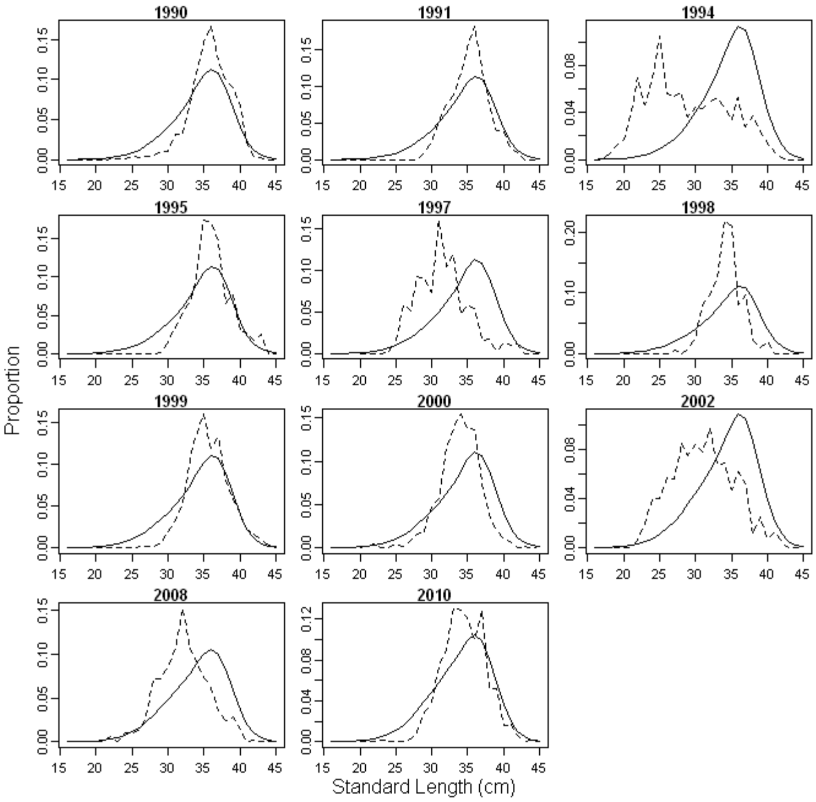


Figure A3.2: Model ABC base run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

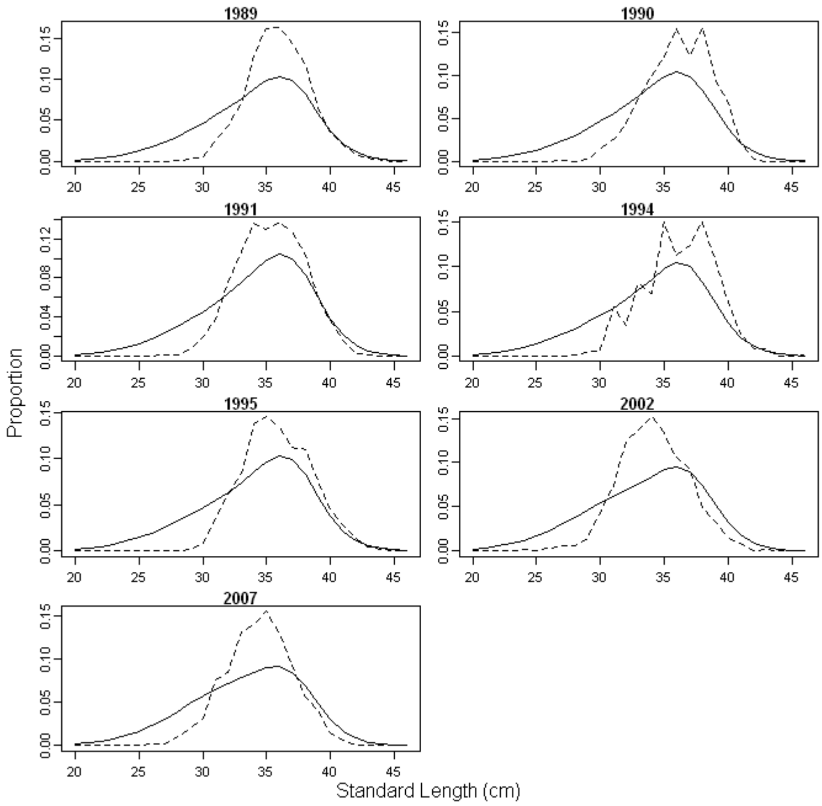


Figure A3.3: Model ABC base run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

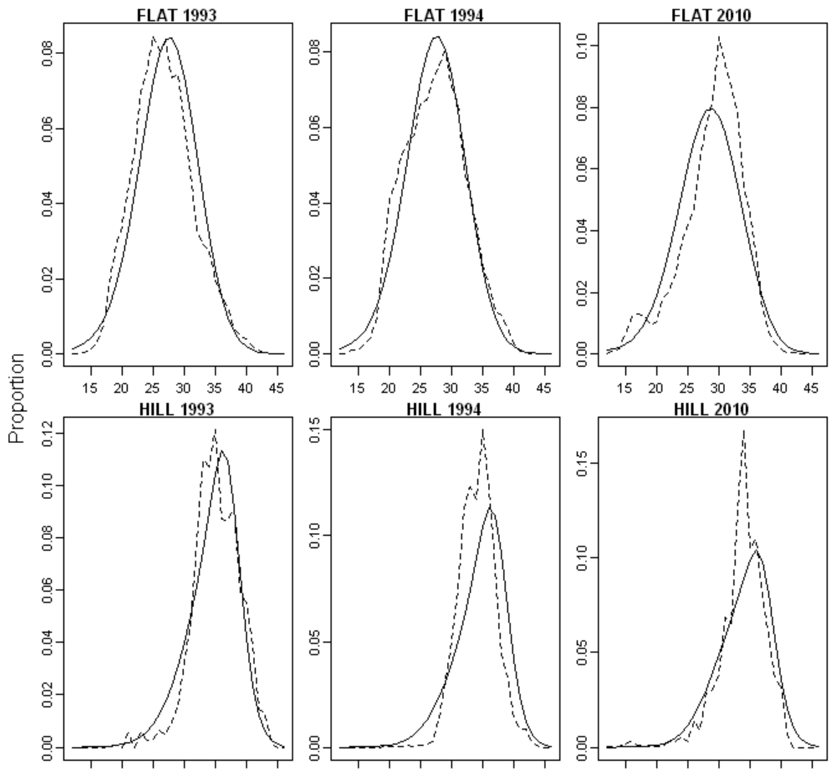


Figure A3.4: Model ABC base run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

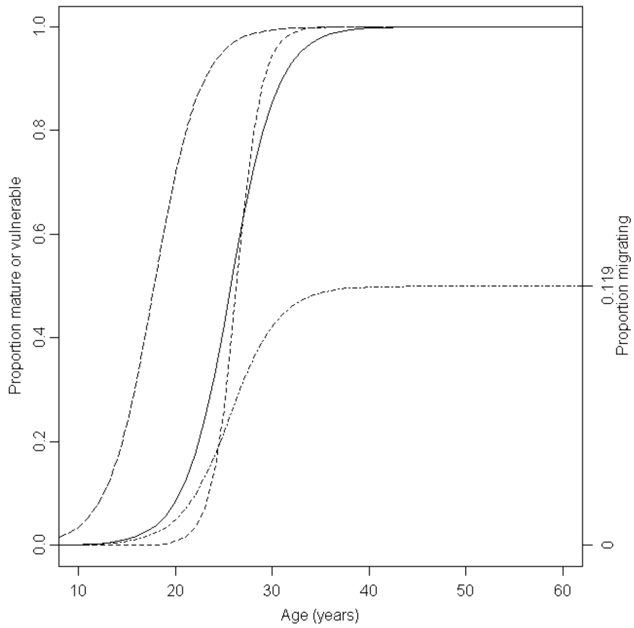


Figure A3.5: Model ABC base run: Ogives. Solid line, maturity ogive (fixed); short dash line, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated).

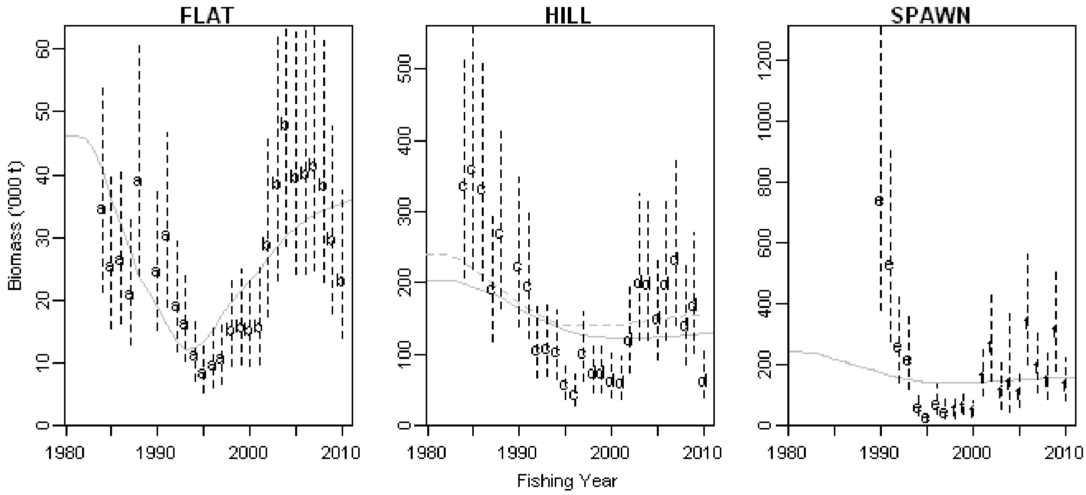


Figure A3.6: Model ABC base run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

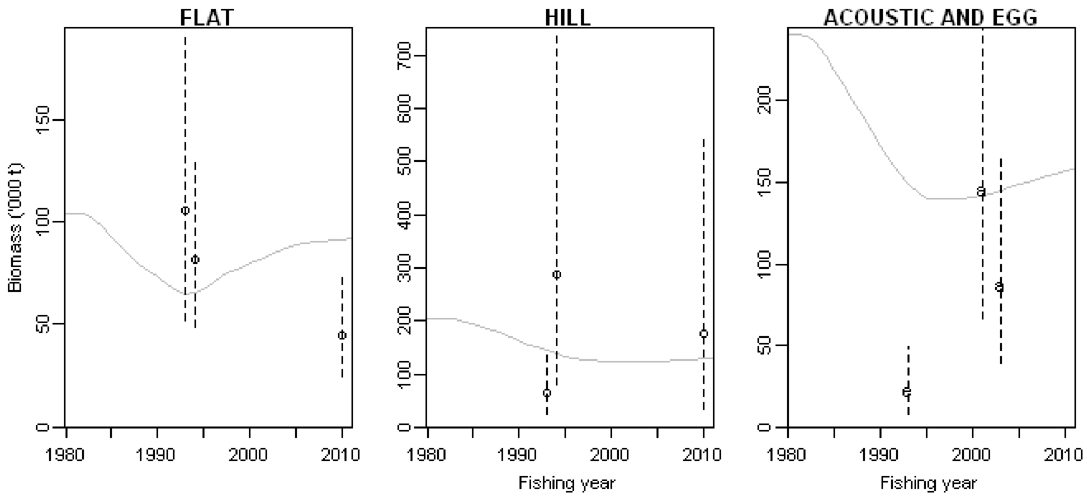


Figure A3.7: Model ABC base run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

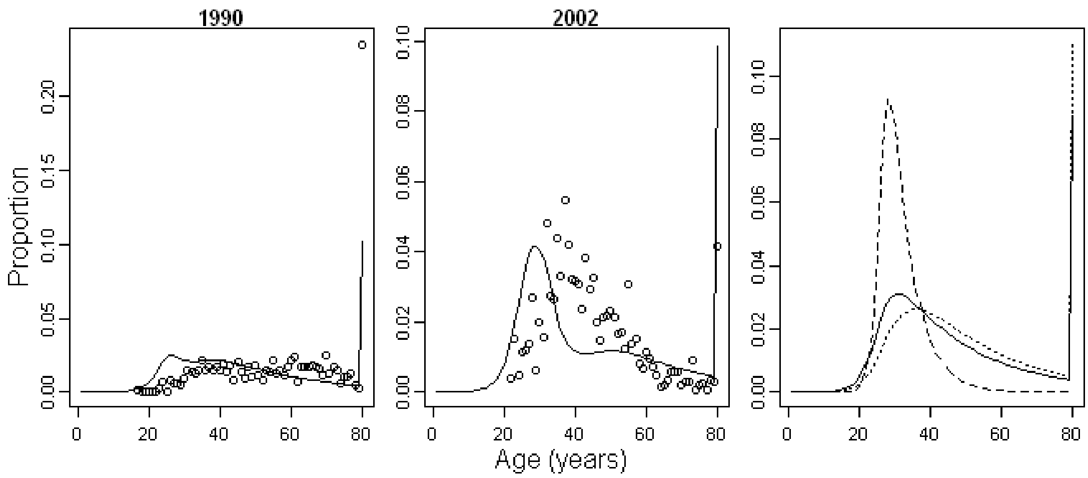


Figure A3.8: Model ABC base run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) in relation to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix IV

Table A4.1: Model AB base run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	124 563
B2011	44 234
B2011/B0	0.36
Flat B0	46 673
Flat B2011	25 809
Flat B2011/B0	0.55
Hill B0	73 441
Hill B2011	13 764
Hill B2011/B0	0.19
Spawn B0	124 121
Spawn B2011	44 237
Spawn B2011/B0	0.36

Likelihood components	
Total	3 252.95
Egg survey	-0.77
FlatCPUE_early	1.53
FlatCPUE_late	-9.58
HillCPUE_early	-11.24
HillCPUE_late	8.30
SpawnCPUE_early	13.73
SpawnCPUE_late	12.06
Acoustic_2001	-0.28
Acoustic_2003	-0.75
Trawl_flat	8.46
Trawl_hill	2.42
Trawl_LF_flat	293.56
Trawl_LF_hill	295.87
Fishery_LF_flat	1 242.12
Fishery_LF_hill	892.74
Fishery_LF_spawn	552.96
Acoustic q ratio	-1.02
Catch penalty hill	0
Catch penalty flat	2.68e-04
Catch penalty spawn	7.89e-30
Prior q_FlatCPUE_early	-9.92
Prior q_FlatCPUE_late	-10.22
Prior q_HillCPUE_early	-10.84
Prior q_HillCPUE_late	-10.19
Prior q_SpawnCPUE_early	-8.22
Prior q_SpawnCPUE_late	-9.08
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.40
Prior on B0	0
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	–

Vulnerability	
Flat A50	27.88
Flat Ato95	5.93
Hill A50	1*
Hill Ato95	1*
Spawn A50	25.73*
Spawn Ato95	7.11*
Survey Flat A50	47.73
Survey Flat Ato95	22.21
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	28.49
Migration Ato95	7.57
Migration cap	0.06

q’s	
FlatCPUE_early	4.86e-05
FlatCPUE_late	3.64e-05
HillCPUE_early	1.97e-05
HillCPUE_late	3.76e-05
SpawnCPUE_early	2.69e-04
SpawnCPUE_late	1.14e-04
Acoustic_2003	0.29
Acoustic_2001	0.62
Trawl_hill	0.03
Trawl_flat	5.00#

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

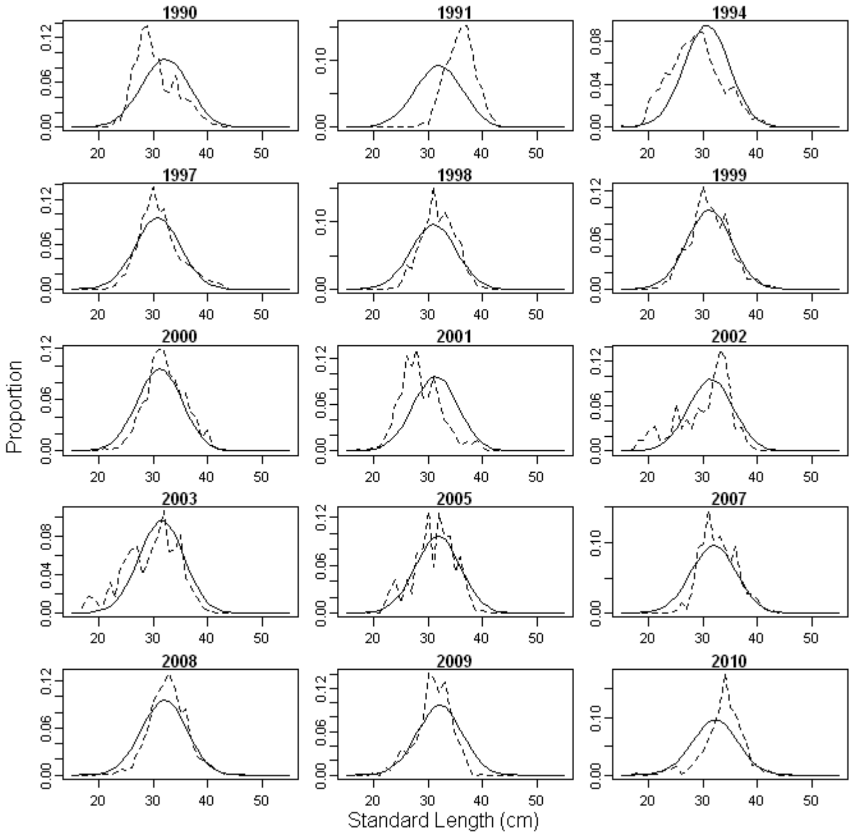


Figure A4.1: Model AB base run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

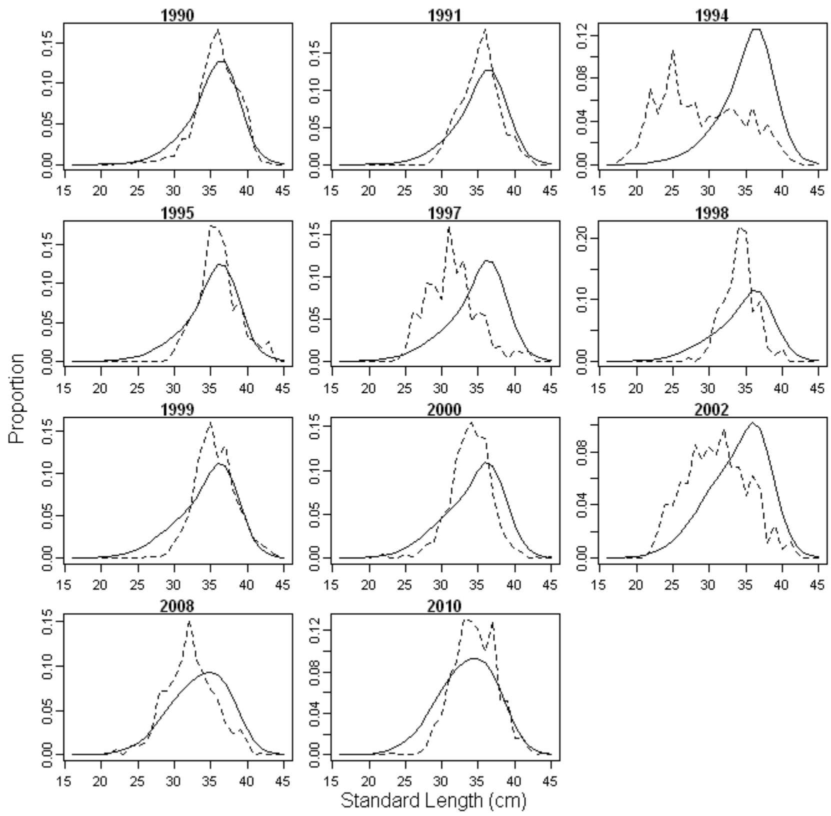


Figure A4.2: Model AB base run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

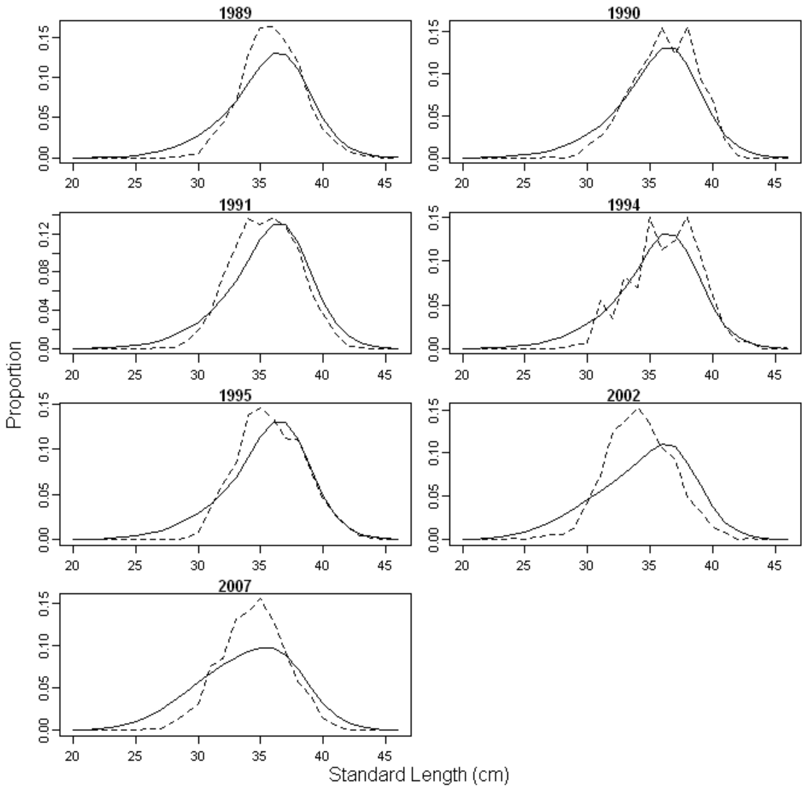


Figure A4.3: Model AB base run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

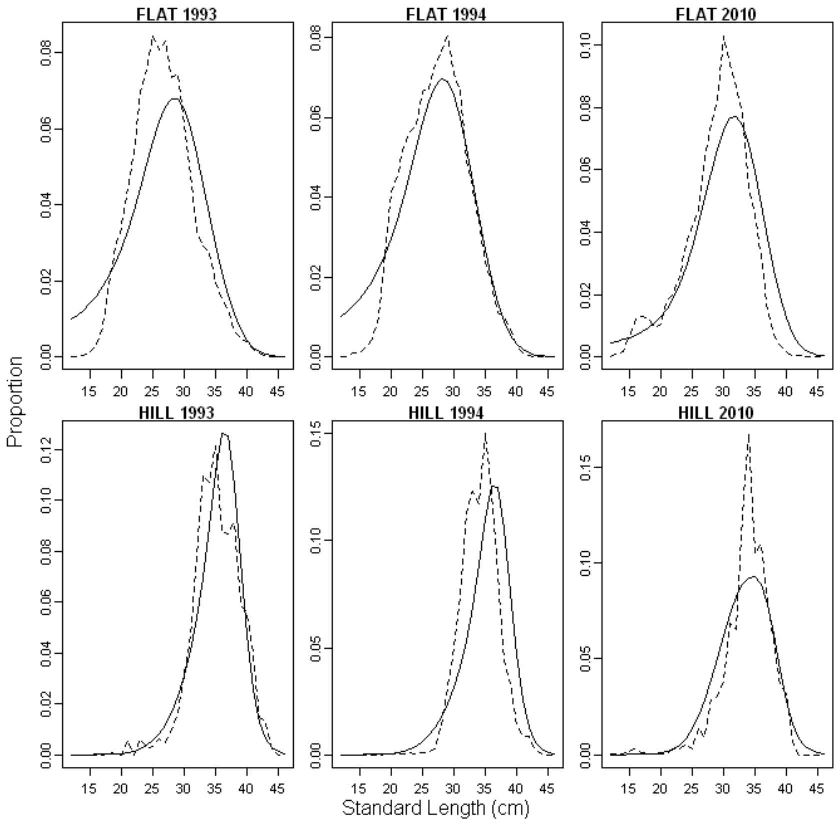


Figure A4.4: Model AB base run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

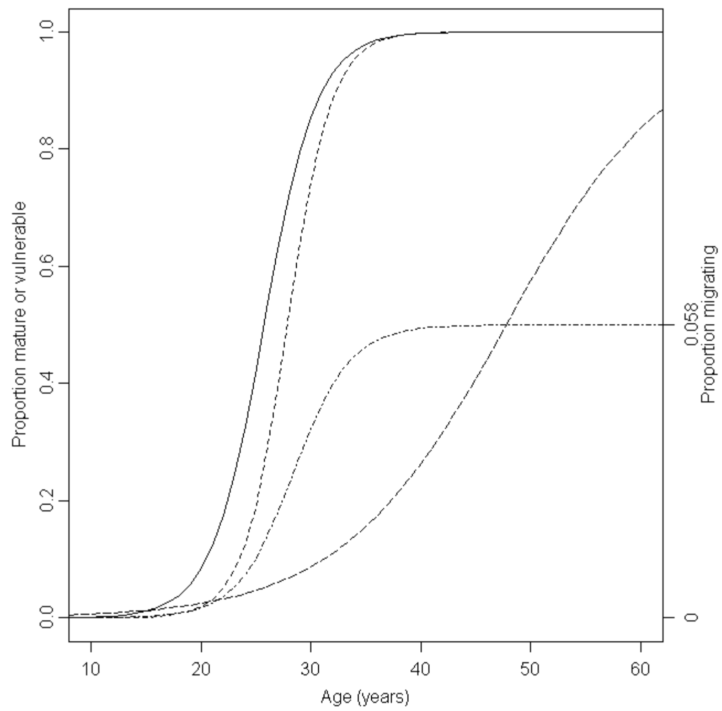


Figure A4.5: Model AB base run, ogives. Solid line, maturity ogive (fixed); short dash line, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated).

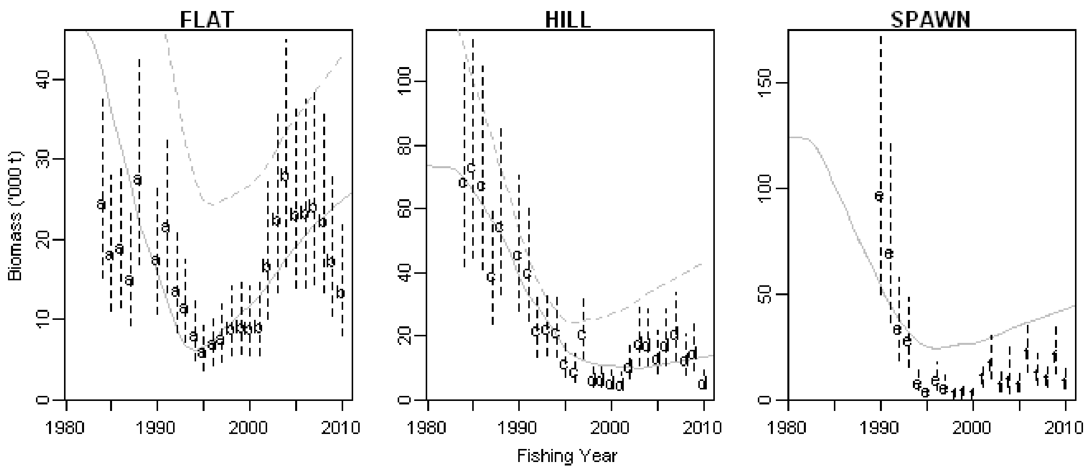


Figure A4.6: Model AB base run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

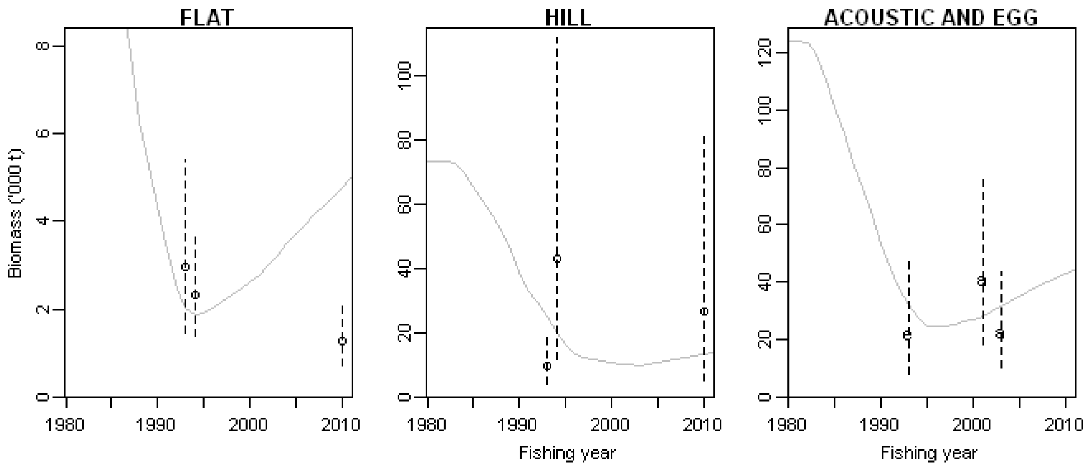


Figure A4.7: Model AB base run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

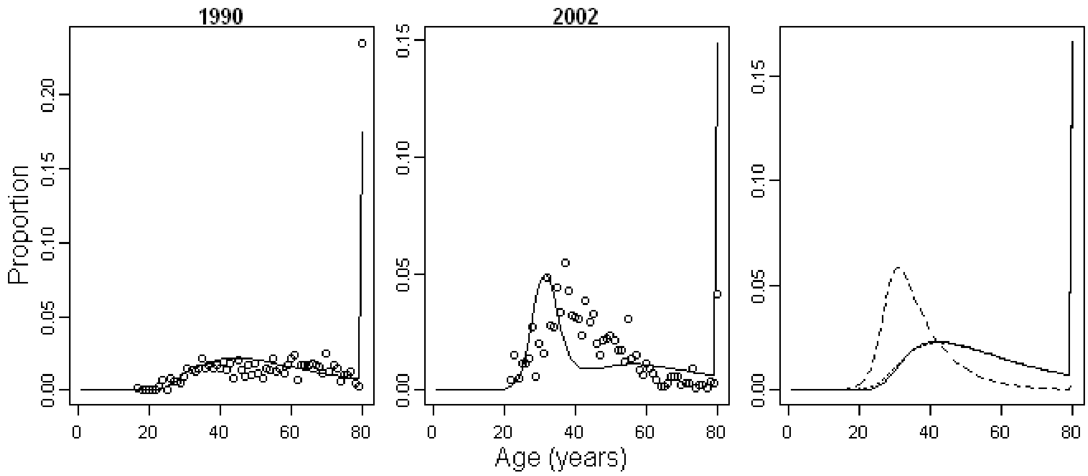


Figure A4.8: Model AB base run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) in relation to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix V

Table A5.1: Model ABC CAF maturity run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	198 892
B2011	119 759
B2011/B0	0.60
Flat B0	46 188
Flat B2011	36 069
Flat B2011/B0	0.78
Hill B0	203 894
Hill B2011	130 034
Hill B2011/B0	0.64
Spawn B0	241 533
Spawn B2011	159 118
Spawn B2011/B0	0.66

Likelihood components	
Total	3555.67
Egg survey	7.25
FlatCPUE_early	-2.31
FlatCPUE_late	-8.50
HillCPUE_early	11.78
HillCPUE_late	7.10
SpawnCPUE_early	34.43
SpawnCPUE_late	10.96
Acoustic_2001	-0.93
Acoustic_2003	-0.41
Trawl_flat	1.02
Trawl_hill	1.16
Trawl_LF_flat	223.96
Trawl_LF_hill	284.99
Fishery_LF_flat	1268.13
Fishery_LF_hill	899.45
Fishery_LF_spawn	874.51
Acoustic q ratio	-1.95
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.28
Prior q_FlatCPUE_late	-10.76
Prior q_HillCPUE_early	-12.44
Prior q_HillCPUE_late	-12.60
Prior q_SpawnCPUE_early	-10.26
Prior q_SpawnCPUE_late	-11.79
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	0.96
Prior on B0	12.20
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0

Vulnerability	
Flat A50	26.35
Flat Ato95	3.83
Hill A50	1*
Hill Ato95	1*
Spawn A50	31.5*
Spawn Ato95	7.11*
Survey Flat A50	17.78
Survey Flat Ato95	6.94
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	25.64
Migration Ato95	7.58
Migration cap	0.12

q's	
FlatCPUE_early	3.44e-05
FlatCPUE_late	2.12e-05
HillCPUE_early	3.97e-06
HillCPUE_late	3.37e-06
SpawnCPUE_early	3.49e-05
SpawnCPUE_late	7.57e-06
Acoustic_2003	0.09
Acoustic_2001	0.22
Trawl_hill	0.01
Trawl_flat	0.14

Biological parameters	
Maturity A50	31.5*
Maturity Ato95	7.11*
M	0.045*

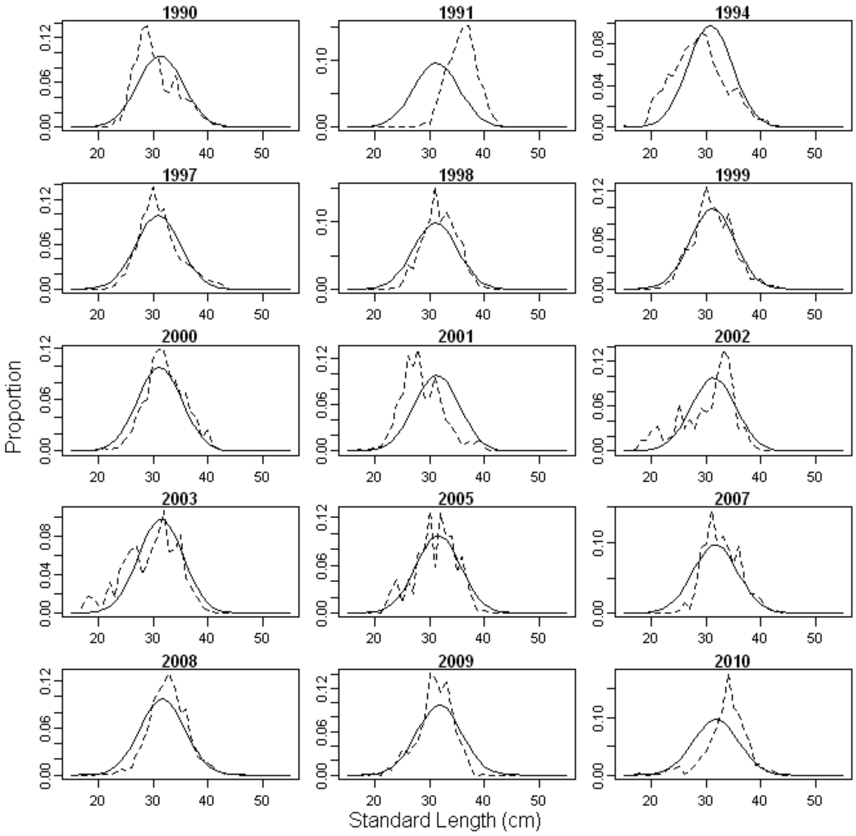


Figure A5.1: Model ABC CAF maturity run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

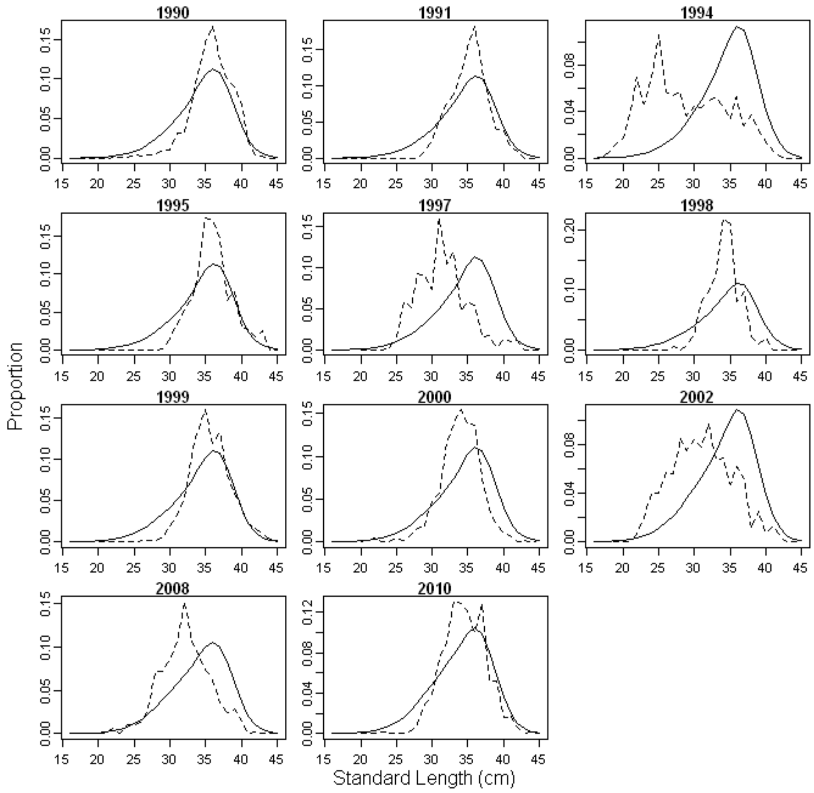


Figure A5.2: Model ABC CAF maturity run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

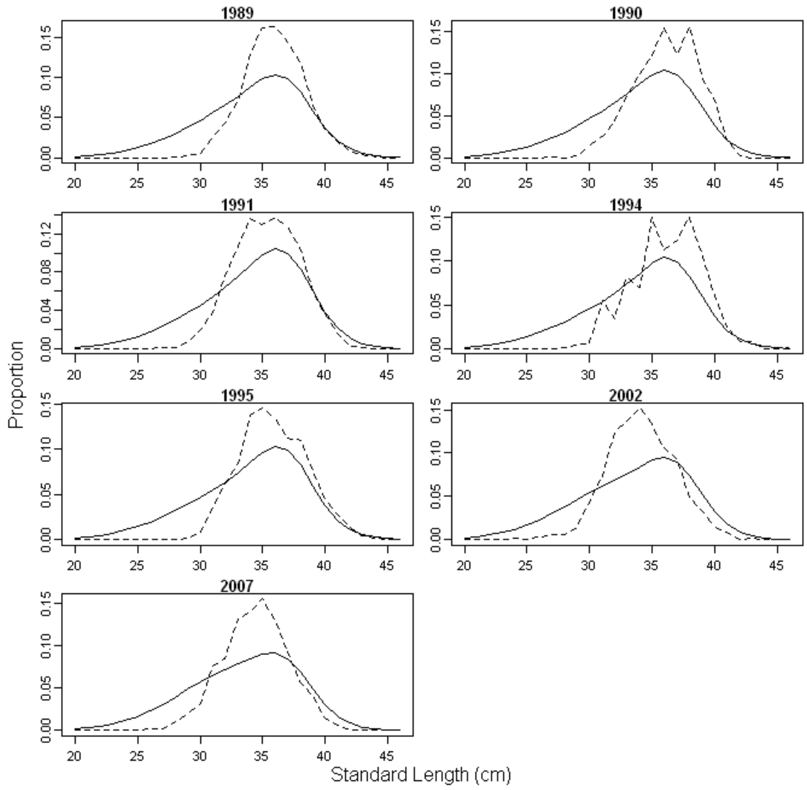


Figure A5.3: Model ABC CAF maturity run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

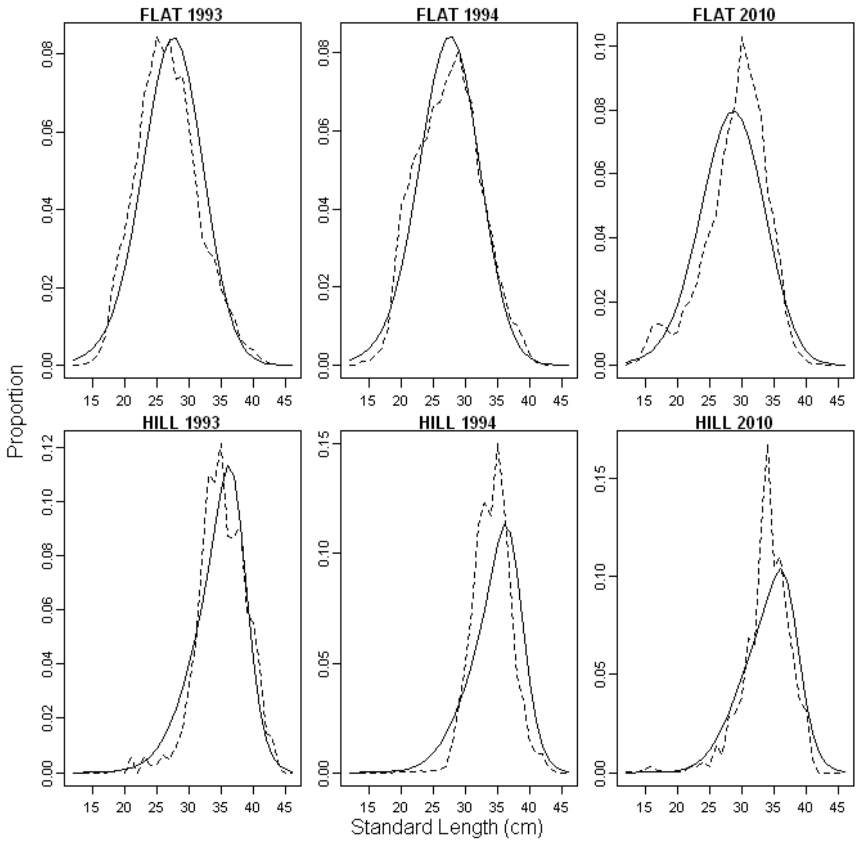


Figure A5.4: Model ABC CAF maturity run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

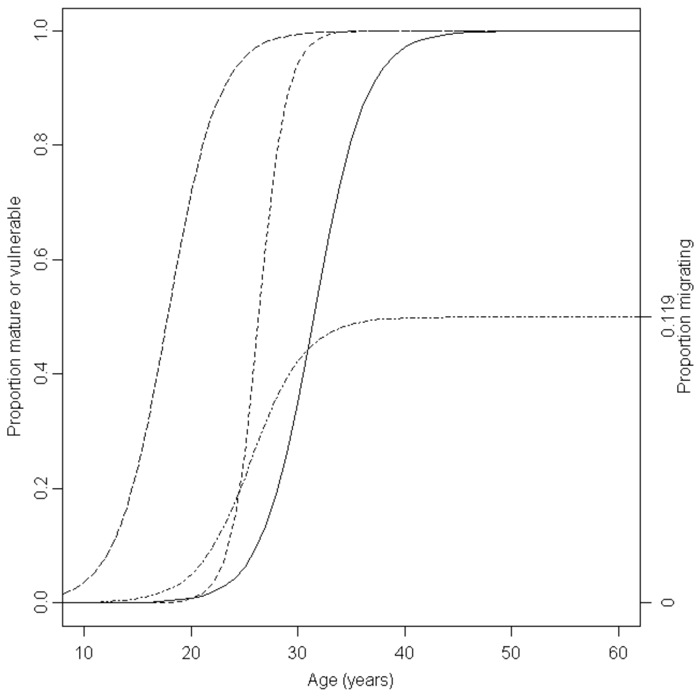


Figure A5.5: Model ABC CAF maturity run, ogives. Solid line, maturity ogive (fixed); short dash line, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated).

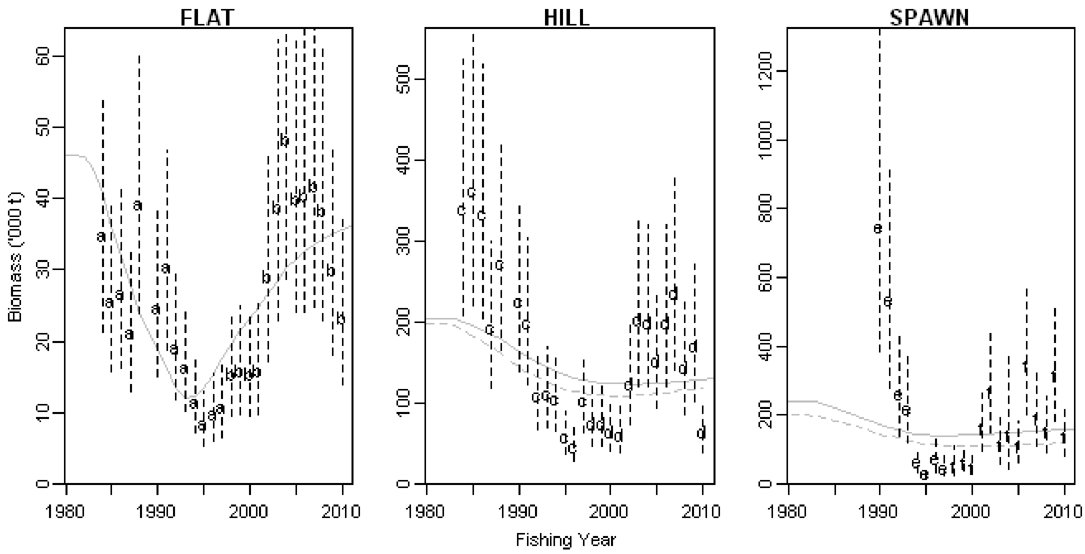


Figure 5.6: Model ABC CAF maturity run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

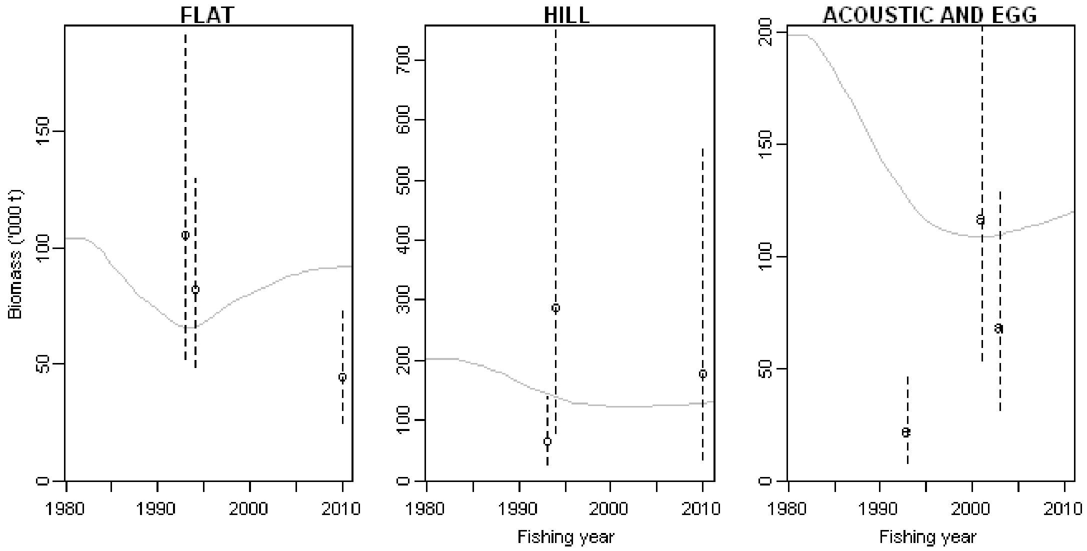


Figure A5.7: Model ABC CAF maturity run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

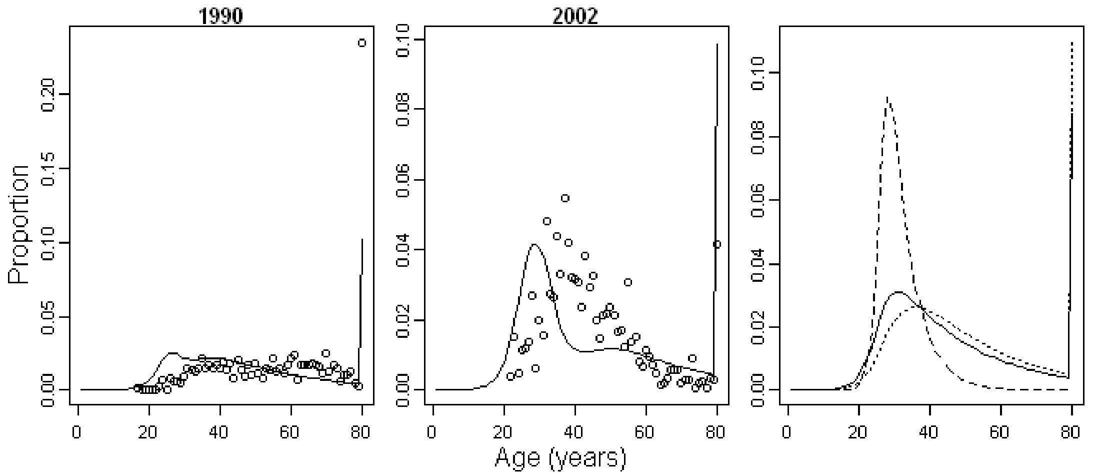


Figure A5.8: Model ABC CAF maturity run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) in relation to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix VI

Table A6.1: Model ABC estimating spawn vulnerability run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	123 954
B2011	44 381
B2011/B0	0.36
Flat B0	64 410
Flat B2011	32 545
Flat B2011/B0	0.51
Hill B0	58 034
Hill B2011	10 341
Hill B2011/B0	0.18
Spawn B0	70 246
Spawn B2011	4 926
Spawn B2011/B0	0.07

Likelihood components	
Total	3 051.77
Egg survey	-0.07
FlatCPUE_early	-7.55
FlatCPUE_late	-7.96
HillCPUE_early	-9.58
HillCPUE_late	5.16
SpawnCPUE_early	3.10
SpawnCPUE_late	13.49
Acoustic_2001	-0.28
Acoustic_2003	-0.74
Trawl_flat	0.34
Trawl_hill	2.47
Trawl_LF_flat	216.69
Trawl_LF_hill	283.57
Fishery_LF_flat	1 261.64
Fishery_LF_hill	882.32
Fishery_LF_spawn	455.48
Acoustic q ratio	-1.02
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.54
Prior q_FlatCPUE_late	-10.59
Prior q_HillCPUE_early	-10.45
Prior q_HillCPUE_late	-9.72
Prior q_SpawnCPUE_early	-7.52
Prior q_SpawnCPUE_late	-7.80
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.40
Prior on B0	11.73
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0

Vulnerability	
Flat A50	26.83
Flat Ato95	6.41
Hill A50	1*
Hill Ato95	1*
Spawn A50	41.00
Spawn Ato95	5.42
Survey Flat A50	14.32
Survey Flat Ato95	3.88
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	25.45
Migration Ato95	1.25
Migration cap	0.03

q's	
FlatCPUE_early	2.64e-05
FlatCPUE_late	2.52e-05
HillCPUE_early	2.89e-05
HillCPUE_late	6.00e-05
SpawnCPUE_early	5.44e-04
SpawnCPUE_late	4.11e-04
Acoustic_2003	0.29
Acoustic_2001	0.62
Trawl_hill	0.04
Trawl_flat	0.17

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

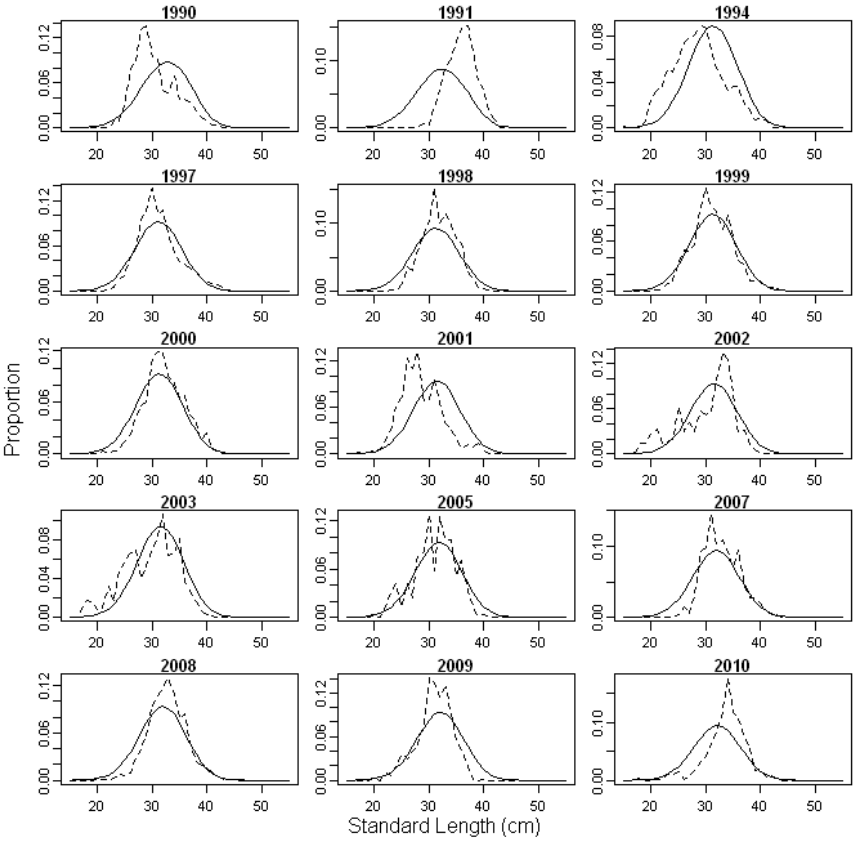


Figure A6.1: Model ABC estimating spawn vulnerability run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

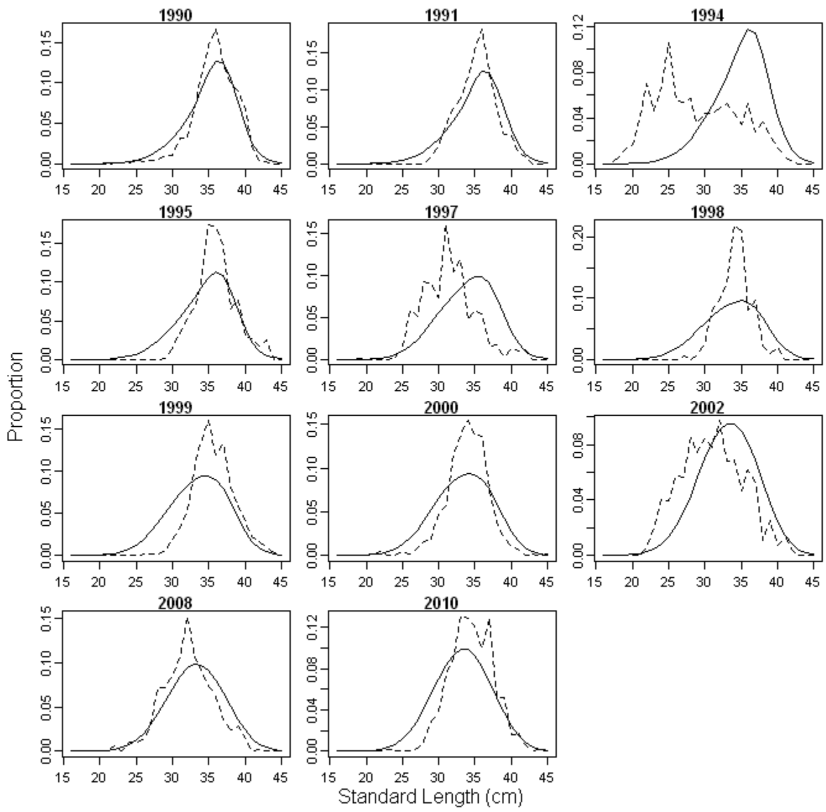


Figure A6.2: Model ABC estimating spawn vulnerability maturity run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

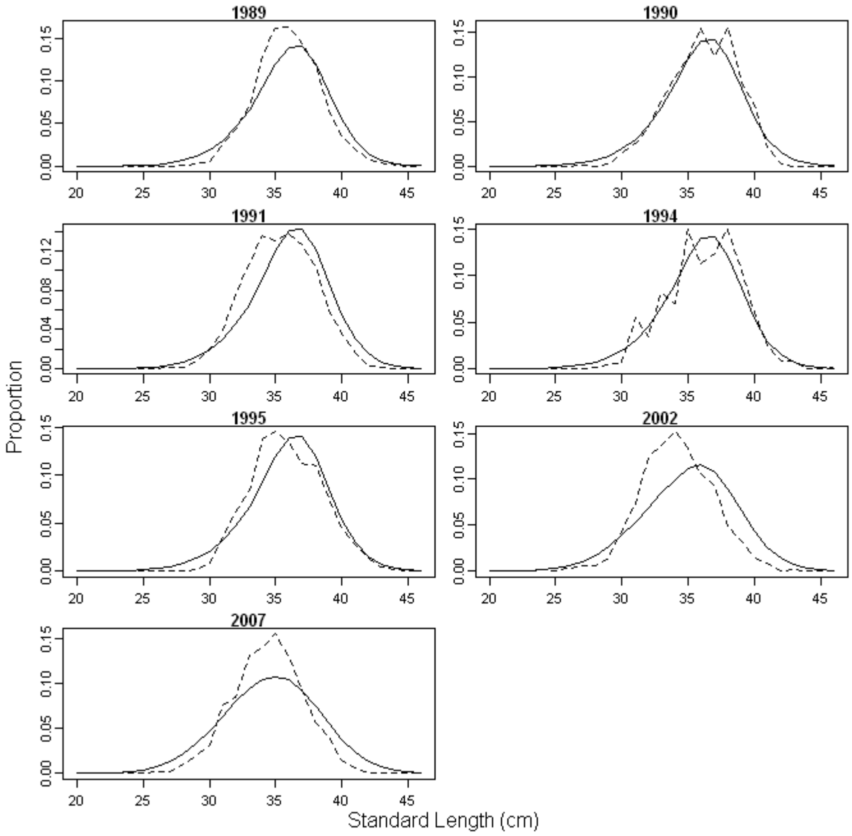


Figure A6.3: Model ABC estimating spawn vulnerability run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

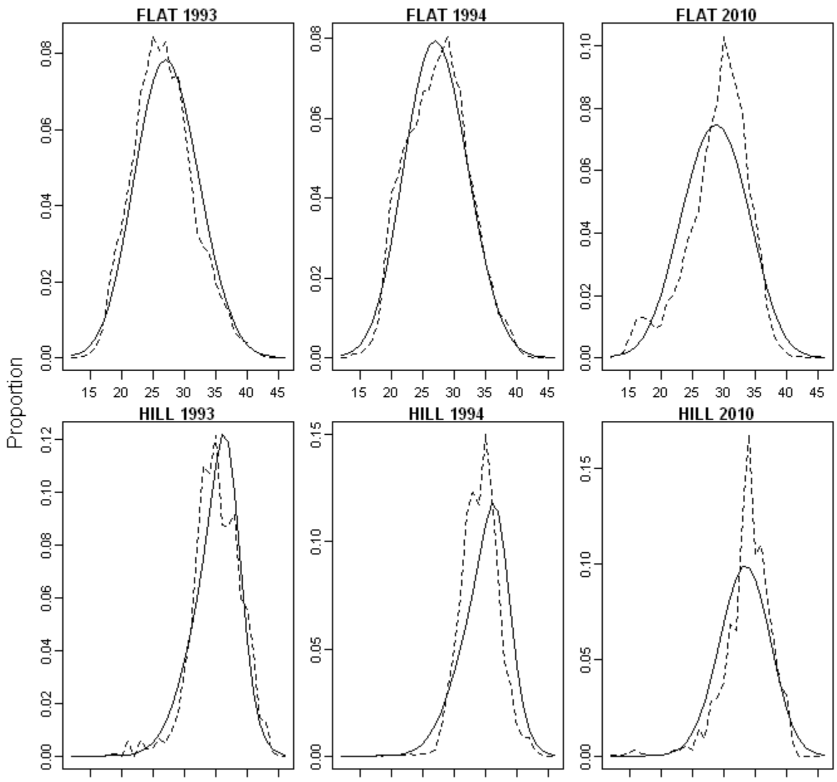


Figure A6.4: Model ABC estimating spawn vulnerability run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

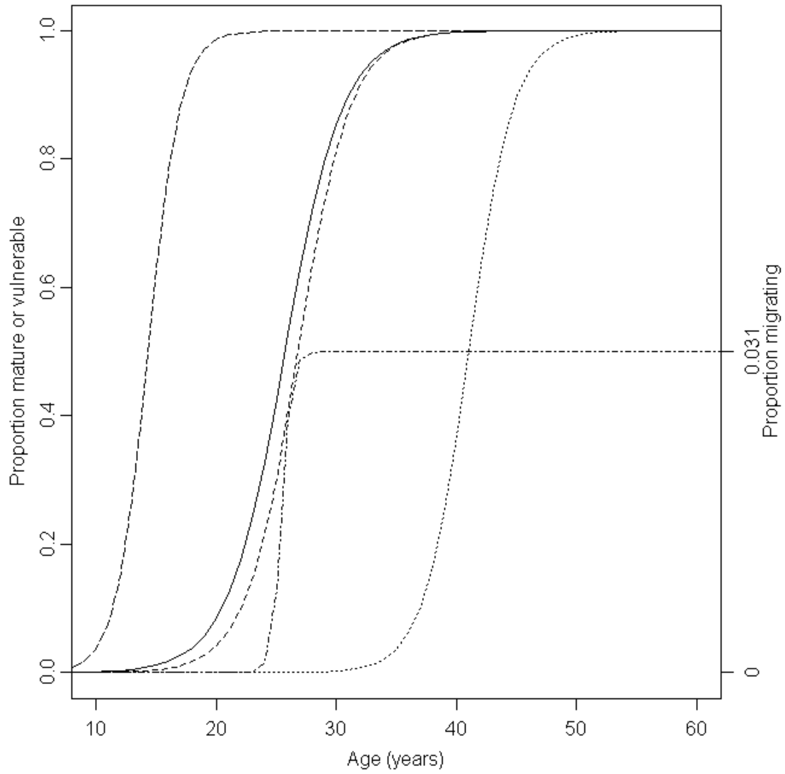


Figure A6.5: Model ABC estimating spawn vulnerability run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

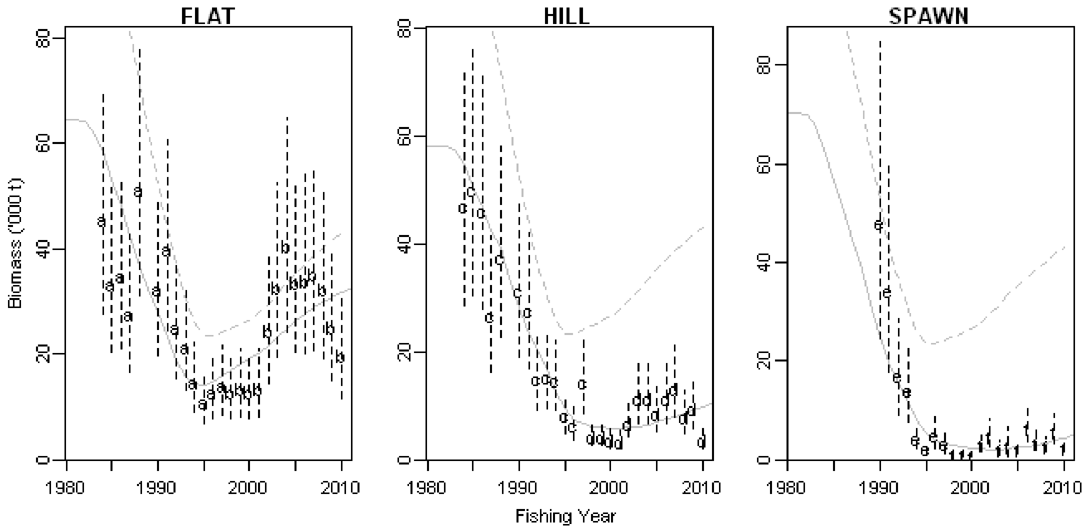
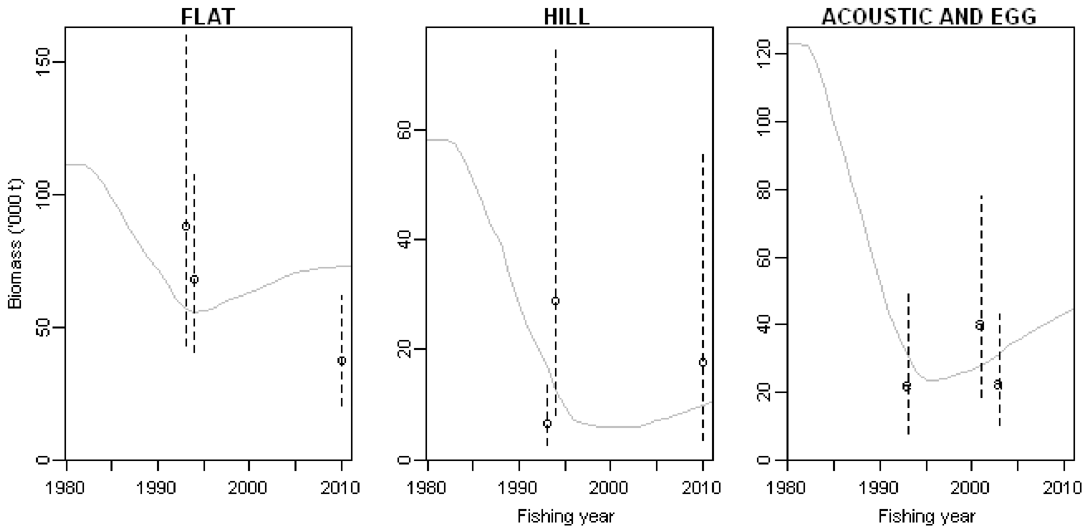


Figure A6.6: Model ABC estimating spawn vulnerability run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.



A6.7: Model ABC estimating spawn vulnerability run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

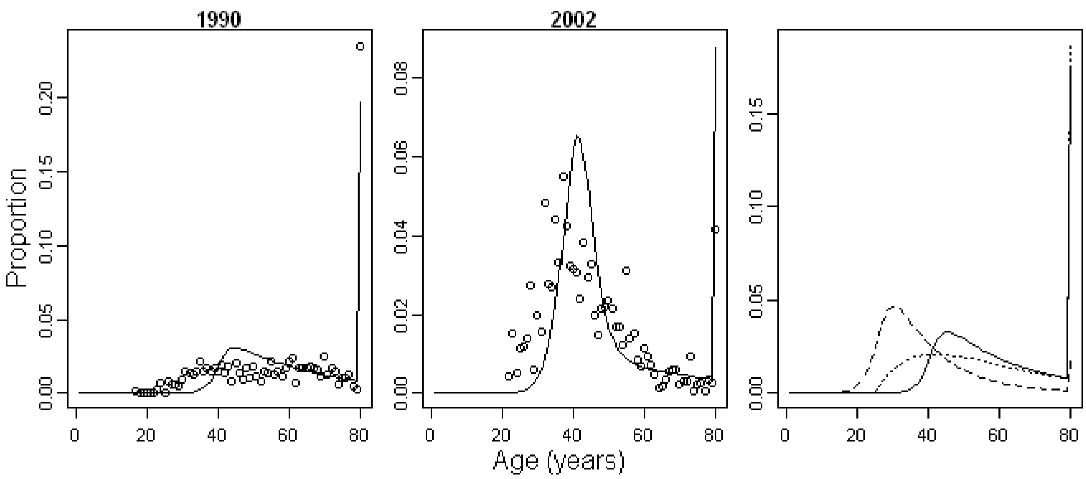


Figure A6.7: Model ABC estimating spawn vulnerability run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) in relation to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix VII

Table A7.1: Model AB estimating spawn vulnerability run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	121 160
B2011	41 759
B2011/B0	0.34
Flat B0	46 784
Flat B2011	22 564
Flat B2011/B0	0.48
Hill B0	68 638
Hill B2011	13 679
Hill B2011/B0	0.20
Spawn B0	86 466
Spawn B2011	12 468
Spawn B2011/B0	0.14

Likelihood components	
Total	3165.88
Egg survey	-0.55
FlatCPUE_early	4.47
FlatCPUE_late	-9.36
HillCPUE_early	-11.29
HillCPUE_late	5.88
SpawnCPUE_early	9.66
SpawnCPUE_late	16.04
Acoustic_2001	-0.22
Acoustic_2003	-0.76
Trawl_flat	7.74
Trawl_hill	2.26
Trawl_LF_flat	293.00
Trawl_LF_hill	288.60
Fishery_LF_flat	1243.35
Fishery_LF_hill	881.29
Fishery_LF_spawn	482.35
Acoustic q ratio	-0.97
Catch penalty hill	0
Catch penalty flat	0.10
Catch penalty spawn	0
Prior q_FlatCPUE_early	-9.87
Prior q_FlatCPUE_late	-10.07
Prior q_HillCPUE_early	-10.72
Prior q_HillCPUE_late	-10.13
Prior q_SpawnCPUE_early	-7.86
Prior q_SpawnCPUE_late	-8.40
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.38
Prior on B0	11.70
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0

Vulnerability	
Flat A50	28.33
Flat Ato95	6.22
Hill A50	1*
Hill Ato95	1*
Spawn A50	35.02
Spawn Ato95	1.05
Survey Flat A50	47.37
Survey Flat Ato95	22.27
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	24.68
Migration Ato95	1.00#
Migration cap	0.04

q's	
FlatCPUE_early	5.16e-05
FlatCPUE_late	4.22e-05
HillCPUE_early	2.20e-05
HillCPUE_late	4.00e-05
SpawnCPUE_early	3.86e-04
SpawnCPUE_late	2.29e-04
Acoustic_2003	0.31
Acoustic_2001	0.66
Trawl_hill	0.03
Trawl_flat	5.00#

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

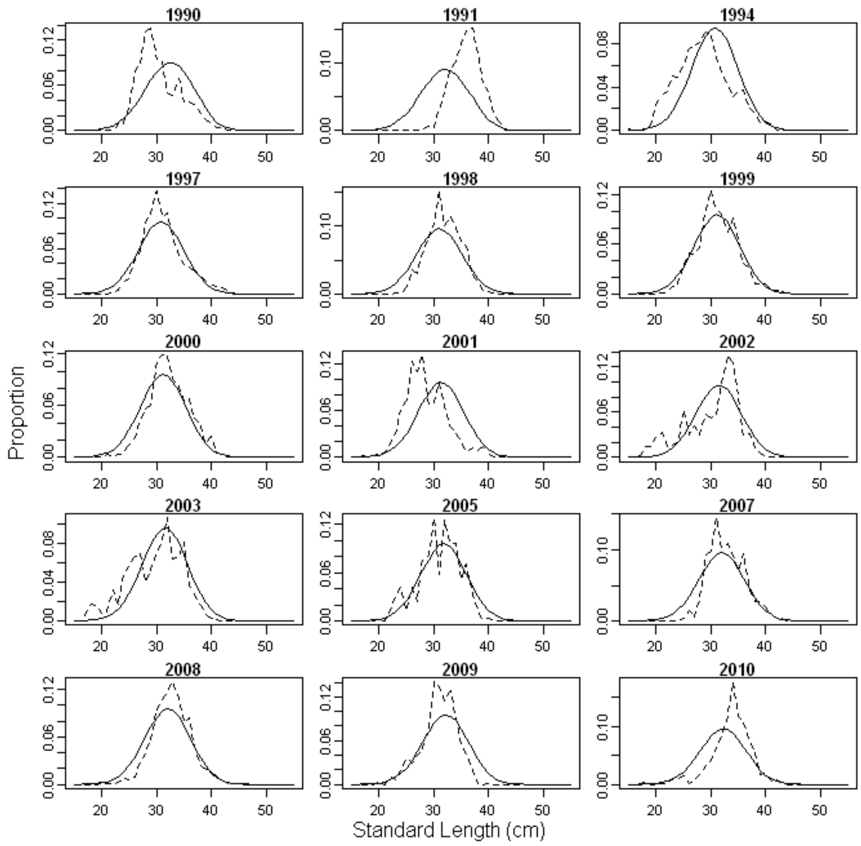


Figure A7.1: Model AB estimating spawn vulnerability run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

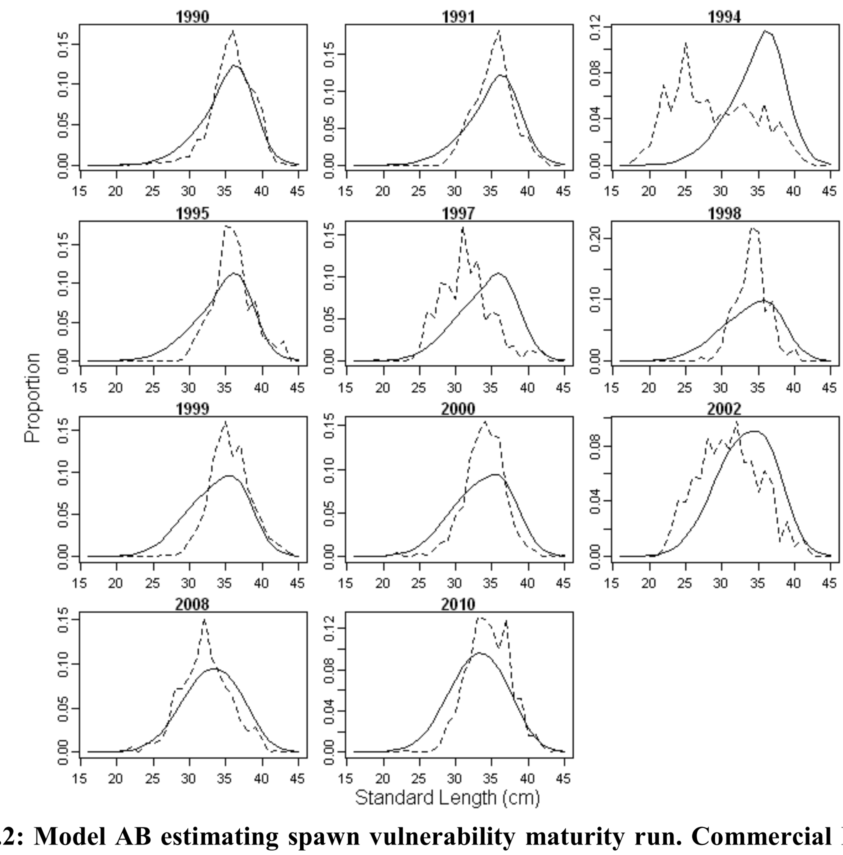


Figure A7.2: Model AB estimating spawn vulnerability maturity run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

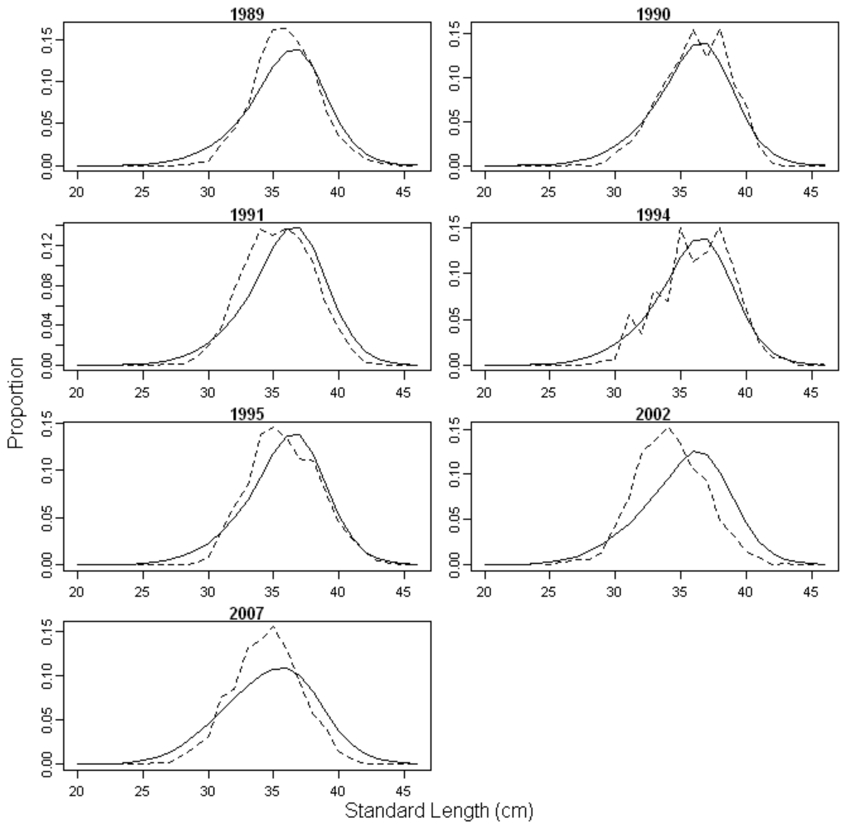


Figure A7.3: Model AB estimating spawn vulnerability run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

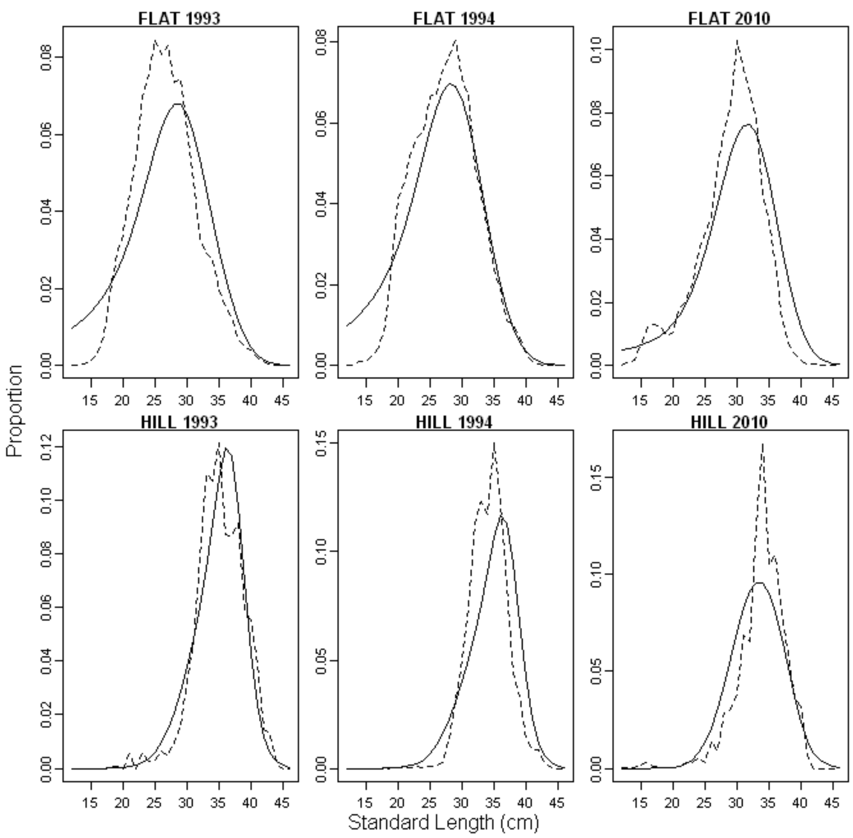


Figure A7.4: Model AB estimating spawn vulnerability run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

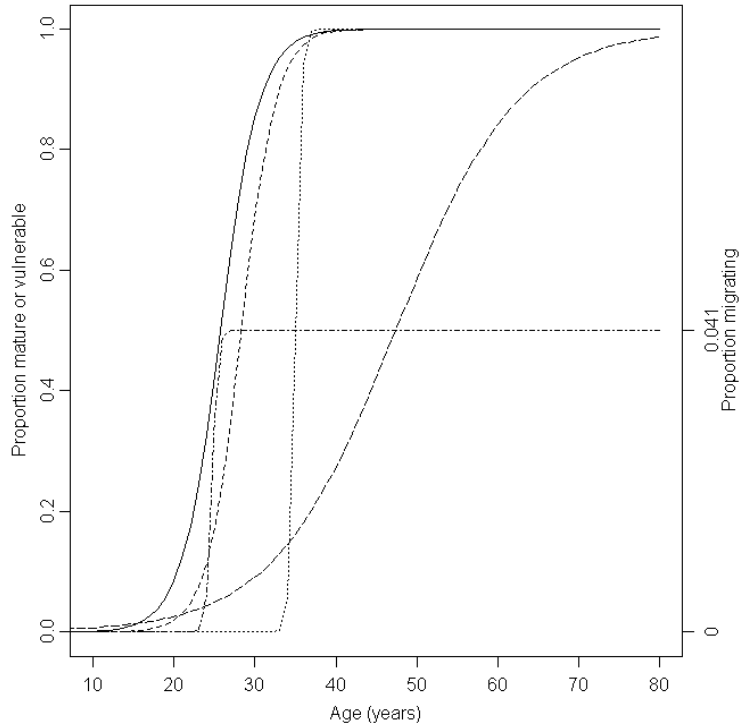


Figure A7.5: Model AB estimating spawn vulnerability run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

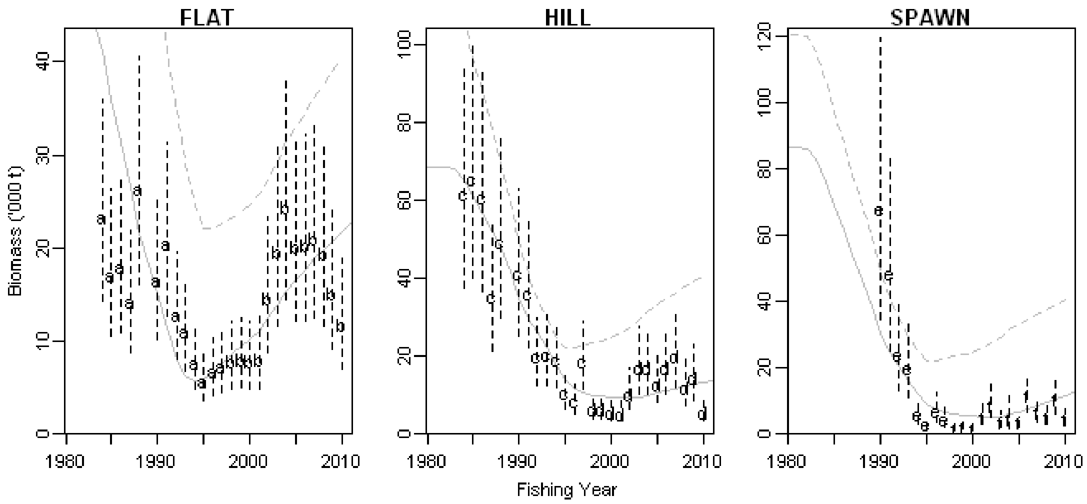


Figure A7.6: Model AB estimating spawn vulnerability run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

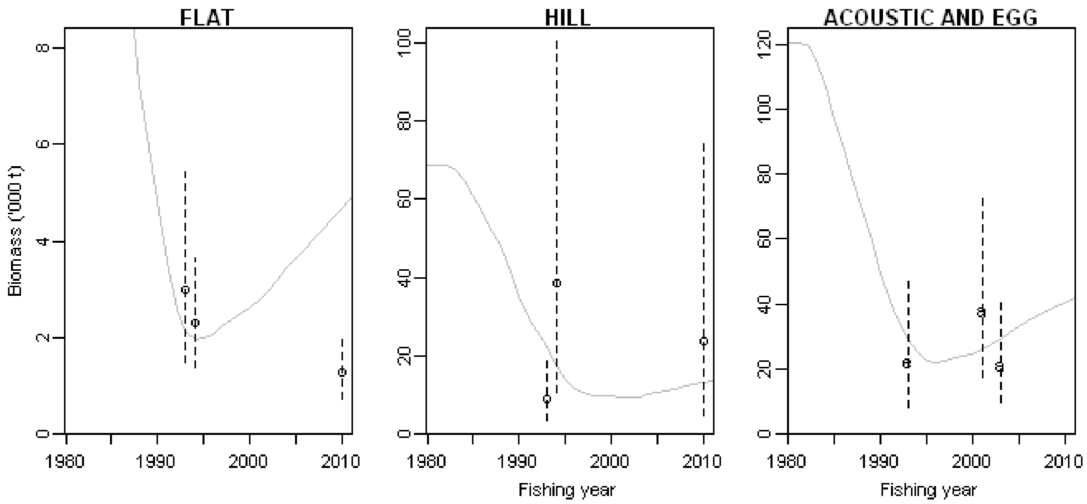


Figure A7.7: Model AB estimating spawn vulnerability run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

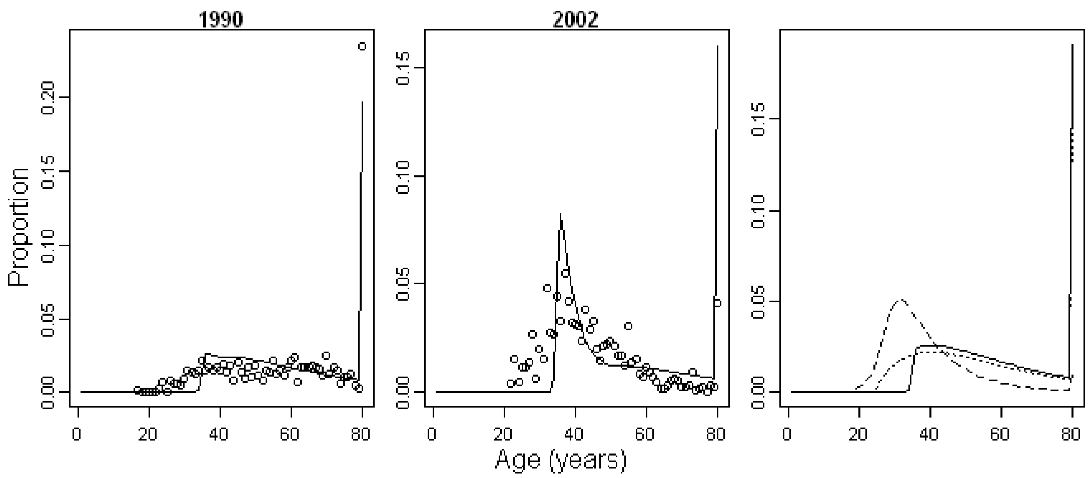


Figure A7.8: Model AB estimating spawn vulnerability run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) in relation to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix VIII

Table A8.1: Model ABC estimating spawn vulnerability including the age frequency data model run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	121 147
B2011	41 537
B2011/B0	0.34
Flat B0	49 027
Flat B2011	22 281
Flat B2011/B0	0.45
Hill B0	65 958
Hill B2011	13 443
Hill B2011/B0	0.20
Spawn B0	77 109
Spawn B2011	8 295
Spawn B2011/B0	0.11

Likelihood components	
Total	2715.68
Egg survey	-0.47
FlatCPUE_early	5.55
FlatCPUE_late	-9.39
HillCPUE_early	-11.22
HillCPUE_late	6.03
SpawnCPUE_early	7.78
SpawnCPUE_late	11.33
Acoustic_2001	-0.21
Acoustic_2003	-0.76
Trawl_flat	7.31
Trawl_hill	2.29
Trawl_LF_flat	292.05
Trawl_LF_hill	286.00
Fishery_LF_flat	1245.21
Fishery_LF_hill	879.55
Fishery_LF_spawn	226.88
Acoustic q ratio	-0.96
Catch penalty hill	0
Catch penalty flat	0.05
Catch penalty spawn	0
Prior q_FlatCPUE_early	-9.91
Prior q_FlatCPUE_late	-10.08
Prior q_HillCPUE_early	-10.69
Prior q_HillCPUE_late	-10.08
Prior q_SpawnCPUE_early	-7.79
Prior q_SpawnCPUE_late	-8.44
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.37
Prior on B0	11.70
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0

Vulnerability	
Flat A50	28.42
Flat Ato95	6.41
Hill A50	1*
Hill Ato95	1*
Spawn A50	38.16
Spawn Ato95	6.40
Survey Flat A50	47.62
Survey Flat Ato95	22.27
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	24.69
Migration Ato95	1.00#
Migration cap	6.40

q's	
FlatCPUE_early	4.97e-05
FlatCPUE_late	4.21e-05
HillCPUE_early	2.28e-05
HillCPUE_late	4.20e-05
SpawnCPUE_early	4.13e-04
SpawnCPUE_late	2.15e-04
Acoustic_2003	0.31
Acoustic_2001	0.67
Trawl_hill	0.03
Trawl_flat	4.99#

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

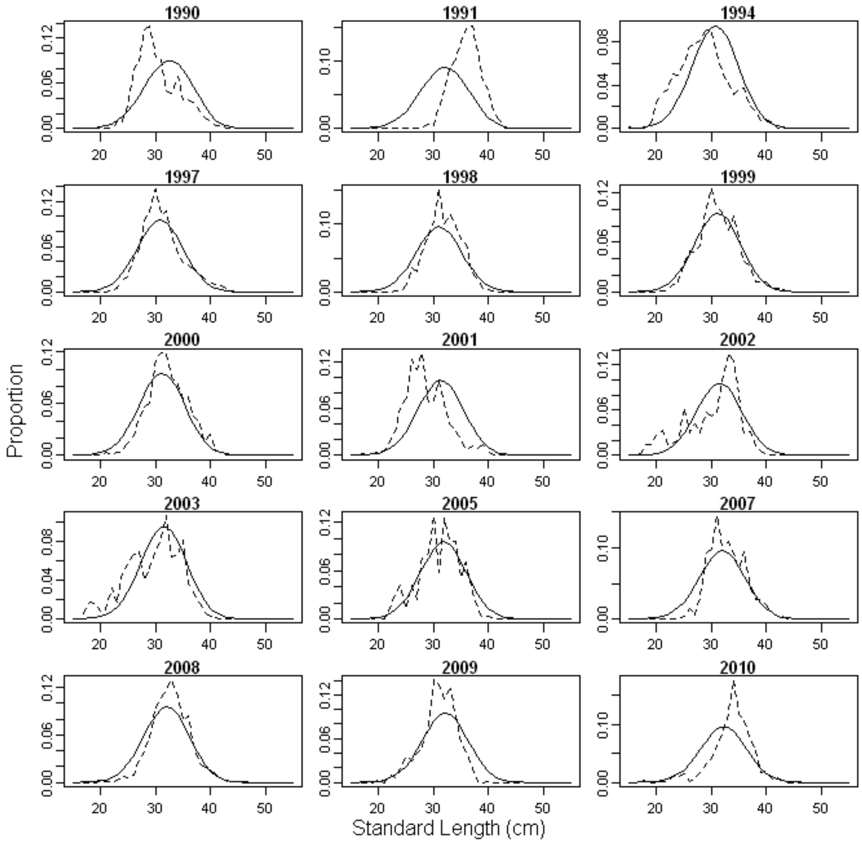


Figure A8.1: Model ABC estimating spawn vulnerability including the age frequency data model run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

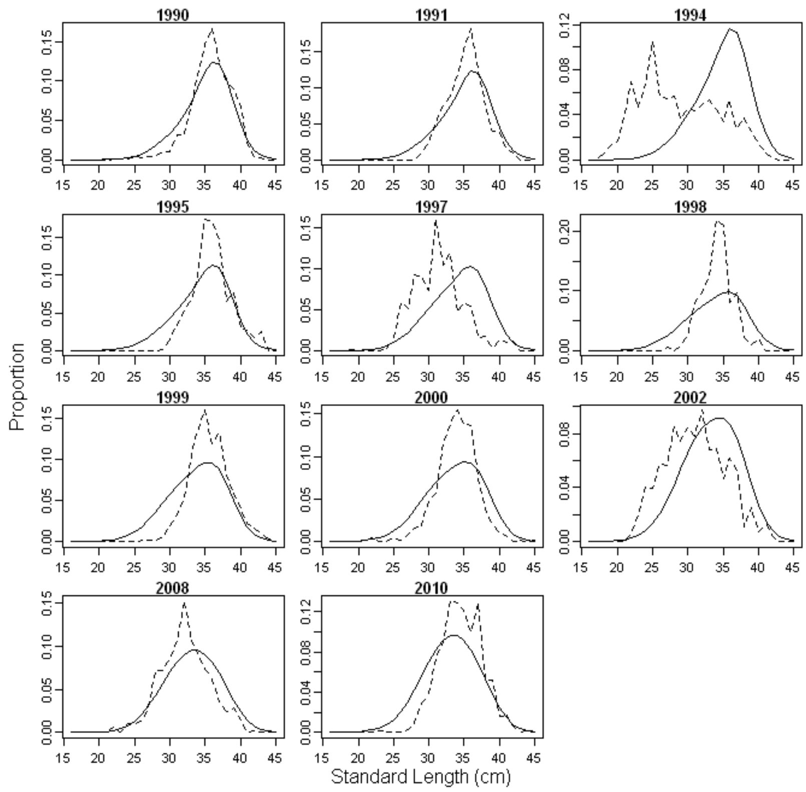


Figure A8.2: Model ABC estimating spawn vulnerability including the age frequency data model run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

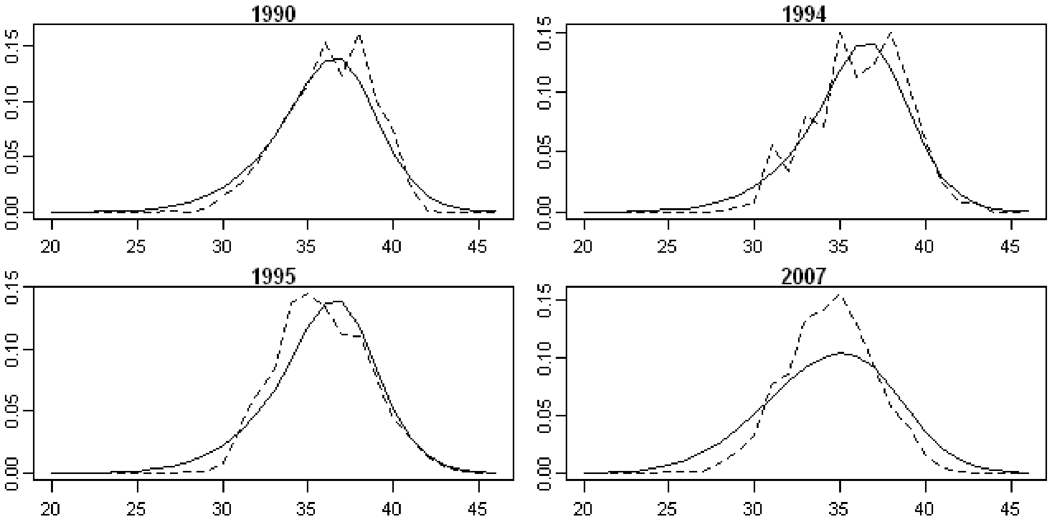


Figure A8.3: Model ABC estimating spawn vulnerability including the age frequency data model run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

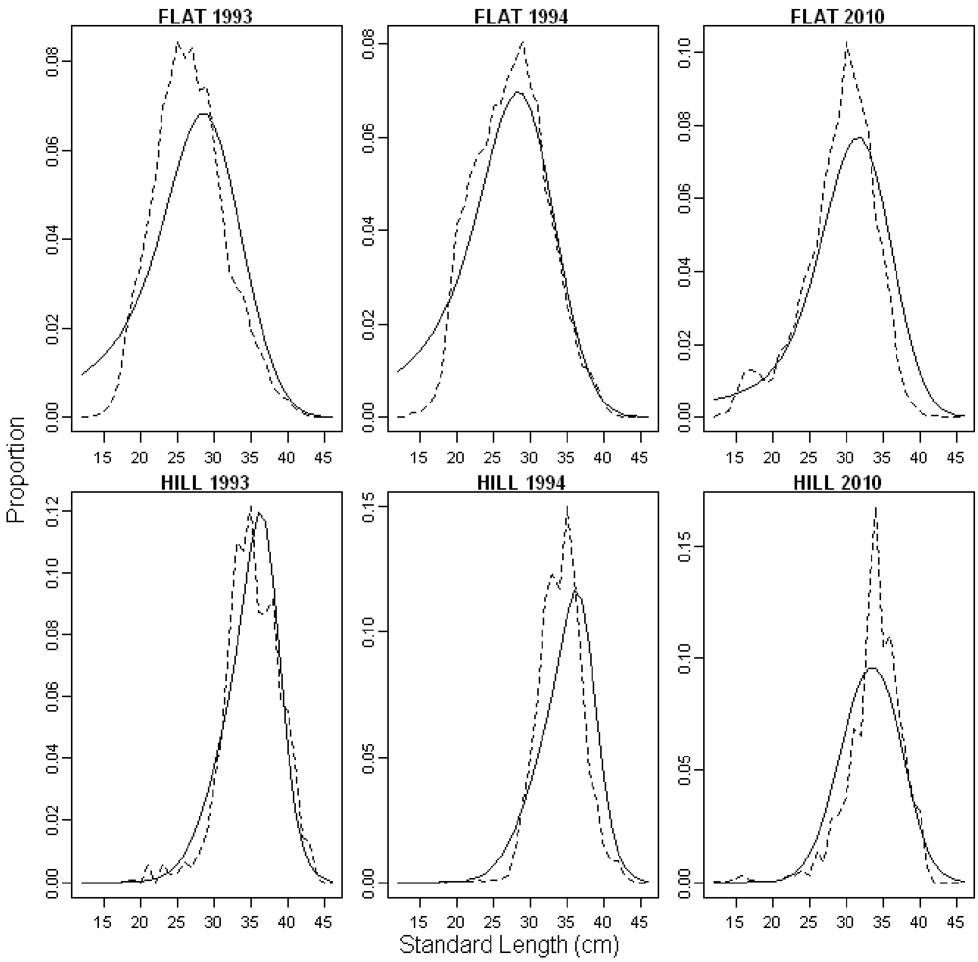


Figure A8.4: Model ABC estimating spawn vulnerability including the age frequency data model run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

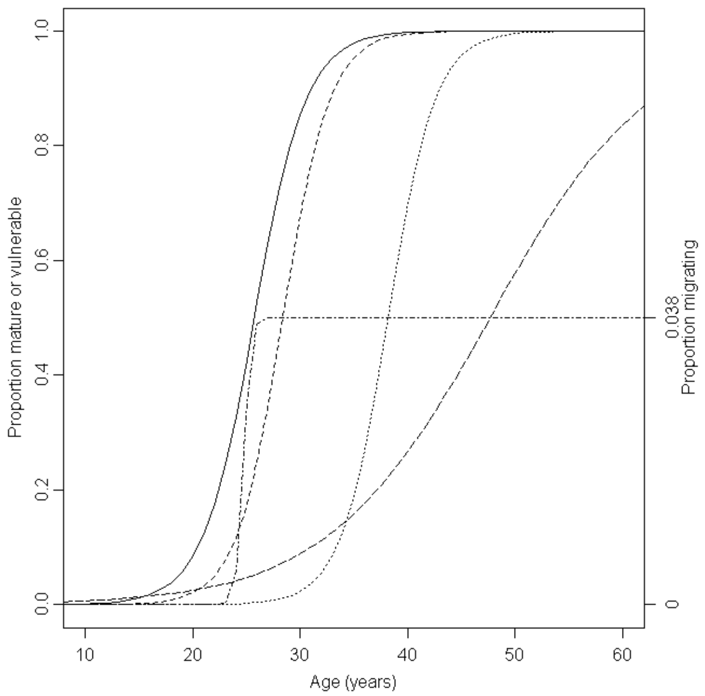


Figure A8.5: Model ABC estimating spawn vulnerability including the age frequency data model run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

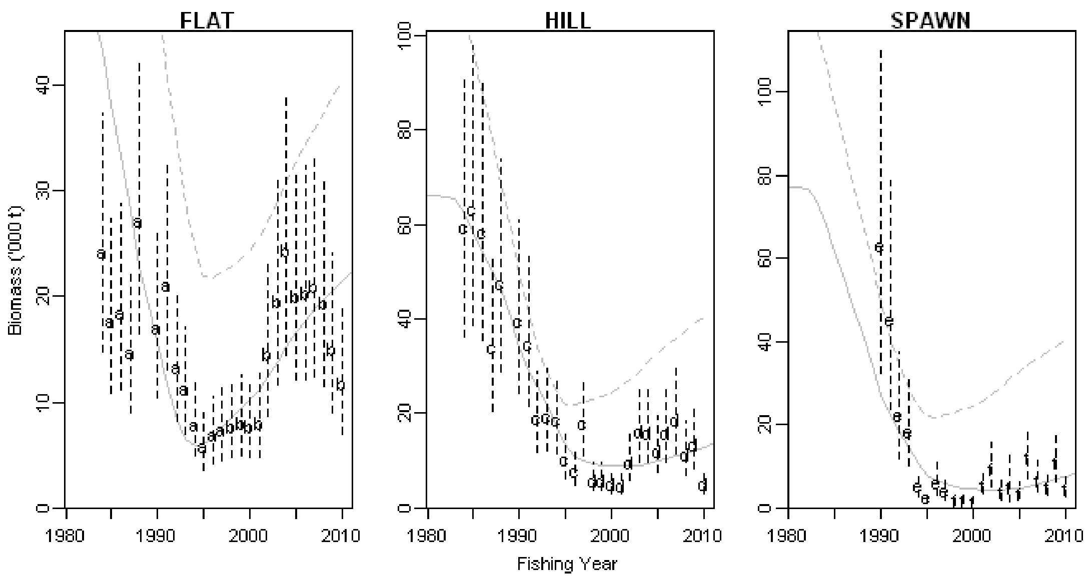


Figure A8.6: Model ABC estimating spawn vulnerability including the age frequency data model run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

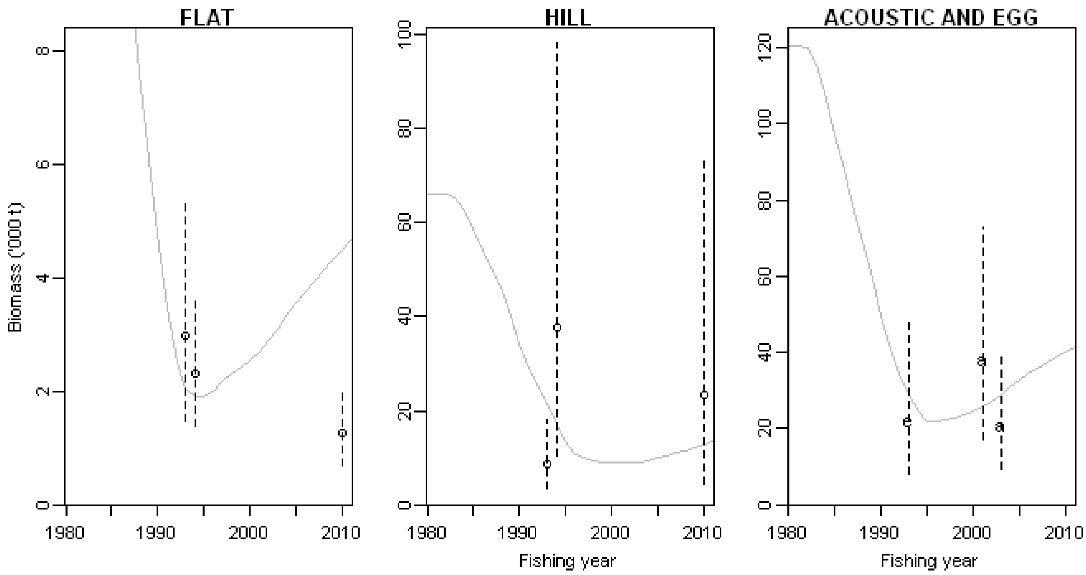


Figure A8.7: Model ABC estimating spawn vulnerability including the age frequency data model run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

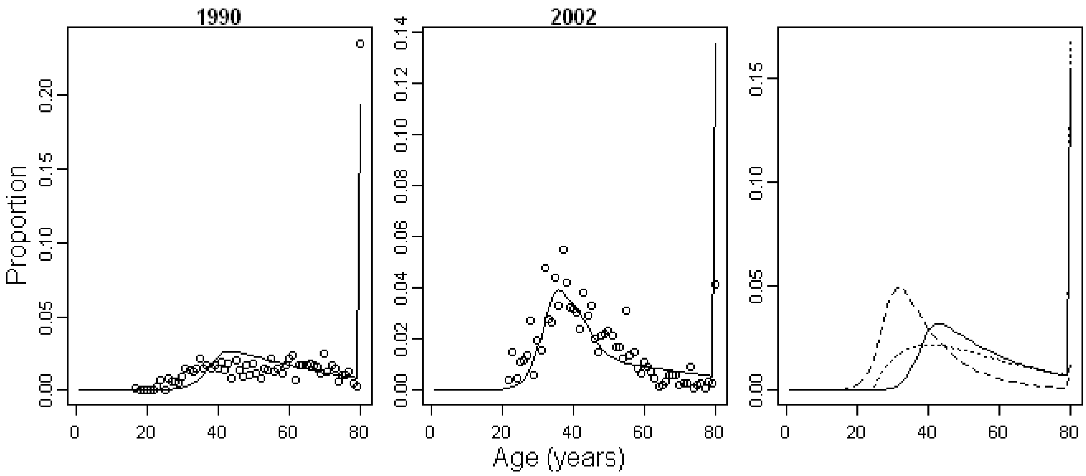


Figure A8.8: Model ABC estimating spawn vulnerability including the age frequency data model run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) fit to observations (points). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix IX

Table A9.1: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	122 170
B2011	43 555
B2011/B0	0.36
Flat B0	61 472
Flat B2011	31 331
Flat B2011/B0	0.51
Hill B0	59 312
Hill B2011	10 759
Hill B2011/B0	0.18
Spawn B0	54 833
Spawn B2011	2 256
Spawn B2011/B0	0.04

Likelihood components	
Total	2626.49
Egg survey	0.78
FlatCPUE_early	-7.03
FlatCPUE_late	-8.14
HillCPUE_early	-9.31
HillCPUE_late	4.76
SpawnCPUE_early	2.04
SpawnCPUE_late	21.87
Acoustic_2001	-0.24
Acoustic_2003	-0.75
Trawl_flat	3.18
Trawl_hill	2.89
Trawl_LF_flat	216.41
Trawl_LF_hill	277.17
Fishery_LF_flat	1257.70
Fishery_LF_hill	886.76
Fishery_LF_spawn	189.66
Acoustic q ratio	-0.99
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.47
Prior q_FlatCPUE_late	-10.54
Prior q_HillCPUE_early	-10.47
Prior q_HillCPUE_late	-9.74
Prior q_SpawnCPUE_early	-7.20
Prior q_SpawnCPUE_late	-6.91
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.39
Prior on B0	11.71
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0
Proportions at age 1990	-74.35
Proportions at age 2002	-91.87

Vulnerability	
Flat A50	26.83
Flat Ato95	6.41
Hill A50	1*
Hill Ato95	1*
Spawn A50	46.82
Spawn Ato95	10.24
Survey Flat A50	14.32
Survey Flat Ato95	3.88
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	25.45
Migration Ato95	1.25
Migration cap	0.033

q's	
FlatCPUE_early	2.83e-05
FlatCPUE_late	2.64e-05
HillCPUE_early	2.84e-05
HillCPUE_late	5.88e-05
SpawnCPUE_early	7.47e-04
SpawnCPUE_late	9.99e-04
Acoustic_2003	0.293
Acoustic_2001	0.638
Trawl_hill	0.041
Trawl_flat	0.170

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.046

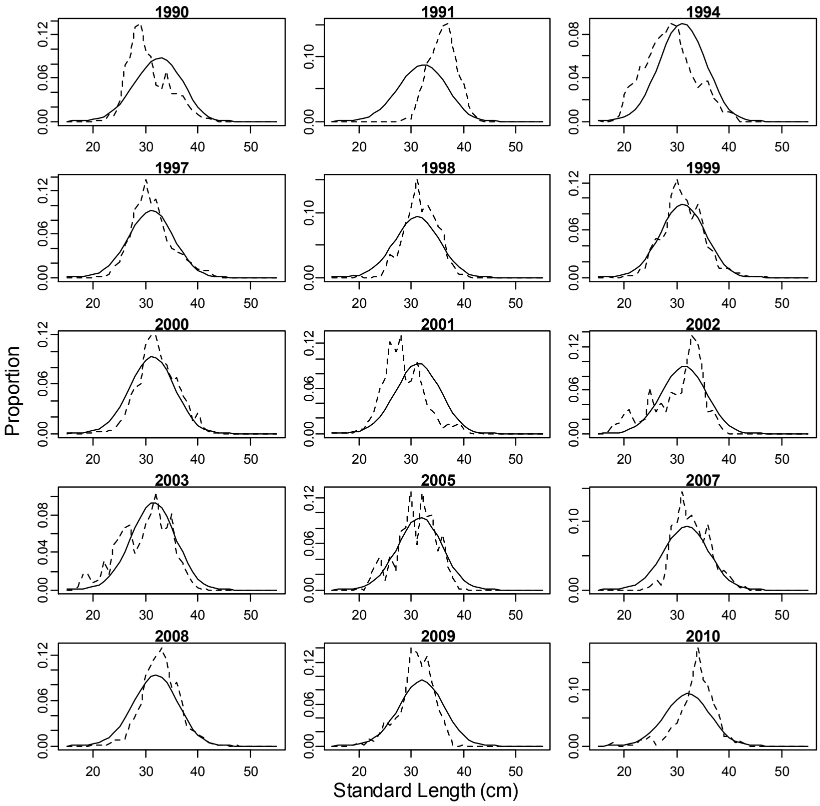


Figure A9.1: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

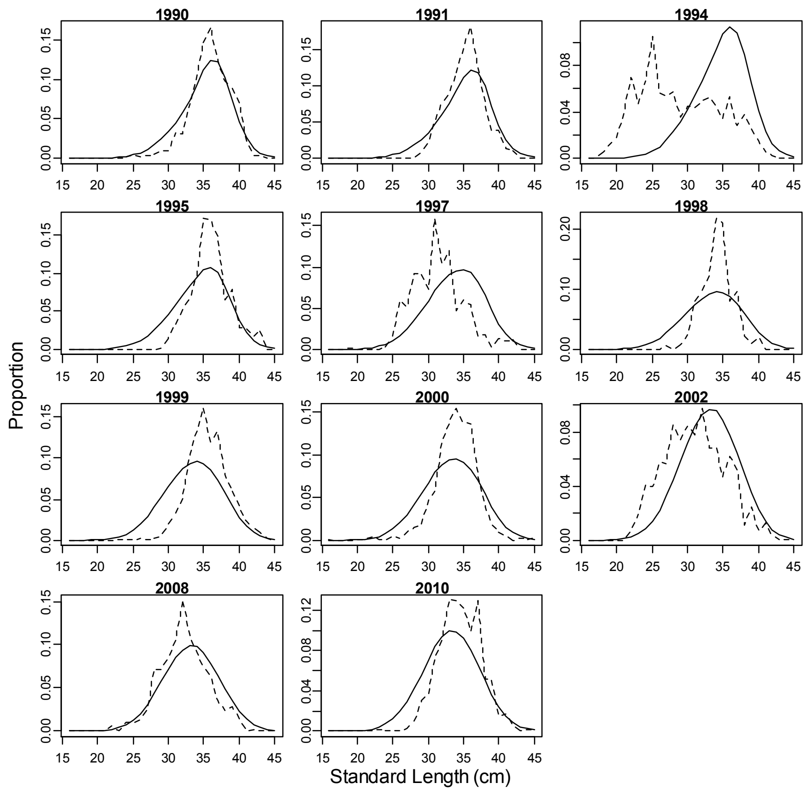


Figure A9.2: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

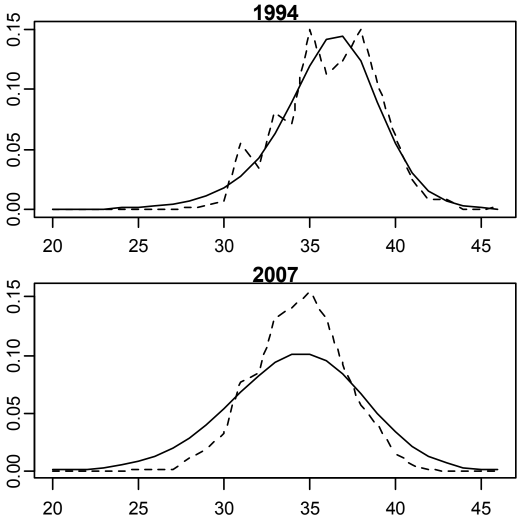


Figure A9.3: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

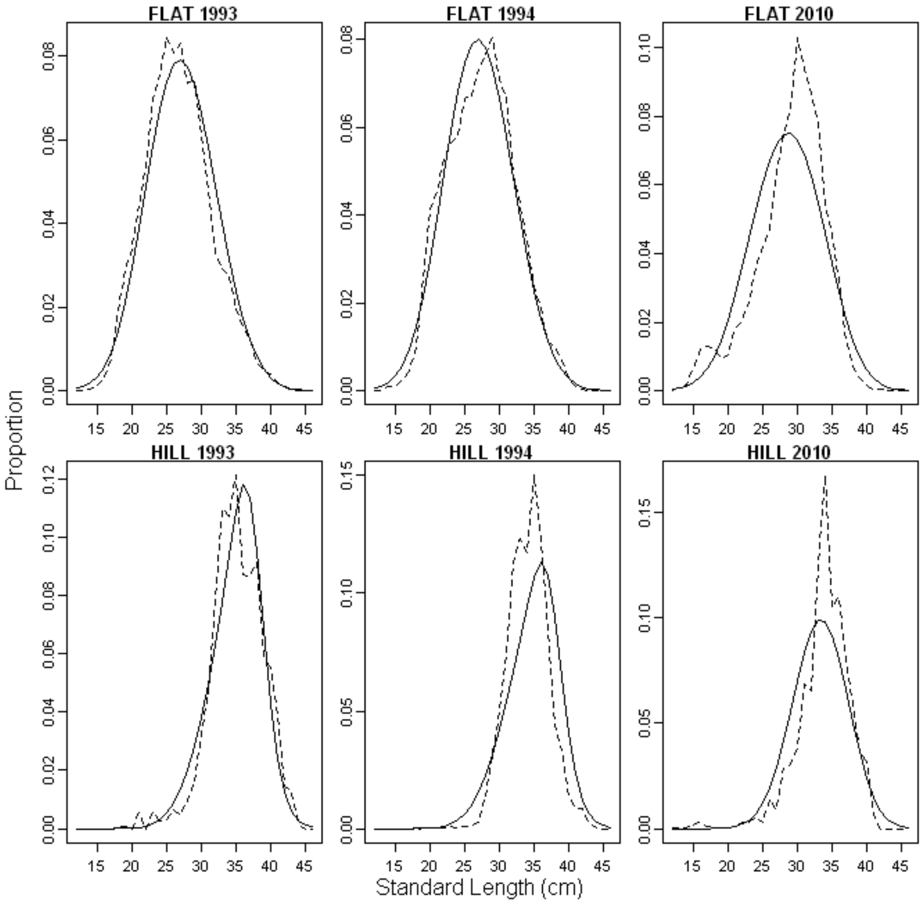


Figure A9.4: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

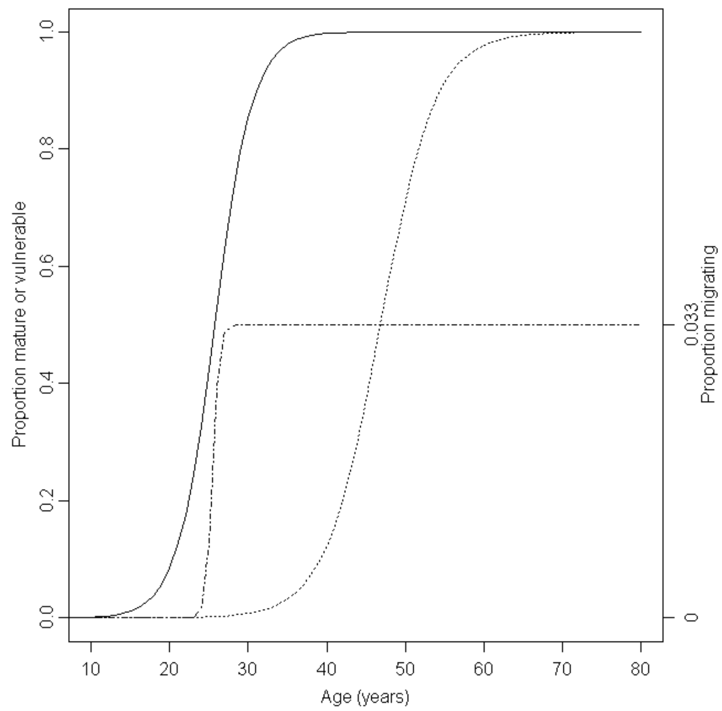


Figure A9.5: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

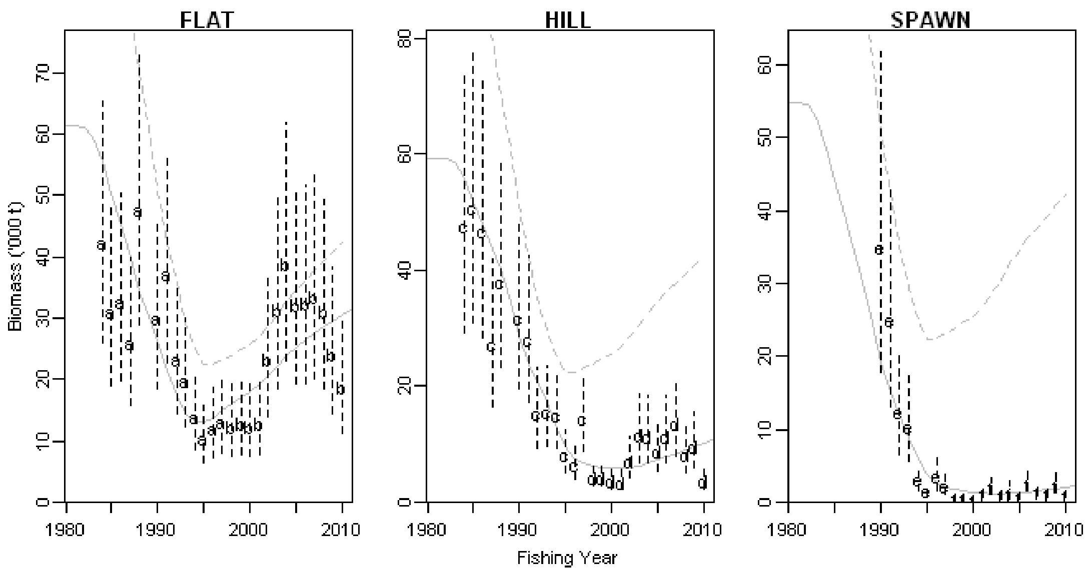


Figure A9.6: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

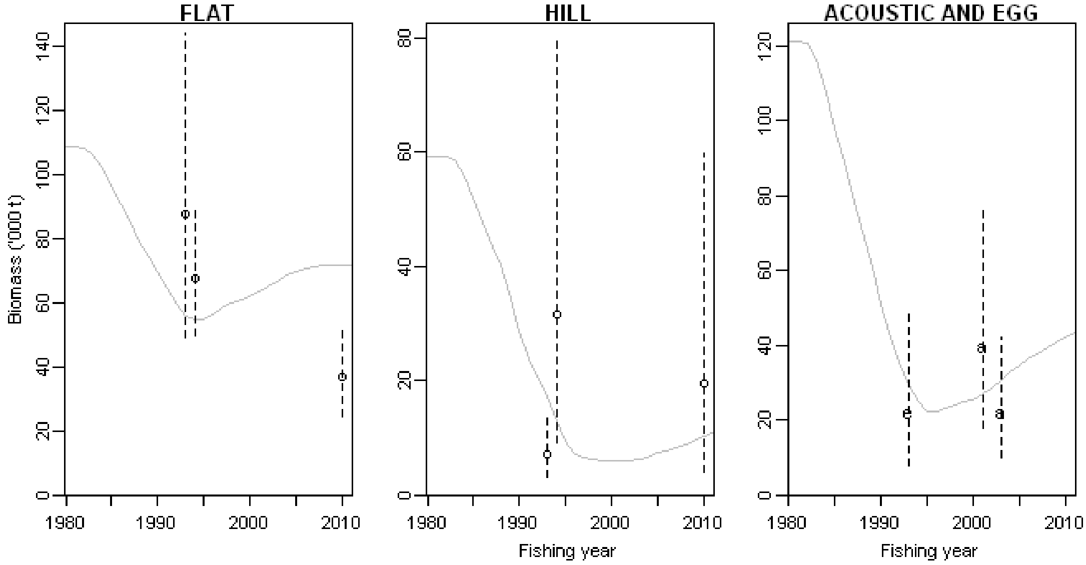


Figure A9.7: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

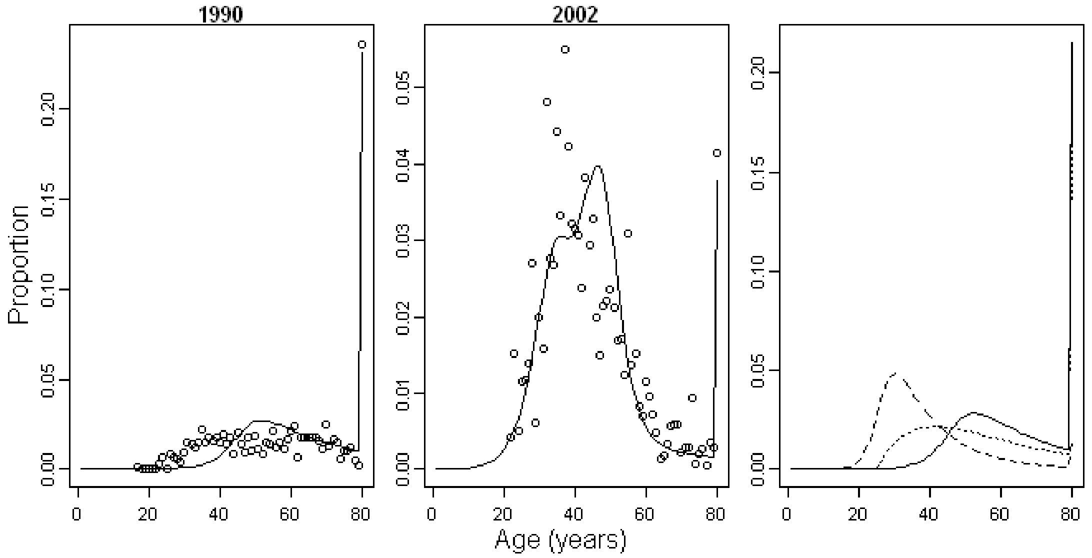


Figure A9.8: Model ABC estimating spawn vulnerability and natural mortality including the age frequency data model run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) fit to observations (points). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix X

Table A10.1: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	595 197
B2011	476 467
B2011/B0	0.80
Flat B0	50 607
Flat B2011	31 533
Flat B2011/B0	0.62
Hill B0	578 021
Hill B2011	479 023
Hill B2011/B0	0.83
Spawn B0	553 428
Spawn B2011	437 445
Spawn B2011/B0	0.79

Likelihood components	
Total	3393.18
Egg survey	19.45
FlatCPUE_early	-3.38
FlatCPUE_late	-9.26
HillCPUE_early	23.98
HillCPUE_late	7.57
SpawnCPUE_early	37.81
SpawnCPUE_late	13.15
Acoustic_2001	-0.92
Acoustic_2003	0.34
Trawl_flat	1.66
Trawl_hill	1.03
Trawl_LF_flat	221.84
Trawl_LF_hill	349.72
Fishery_LF_flat	1247.1
Fishery_LF_hill	957.66
Fishery_LF_spawn	580.97
Acoustic q ratio	-2.83
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.18
Prior q_FlatCPUE_late	-10.52
Prior q_HillCPUE_early	-13.64
Prior q_HillCPUE_late	-13.96
Prior q_SpawnCPUE_early	-11.37
Prior q_SpawnCPUE_late	-12.87
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	6.54
Prior on B0	13.30
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0

Vulnerability	
Flat A50	26.71
Flat Ato95	4.51
Hill A50	1*
Hill Ato95	1*
Spawn A50	29.75
Spawn Ato95	1#
Survey Flat A50	18.63
Survey Flat Ato95	7.15
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	16.19
Migration Ato95	1.00#
Migration cap	0.08

q’s	
FlatCPUE_early	3.77e-05
FlatCPUE_late	2.71e-05
HillCPUE_early	1.19e-06
HillCPUE_late	8.69e-07
SpawnCPUE_early	1.15e-05
SpawnCPUE_late	2.58e-06
Acoustic_2003	0.027
Acoustic_2001	0.066
Trawl_hill	0.0012
Trawl_flat	0.183

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.025*

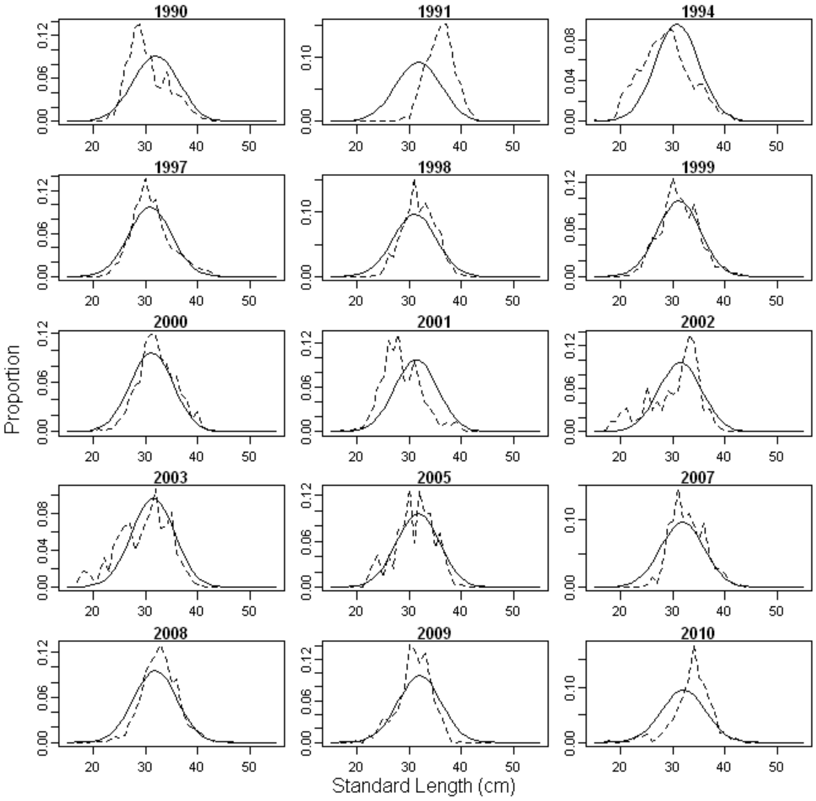


Figure A10.1: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

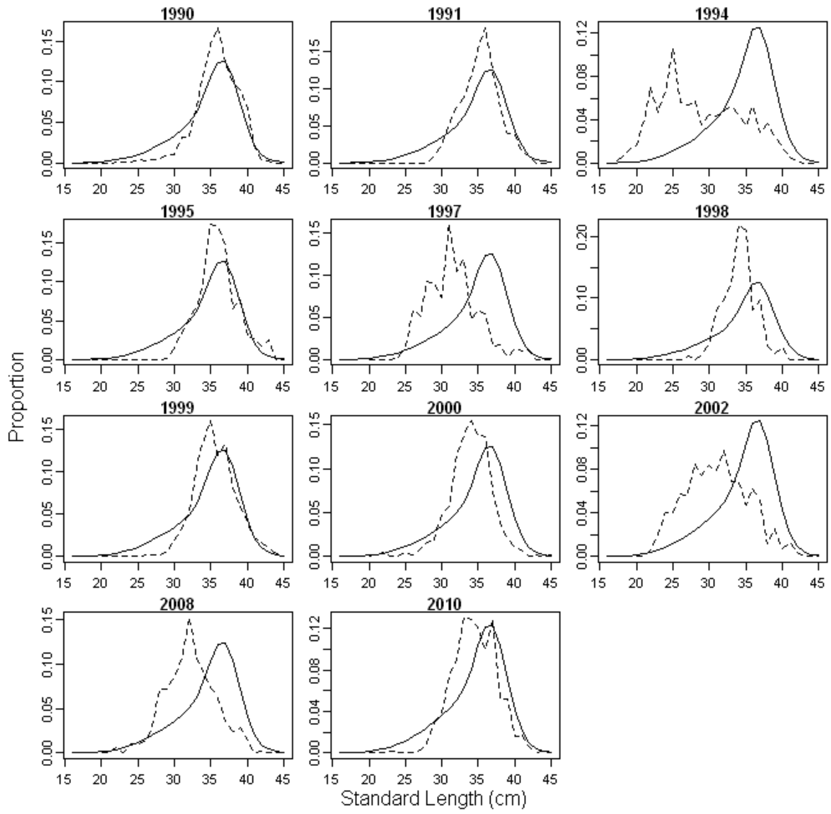


Figure A10.2: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

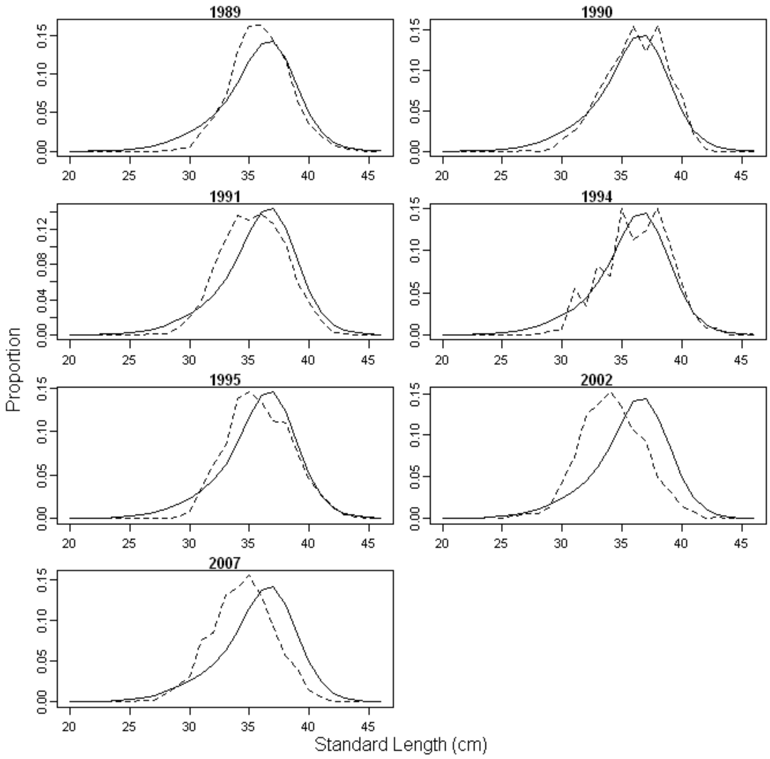


Figure A10.3: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

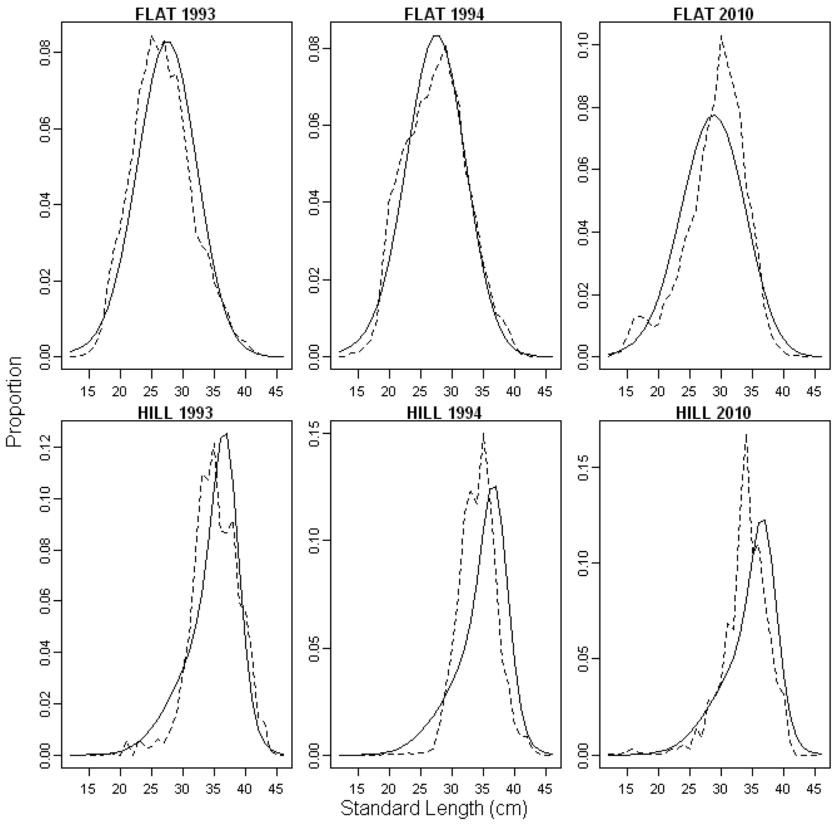


Figure A10.4: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

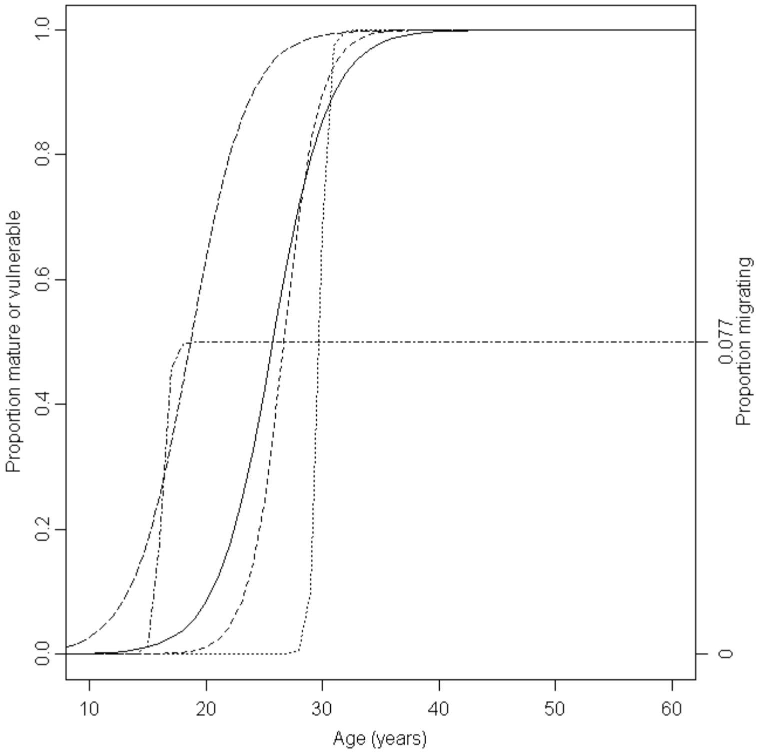


Figure A10.5: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

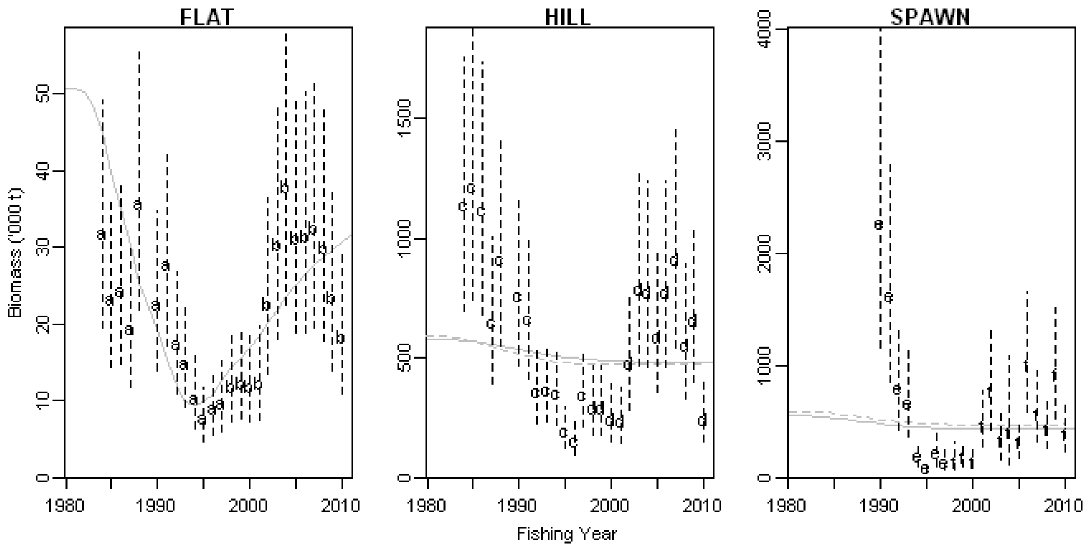


Figure A10.6: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

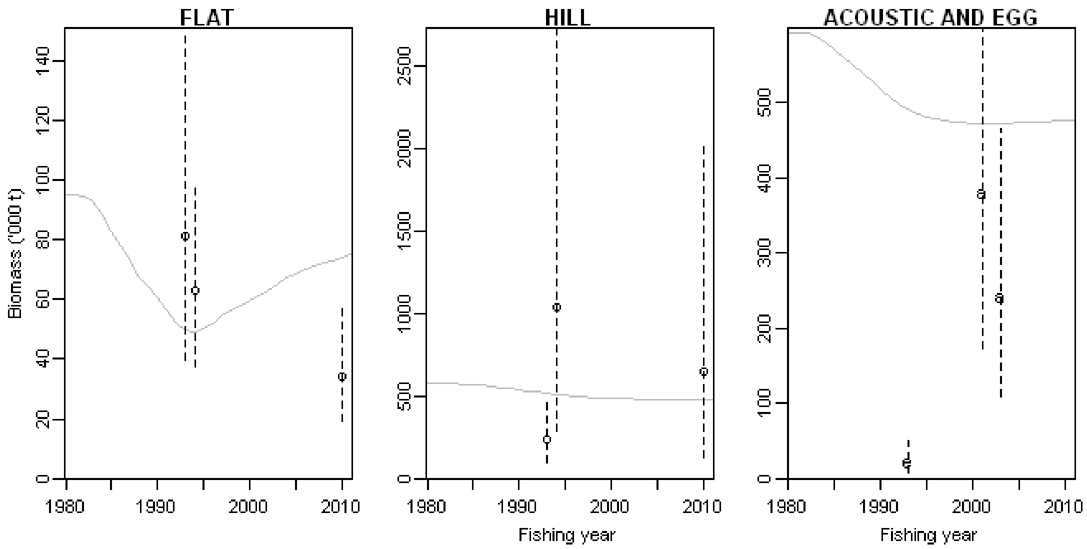


Figure A10.7: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

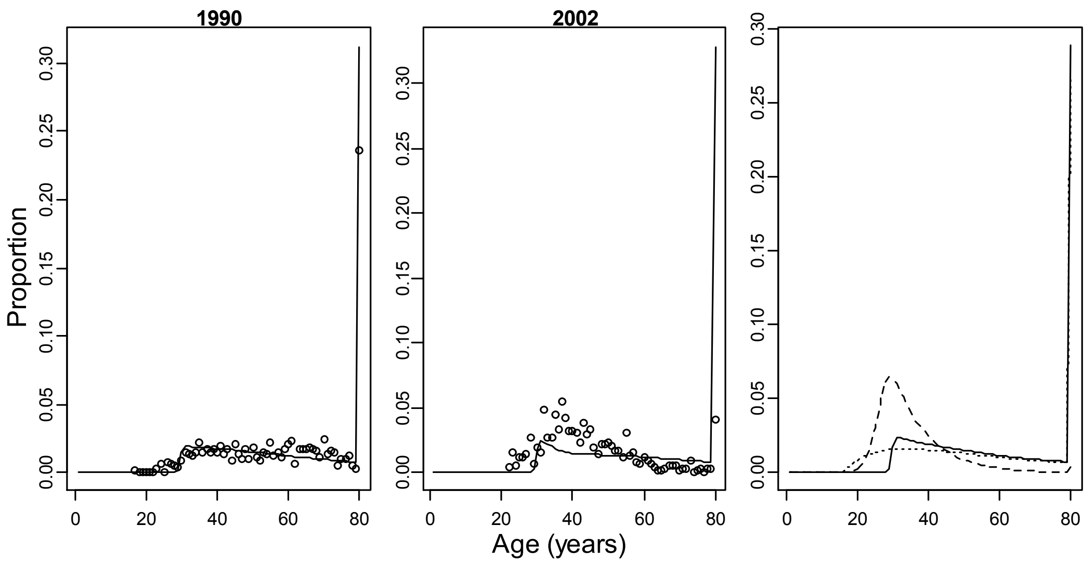


Figure A10.8: Model ABC estimating spawn vulnerability assuming low M (2.5%) and excluding the age frequency data model run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) fit to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Appendix XI

Table A11.1: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	
B2011	
B2011/B0	
Flat B0	
Flat B2011	
Flat B2011/B0	
Hill B0	
Hill B2011	
Hill B2011/B0	
Spawn B0	
Spawn B2011	
Spawn B2011/B0	

Likelihood components	
Total	2617.04
Egg survey	-0.18
FlatCPUE_early	-5.37
FlatCPUE_late	-9.92
HillCPUE_early	-11.67
HillCPUE_late	2.07
SpawnCPUE_early	9.19
SpawnCPUE_late	6.14
Acoustic_2001	-0.59
Acoustic_2003	-0.46
Trawl_flat	1.19
Trawl_hill	1.41
Trawl_LF_flat	214.43
Trawl_LF_hill	283.78
Fishery_LF_flat	1258.55
Fishery_LF_hill	855.49
Fishery_LF_spawn	190.06
Acoustic q ratio	-1.46
Catch penalty hill	0
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-10.71
Prior q_FlatCPUE_late	-11.26
Prior q_HillCPUE_early	-10.64
Prior q_HillCPUE_late	-10.52
Prior q_SpawnCPUE_early	-7.68
Prior q_SpawnCPUE_late	-8.77
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.11
Prior on B0	12.31
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	0
Proportions at age 1990	-106.14
Proportions at age 2002	-95.36

Vulnerability	
Flat A50	26.71
Flat Ato95	4.51
Hill A50	1*
Hill Ato95	1*
Spawn A50	29.75
Spawn Ato95	1#
Survey Flat A50	18.63
Survey Flat Ato95	7.15
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	16.19
Migration Ato95	1.00#
Migration cap	0.08

q's	
FlatCPUE_early	3.77e-05
FlatCPUE_late	2.71e-05
HillCPUE_early	1.19e-06
HillCPUE_late	8.69e-07
SpawnCPUE_early	1.15e-05
SpawnCPUE_late	2.58e-06
Acoustic_2003	0.027
Acoustic_2001	0.066
Trawl_hill	0.0012
Trawl_flat	0.183

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.025*

Likelihood (cont.)	
Prior on YCS	-27.49
Mean YCS=1 penalty	98.02
YCS smoothing penalty	2.72

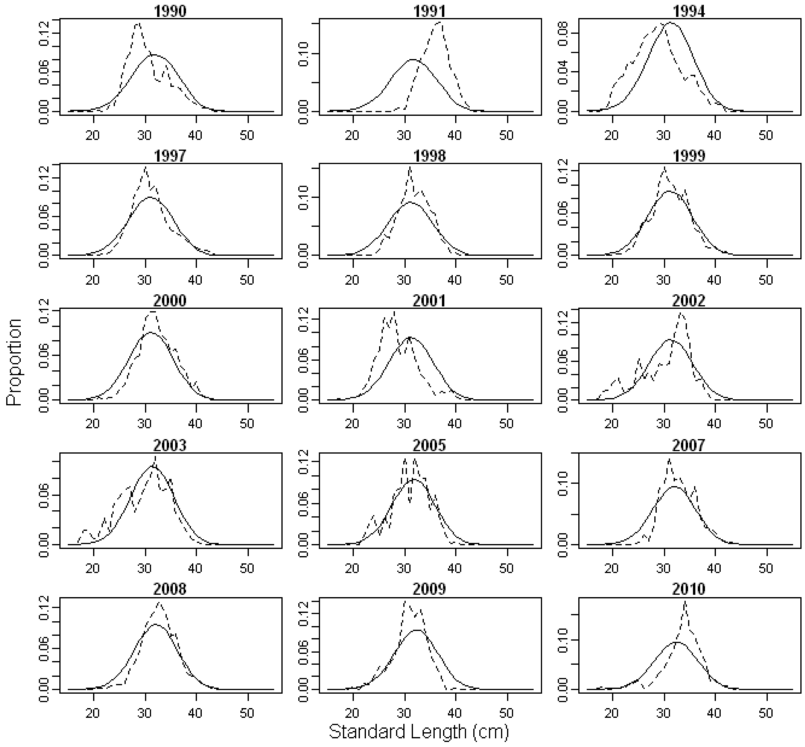


Figure A11.1: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

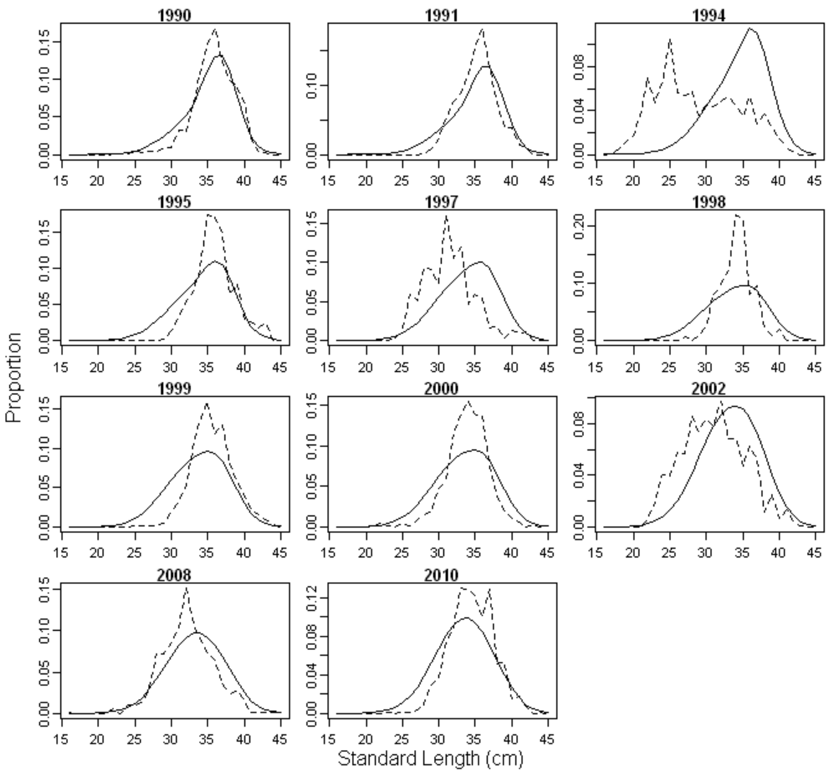


Figure A11.2: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

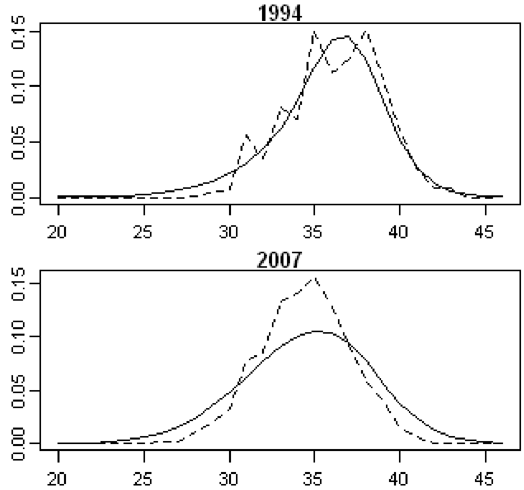


Figure A11.3: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

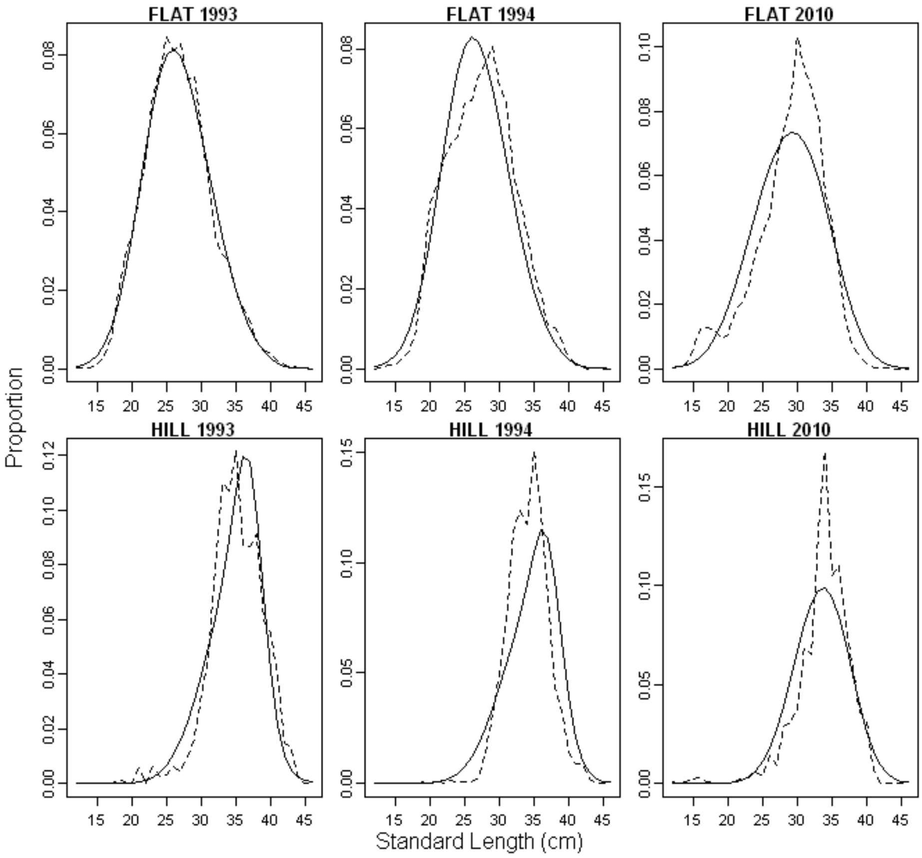


Figure A11.4: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

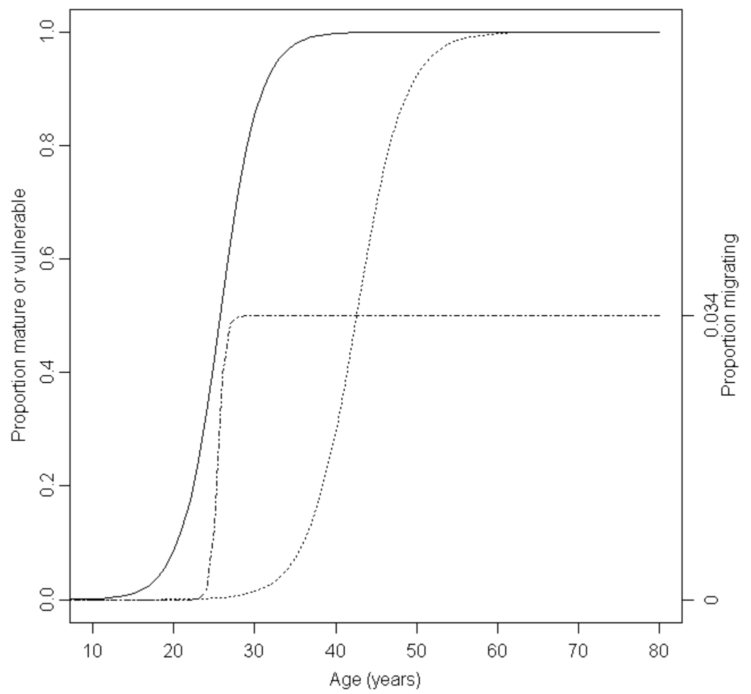


Figure A11.5: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

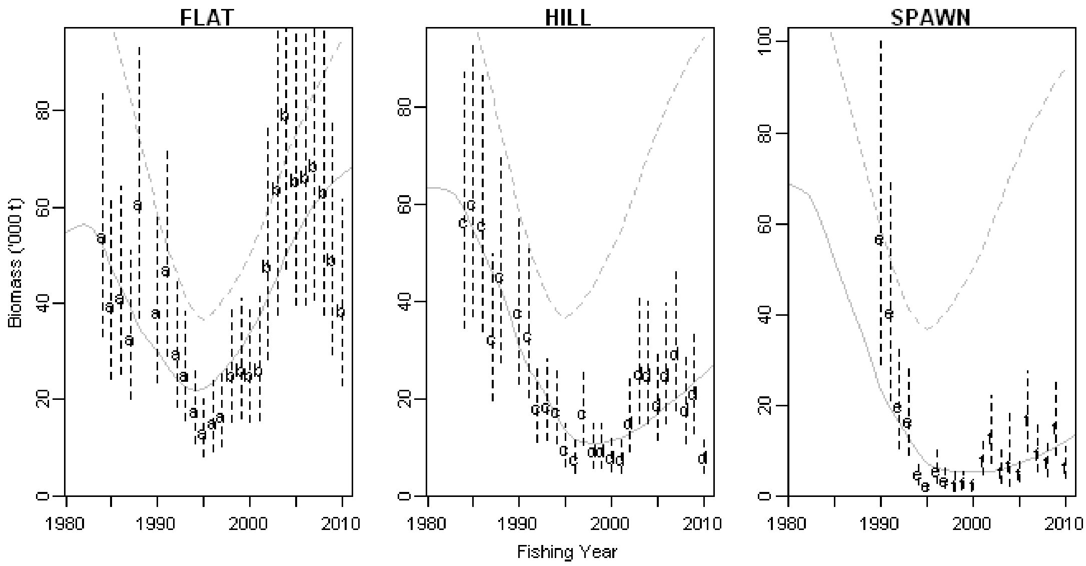


Figure A11.6: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

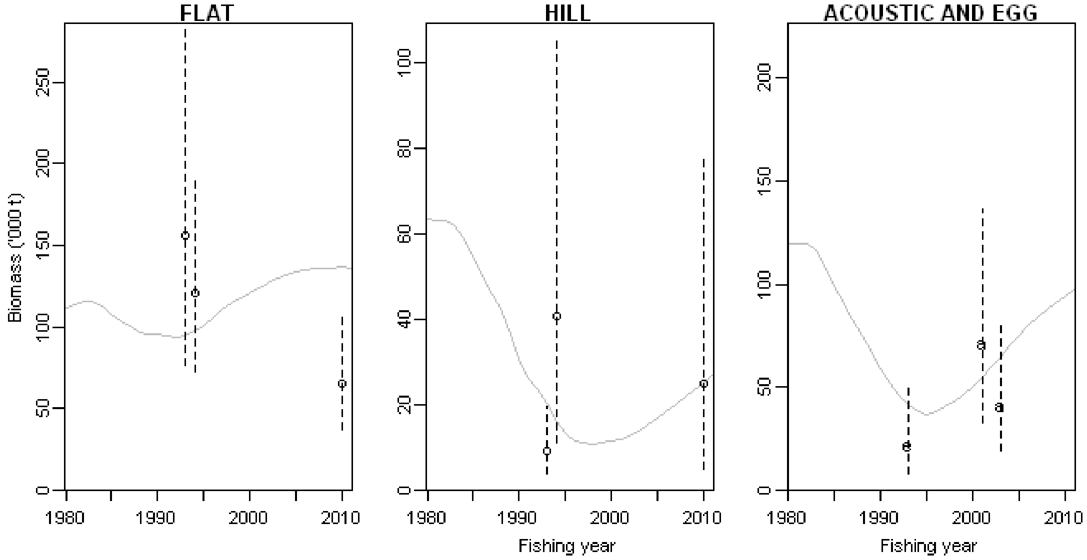


Figure A11.7: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

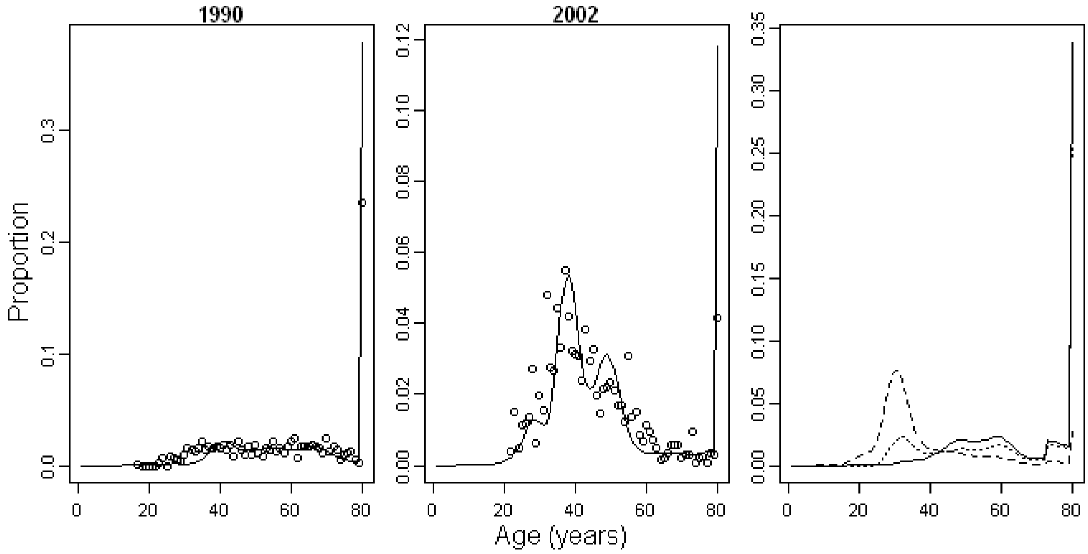


Figure A11.8: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) fit to observations (points) (FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

Figure A11.9: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment model run. Estimated year class strength (YCS).

Appendix XII

Table A12.1: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5%; model run biomass estimates, likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	82 559
B2011	31 574
B2011/B0	0.38
Flat B0	105 502
Flat B2011	29 001
Flat B2011/B0	0.27
Hill B0	28 421
Hill B2011	1 356
Hill B2011/B0	0.05
Spawn B0	77 758
Spawn B2011	4 301
Spawn B2011/B0	0.06

Likelihood components	
Total	3702.51
Egg survey	0.82
FlatCPUE_early	-10.92
FlatCPUE_late	-2.58
HillCPUE_early	131.94
HillCPUE_late	17.83
SpawnCPUE_early	3.58
SpawnCPUE_late	8.00
Acoustic_2001	-0.20
Acoustic_2003	-0.83
Trawl_flat	59.25
Trawl_hill	387.64
Trawl_LF_flat	277.69
Trawl_LF_hill	345.79
Fishery_LF_flat	1432.2
Fishery_LF_hill	854.69
Fishery_LF_spawn	193.65
Acoustic q ratio	-0.89
Catch penalty hill	31.47
Catch penalty flat	0
Catch penalty spawn	0
Prior q_FlatCPUE_early	-11.12
Prior q_FlatCPUE_late	-10.61
Prior q_HillCPUE_early	-8.32
Prior q_HillCPUE_late	-6.91
Prior q_SpawnCPUE_early	-7.33
Prior q_SpawnCPUE_late	-7.97
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	-0.31
Prior on B0	11.32
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	0
Prior on migration	0
Prior on selectivity_survey_flat	–
Prior on selectivity_spawn	–
Proportions at age 1990	-81.25
Proportions at age 2002	-73.87

Vulnerability	
Flat A50	26.83
Flat Ato95	6.41
Hill A50	1*
Hill Ato95	1*
Spawn A50	42.57
Spawn Ato95	8.80
Survey Flat A50	14.32#
Survey Flat Ato95	3.88#
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	25.45#
Migration Ato95	1.25#
Migration cap	0.01

q's	
FlatCPUE_early	1.47e-08
FlatCPUE_late	2.46e-05
HillCPUE_early	2.44e-04
HillCPUE_late	9.99e-04
SpawnCPUE_early	6.56e-04
SpawnCPUE_late	3.44e-04
Acoustic_2003	0.34
Acoustic_2001	0.73
Trawl_hill	0.93
Trawl_flat	0.17

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

Likelihood (cont.)	
Prior on YCS	61.93
Mean YCS=1 penalty	98.03
YCS smoothing penalty	9.81

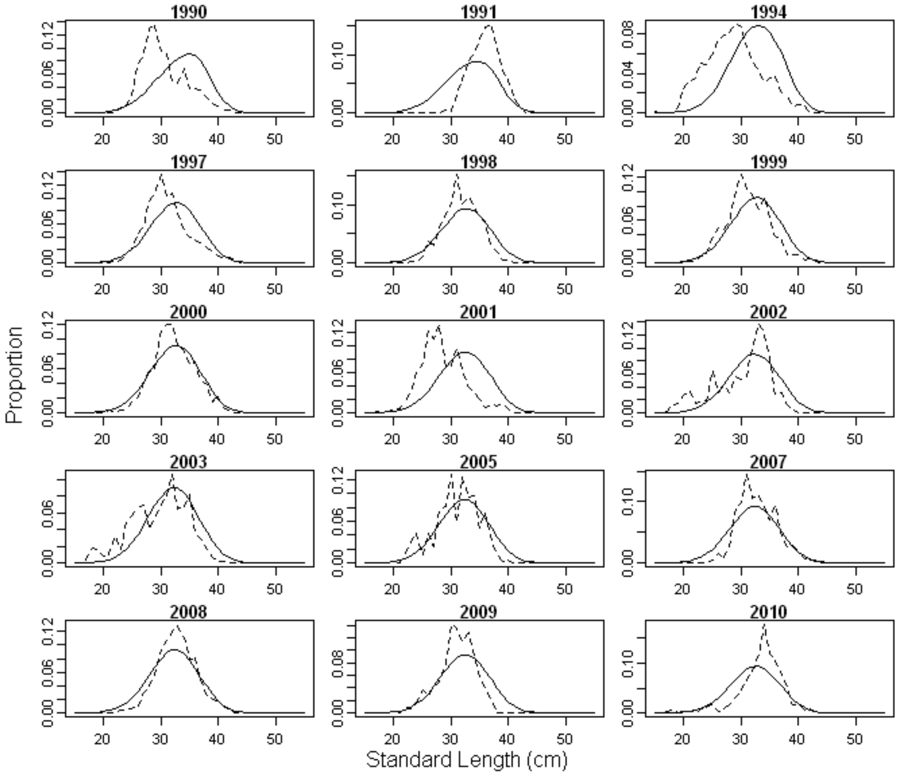


Figure A12.1: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Commercial FLAT length frequencies. Broken line, observations; Solid line, model fit.

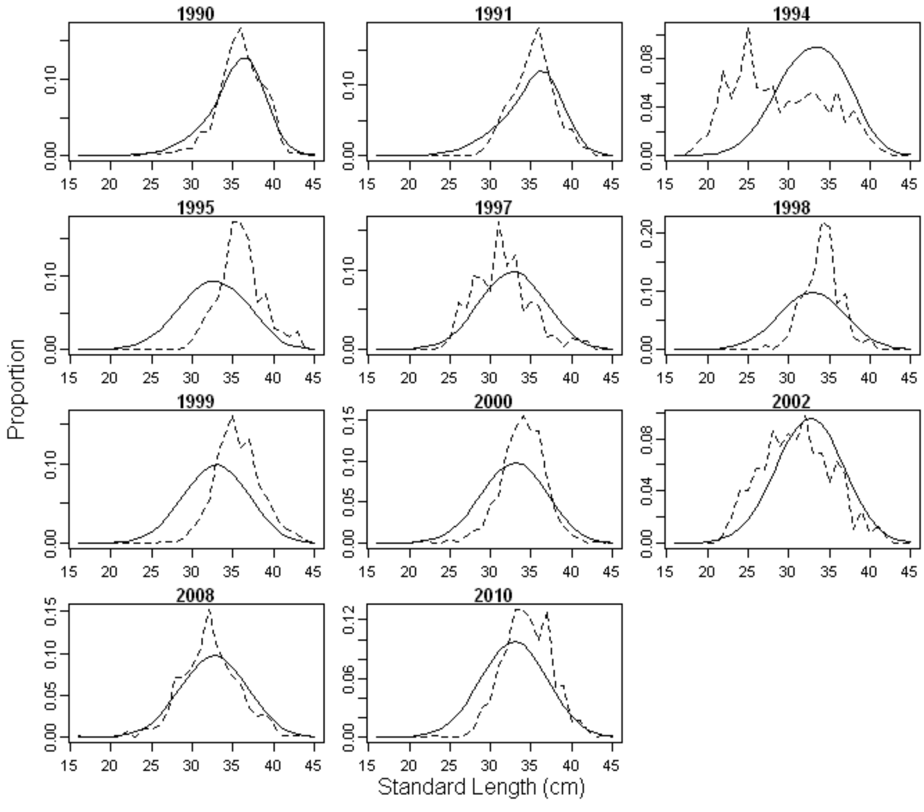


Figure A12.2: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Commercial HILL length frequencies. Broken line, observations; Solid line, model fit.

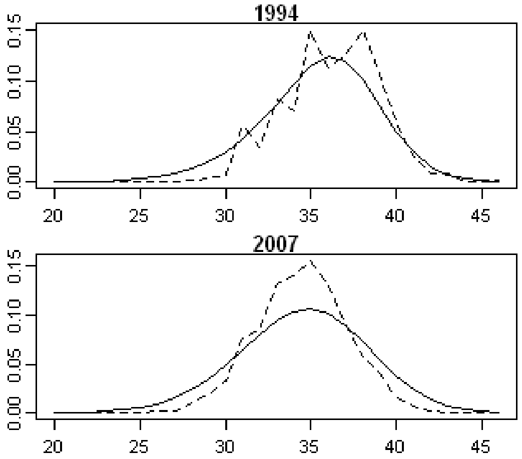


Figure A12.3: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Commercial SPAWN length frequencies. Broken line, observations; Solid line, model fit.

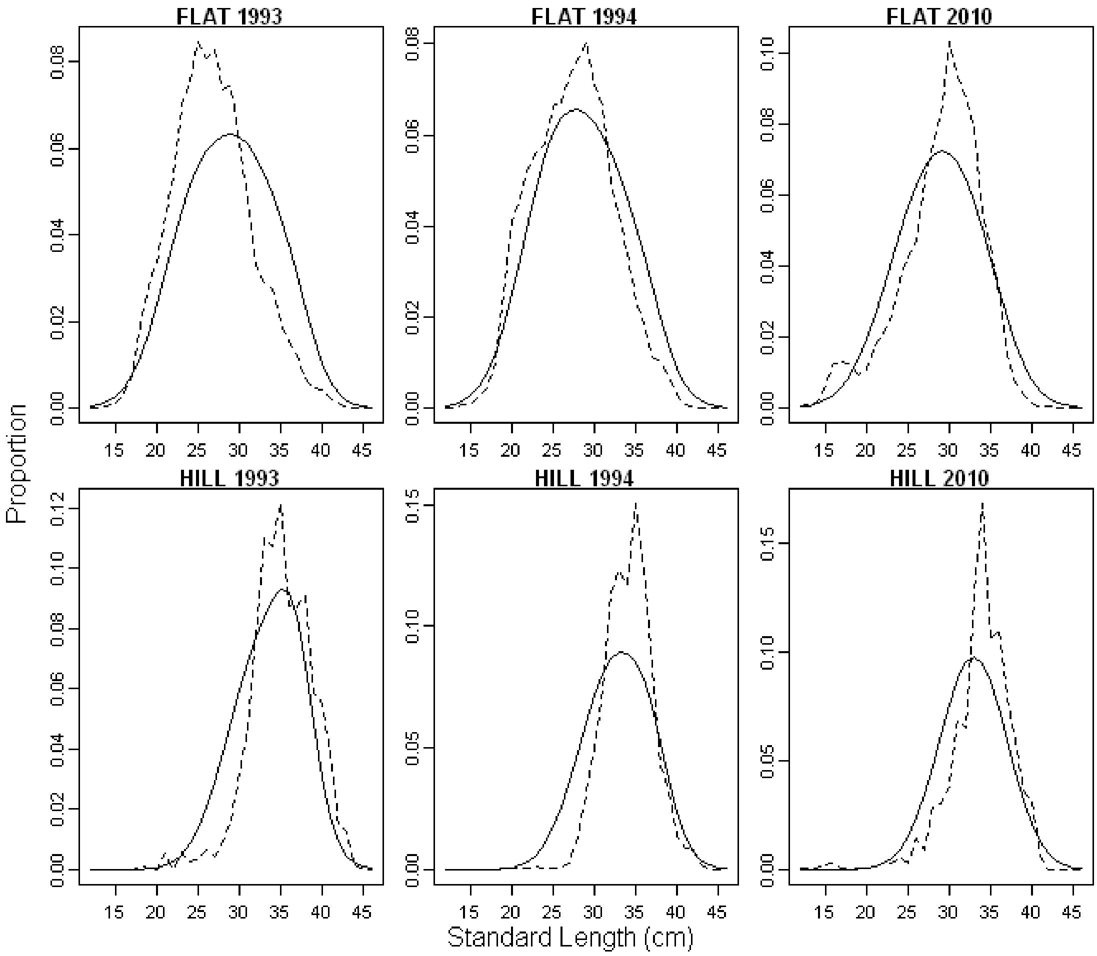


Figure A12.4: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

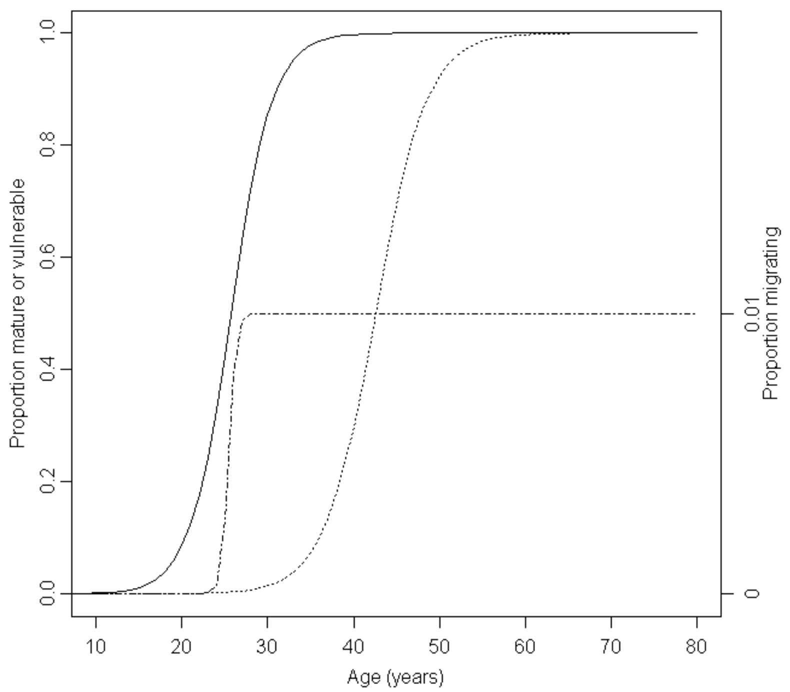


Figure A12.5: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run, ogives. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

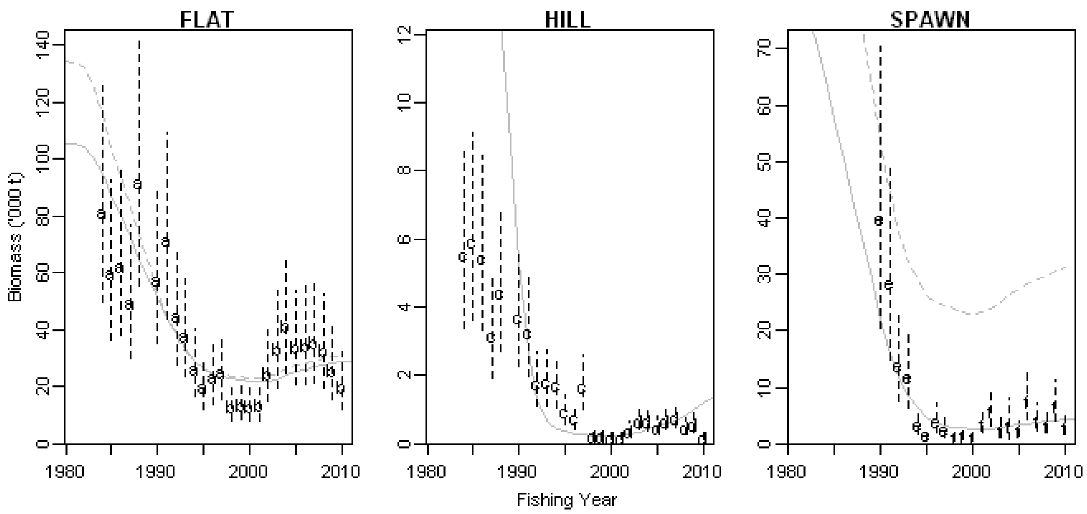


Figure A12.6: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

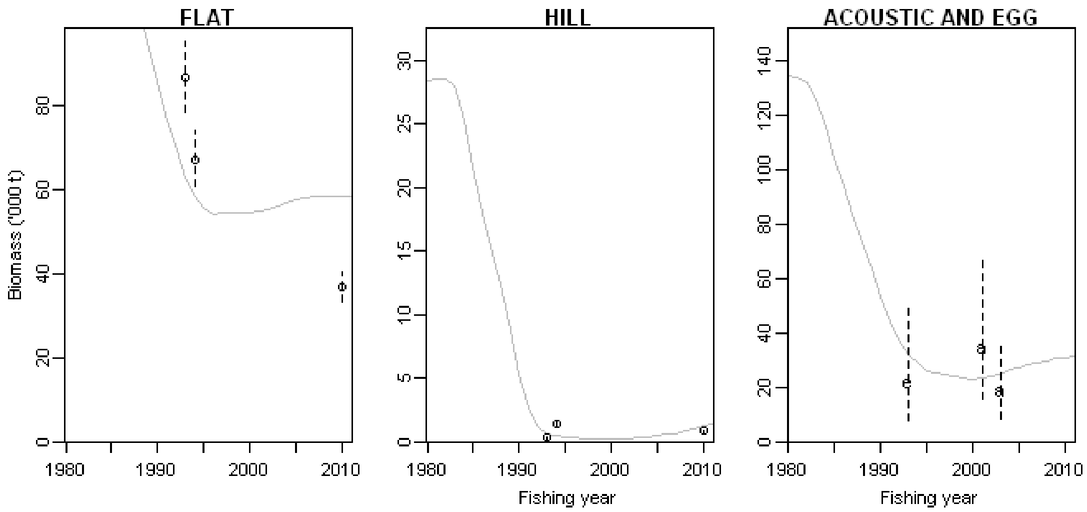


Figure A12.7: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Fit to fishery independent indices; left and centre panels research trawl survey; right panel acoustic ("a") and egg ("e") surveys. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

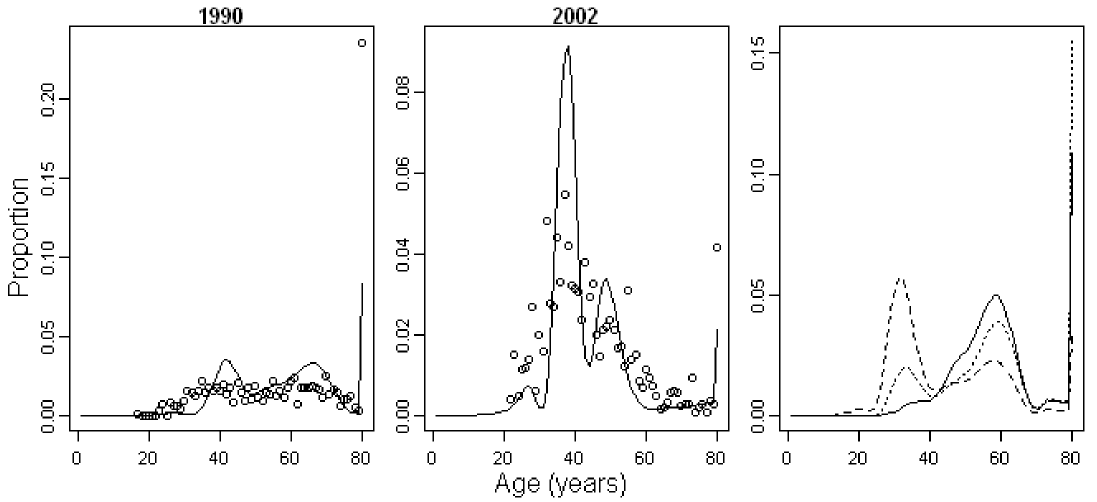


Figure A12.8: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) fit to observations (points) (FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

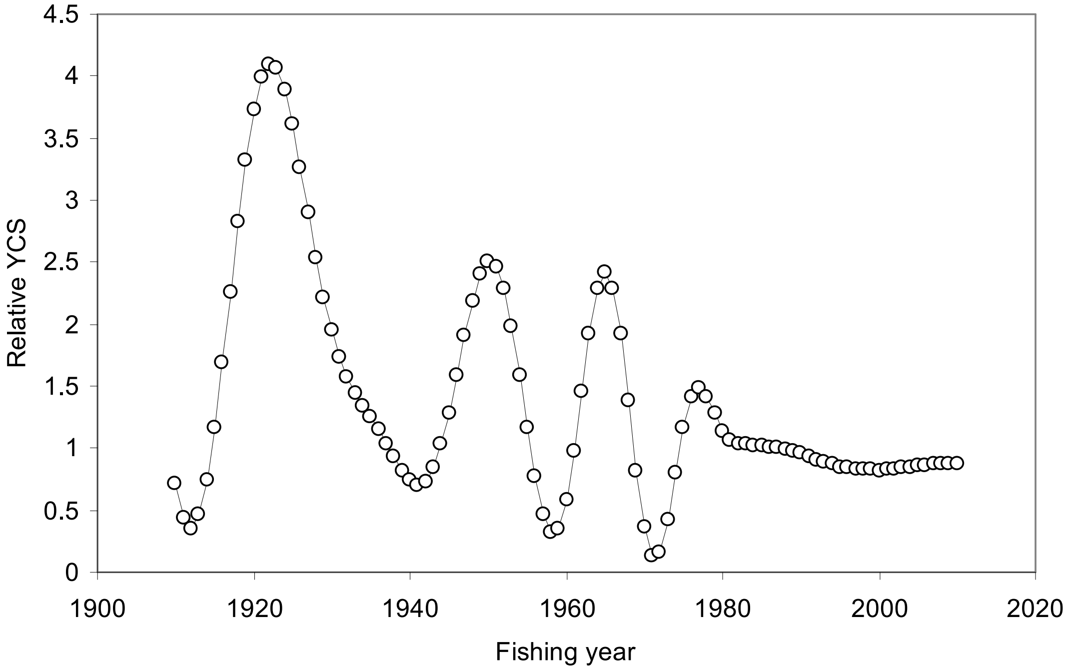


Figure A12.9: Model ABC estimating spawn vulnerability including age frequency data and estimating recruitment and fixing research trawl survey c.v.s to 5% model run. Estimated year class strength (YCS).

Appendix XIII

Table A13.1: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices; biomass estimates (note that B1980 is reported in lieu of B0), likelihood components, and parameters (*, fixed parameter; #, at bound).

Biomass estimates	
B0	57 131
B2011	3 163
B2011/B0	0.06
Flat B1980	1 357
Flat B2011	1 205
Flat B2011/B1980	0.89
Hill 19800	17 692
Hill B2011	1 979
Hill B2011/B1980	0.11
Spawn B1980	20 321
Spawn B2011	3 164
Spawn B2011/B1980	0.16

Likelihood components	
Total	429.54
Egg survey	–
FlatCPUE_early	0.74
FlatCPUE_late	-9.82
HillCPUE_early	12.75
HillCPUE_late	6.81
SpawnCPUE_early	12.15
SpawnCPUE_late	6.87
Acoustic_2001	2.09
Acoustic_2003	-0.98
Trawl_flat	-8.89
Trawl_hill	282.00
Trawl_LF_flat	25.88
Trawl_LF_hill	28.89
Fishery_LF_flat	–
Fishery_LF_hill	–
Fishery_LF_spawn	–
Acoustic q ratio	0.84
Catch penalty hill	3.12
Catch penalty flat	21.11
Catch penalty spawn	0
Prior q_FlatCPUE_early	-8.83
Prior q_FlatCPUE_late	-8.48
Prior q_HillCPUE_early	-7.11
Prior q_HillCPUE_late	-7.66
Prior q_SpawnCPUE_early	-7.96
Prior q_SpawnCPUE_late	-7.86
Prior on q_acoustic 2003	0
Prior on q_acoustic 2001	6.10
Prior on Bmean	10.90
Prior on q_survey_hill	0
Prior on q_survey_flat	0
Prior on selectivity_flat	–
Prior on migration	0
Prior on selectivity_survey_flat	0
Prior on selectivity_spawn	–

Vulnerability	
Flat A50	26.33*
Flat Ato95	6.41*
Hill A50	1*
Hill Ato95	1*
Spawn A50	25.73*
Spawn Ato95	7.11*
Survey Flat A50	15.60
Survey Flat Ato95	5.43
Survey Hill A50	1*
Survey Hill Ato95	1*

Migration	
Migration A50	32.27
Migration Ato95	7.59*
Migration cap	0.91

q's	
FlatCPUE_early	1.46e-04
FlatCPUE_late	2.07e-04
HillCPUE_early	8.15e-04
HillCPUE_late	4.68e-04
SpawnCPUE_early	3.47e-04
SpawnCPUE_late	3.87e-04
Acoustic_2003	2.29
Acoustic_2001	4.37
Trawl_hill	0.43
Trawl_flat	0.53

Biological parameters	
Maturity A50	25.73*
Maturity Ato95	7.11*
M	0.045*

Likelihood (cont.)	
Mean YCS=1 penalty	49.01
YCS smoothing penalty	4.97

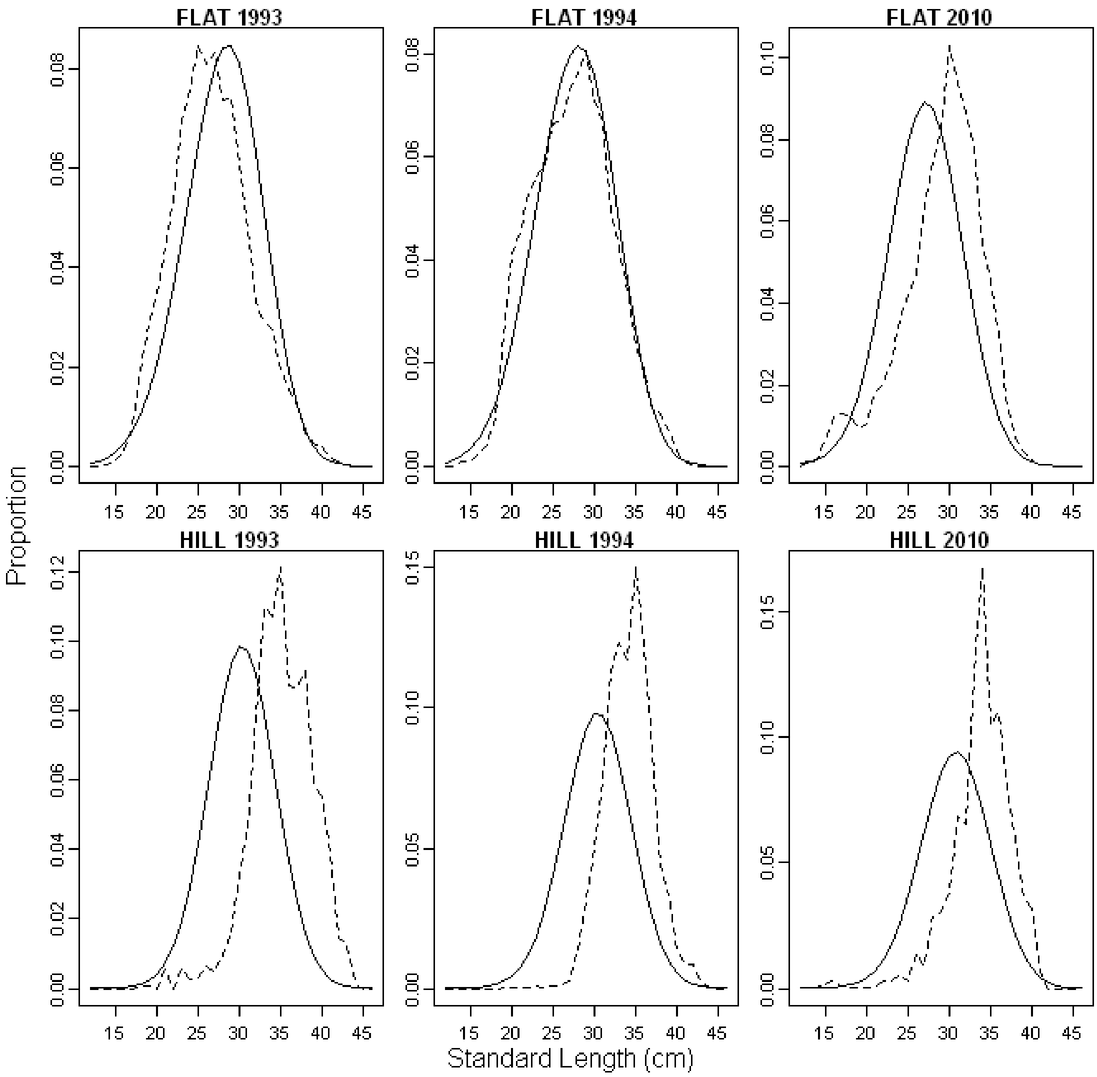


Figure A13.1: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Research trawl survey length frequencies. Broken line, observations; Solid line, model fit.

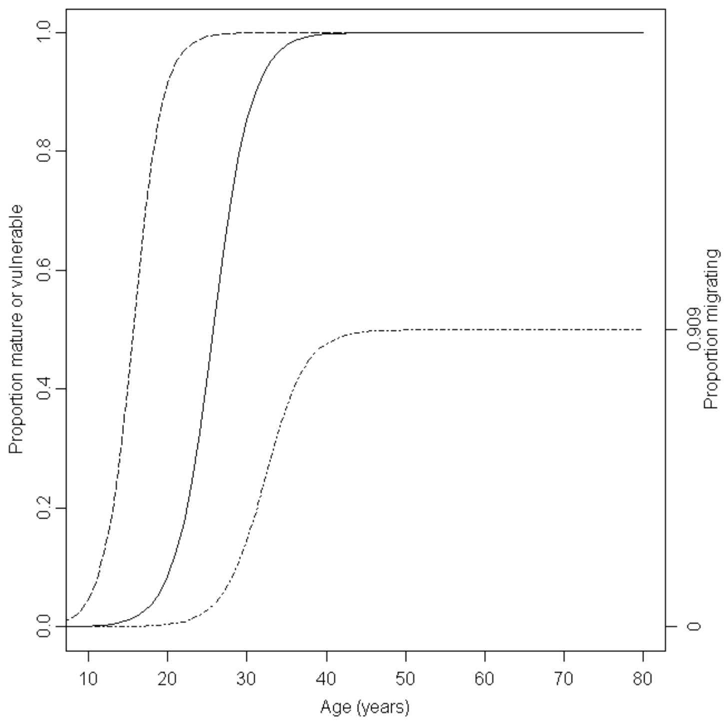


Figure A13.2: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Solid line, maturity ogive (fixed); short dash, commercial FLAT ogive (estimated); long dash line, research trawl survey flat selectivity (estimated); dot and dash line, migration ogive (estimated); dotted line, spawn fishery ogive (estimated).

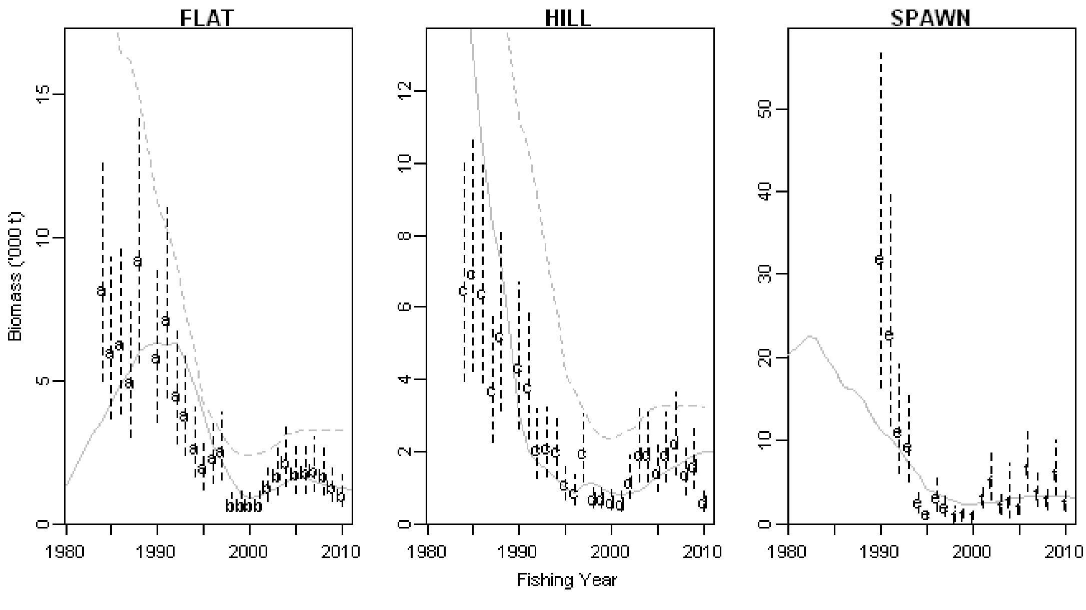


Figure A13.3: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Fit to commercial CPUE indices: a, flat early; b, flat late; c, hill early; d, hill late; e, spawn early; f, spawn late. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit to the vulnerable biomass, the broken grey line is the estimated mature biomass.

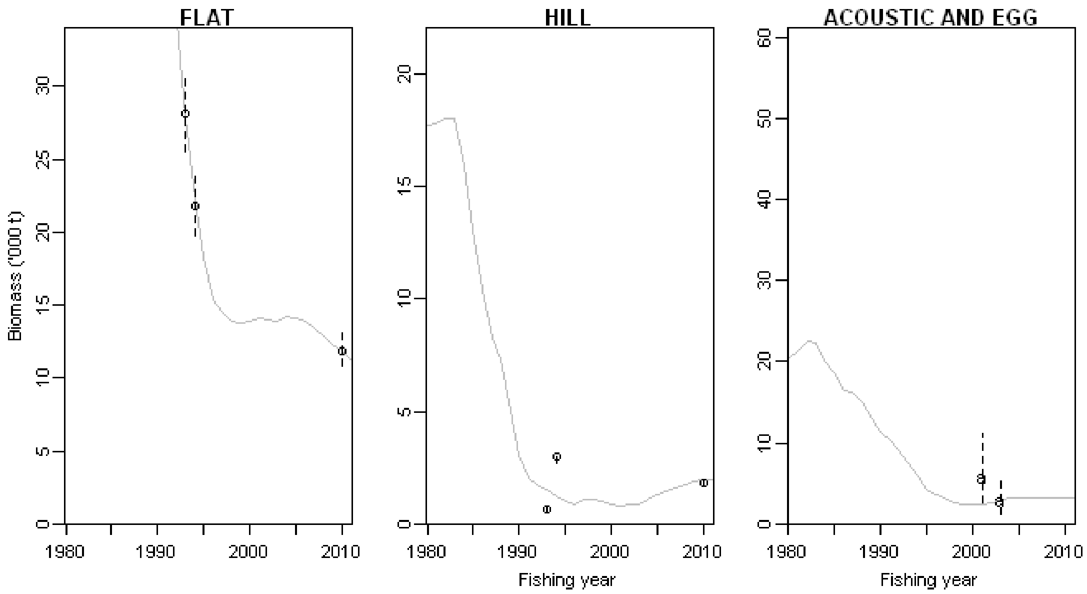


Figure A13.4: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Fit to fishery independent indices; left and centre panels research trawl survey. Vertical broken lines indicate the 95% confidence intervals around observations. The solid grey line is the model fit.

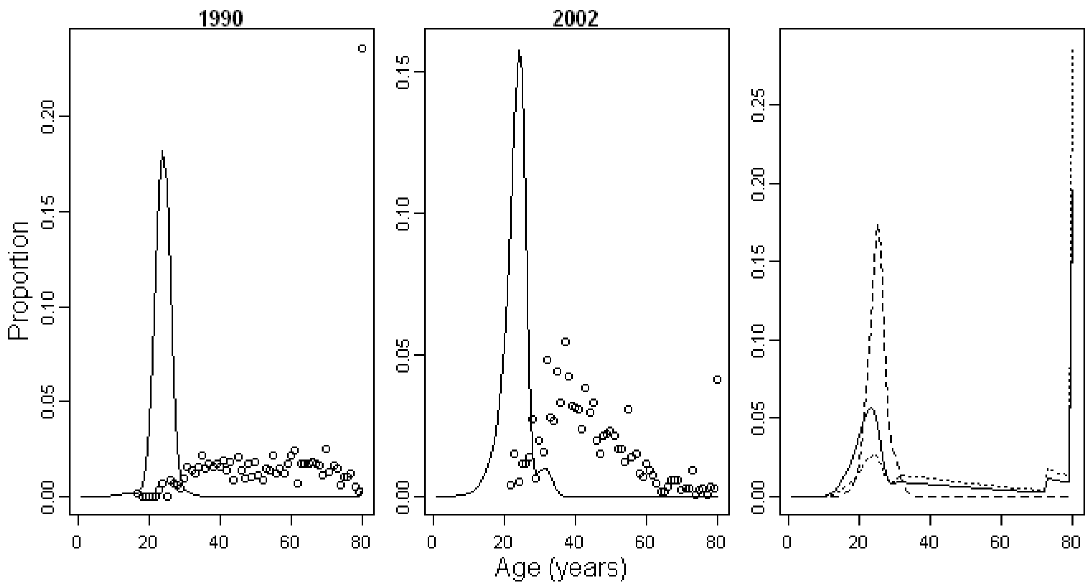


Figure A13.5: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Left and middle panels: predicted age structure in 1990 and 2002 (solid lines) comparison to observations (points) (NOT FITTED). Right hand panel shows the age structure in 1982 for the spawn (dotted line), flat (dashed line), and hill (solid line).

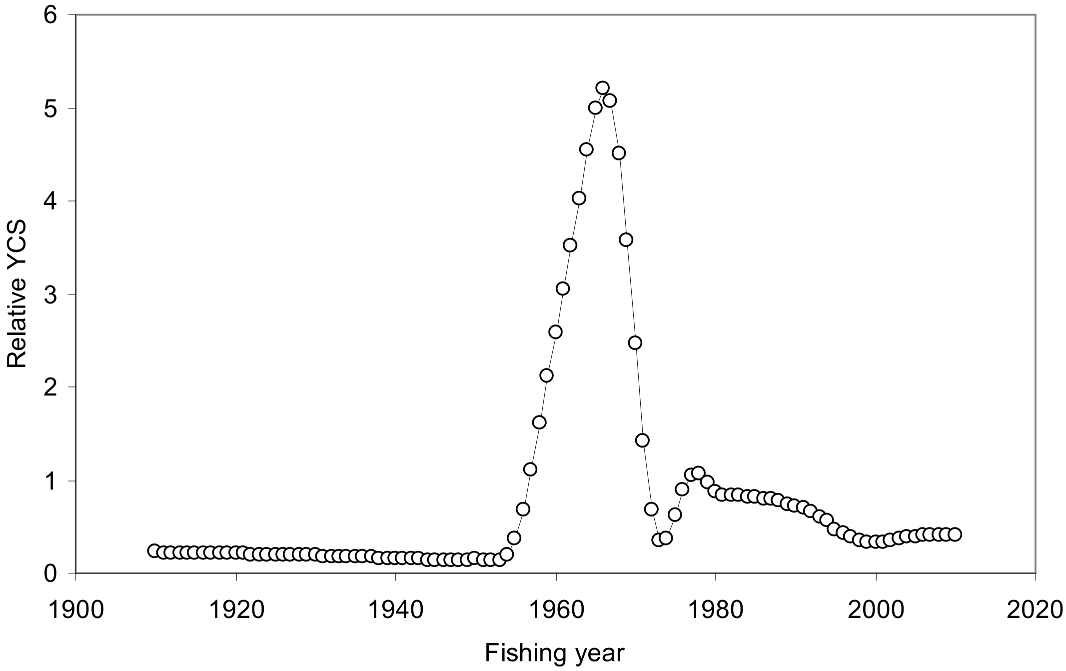


Figure A13.6: Model ABC model run estimating recruitment, fitted to only the trawl survey observations, acoustic biomass estimates, and CPUE indices. Estimated year class strength (YCS).