Fitting to catch-at-age data for North Pacific common minke whales in the Pacific side of Japan

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ABSTRACT

The catch-at-age data for common minke whales in the western North Pacific provided by the JARPN/JARPNII program are used to refine existing RMP *Implementation Simulation Trials (ISTs)* in a simple way, so as to investigate the relative plausibility of the single- and two (Ow and Oe) stock hypotheses for the O whales in the Pacific side of Japan. While the single stock scenario seems consistent with these age data, it is difficult to reconcile the two stock hypothesis with these data because of the relative absence of particularly younger whales in a supposedly separate discrete Oe stock. The analysis demonstrates the importance for management purposes of obtaining age data for the minke whales in the western North Pacific, which in turn necessitates lethal sampling. Such age data need to be incorporated in the conditioning of revised RMP *ISTs* for common minke whales in this region.

INTRODUCTION

Despite considerable investment in the analyses of genetic and non-genetic data, different views remain in the IWC Scientific Committee (IWC SC) on the plausibility or otherwise of sub-structure within the O stock of common minke whales in the Pacific side of Japan. In terms of the RMP trials for common minke whales in the western North Pacific, there could be only one stock (hypothesis A), or there could be two: a coastal (Ow) and an offshore (Oe) stock (hypothesis C) (IWC, 2014). This distinction has important implications for management, particularly as regards sustainable catches of O minke whales in coastal regions in the Pacific side of Japan, as these could be set much higher if the two-O-stock scenario of hypothesis C could be refuted. In the trials, most of the 'Unacceptable Trials' were under the stock scenario of the hypothesis C (IWC, 2014).

The recent availability of age data from the JARPN and JARPNII catches of these whales (see Maeda *et al*., 2016; SC/F16/JR53) provides a basis to improve the accuracy of the RMP *Implementation Simulation Trials (ISTs)* of IWC (2014) for these minke whales through taking these data into account when conditioning these trials. This document provides a first step in this direction by using these new data in a simple way to examine the plausibility of the Ow-Oe stock scenario, through use of a Statistical-Catch-At-Age (SCAA) assessment approach.

MATERIALS AND METHOD

The data used for these analyses are listed in Appendix A.

The SCAA methodology applied is described in detail in Appendix B. Essentially this methodology takes inputs from the hypotheses A and C for the baseline $MSYR_{mat}$ 1% and 4% trials, conditions on their 2000 estimates of mature female abundance, and fits to the historical catch and JARPN/JARPNII catch-at-age data to determine pre-exploitation abundances and selectivity-at-age vectors over the period of these research permit catches. Note that for the Hypothesis A of a single O stock, it is necessary to allow for different selectivity-at-age vectors for the coastal and offshore regions, given the catch-at-age composition differences between the two (for the earlier period of commercial catches, the assumptions made for the *ISTs* (IWC, 2014) are retained).

RESULTS AND DISCUSSION

Four runs have been carried out, corresponding to trials A01_1, A01_4 (one O stock, $MSYR_{mat}$ of 1% and 4%, respectively) and trials C01_1, C01_4 (Ow and Oe stocks, $MSYR_{mat}$ of 1% and 4%, respectively). Results for these four runs are presented in Table 1 and Figures 1 to 4.

In the Figures, the top row plots shows the trajectories of mature females, followed by total numbers and the catches by gender and region/stock. The second row of plots shows the estimated selectivities for each region/stock. The third and fourth rows show the fit to the catch-at-age data, first aggregated over the years for which data are available and then as bubble plots of the standardised residuals.

The key results from these analyses are the selectivity vector estimates shown in Figures 1-4. For hypothesis A in Figures 1 and 2 (the single O stock scenario), the coastal region (corresponding to that assigned to the postulated Ow stock) selectivity is virtually independent of age, and reflects the presence of the youngest animals in the stock. However these animals are generally absent offshore, where the selectivity vector rises slowly to asymptote only once reaching ages of 20 and greater. This is compatible with the concept of a single stock that is not homogeneously distributed in terms of age, with the younger animals more concentrated in the coastal region. Of course, future revised *ISTs*, which take explicit account of age-specific movement patterns, would need to seek selectivity curves which were all closer to uniform over ages, which might in turn necessitate modifications to the natural mortality-at-age vector that is adopted at present for these trials.

For hypothesis C in Figures 3 and 4, the selectivity curves estimated are very similar to those for hypothesis A, but their interpretation is different, which is important. The near flat selectivity curves for the Ow stock are not problematic – all age groups within a supposedly discrete population are represented. In contrast though, the slowly increasing selectivity curves for the supposedly discrete Oe stock are very difficult to explain. Certainly the youngest whales are missing, and furthermore females up to about age 20 are more heavily under-represented than males. While this might in part be explained by some mature females having entered the Okhotsk Sea before the JARPN/JARPNII sampling further to the southeast took place, the overall under-representation of younger animals is hardly possible to reconcile with the associated hypothesis of a separate Oe stock which would need to reflect reasonable proportions of all age components of the stock.

CONCLUDING REMARKS

These “missing” younger whales from the Oe stock in the two-O-stock hypothesis C scenario raise serious questions about the plausibility of this hypothesis. In future RMP *ISTs*, the conditioning needs to take age-structure data into account to better reflect the underlying dynamics of this population.

This analysis demonstrates the importance for management purposes of obtaining age data for the whales in the region concerned, which necessitates lethal sampling.

ACKNOWLEDGEMENTS

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Maeda, H., Bando, T., Kishiro, T., Kitakado, T. and Kato, H. 2016. Basic information of earplug as age character of common minke whales in western North Pacific. Paper SC/F16/JR53 presented to the JARPNII special permit expert panel review workshop, Tokyo, February 2016 (unpublished).10pp.

Table 1: Results for the four SCAA runs

		A01_1	A01_4	C01_1		C01_4	
Total_nll		1033.42	1033.06	1032.94		1033.73	
Index_nll*	OW	0.00	0.00	0.00		0.00	
	OE			0.00		0.00	
CAA_nll	OW-males	382.06	381.60	382.43		384.49	
	OW-females	259.61	259.71	258.61		257.44	
	OE-males	337.67	337.63	337.75		337.63	
	OE-females	54.08	54.12	54.15		54.18	
MSYR		0.01	0.04	0.01		0.04	
MSYL		0.6	0.6	0.6		0.6	
		O	O	OW	OE	OW	OE
K mature female		11056	9922	3015	8674	2244	8167
z		2.38475	2.37389	2.38475	2.38475	2.37389	2.37389
A		0.12053	0.48523	0.12053	0.12053	0.48523	0.48523

*These contributions are zero because very small values are input for the standard errors of the abundance estimates to force trajectories to hit the abundance value given.

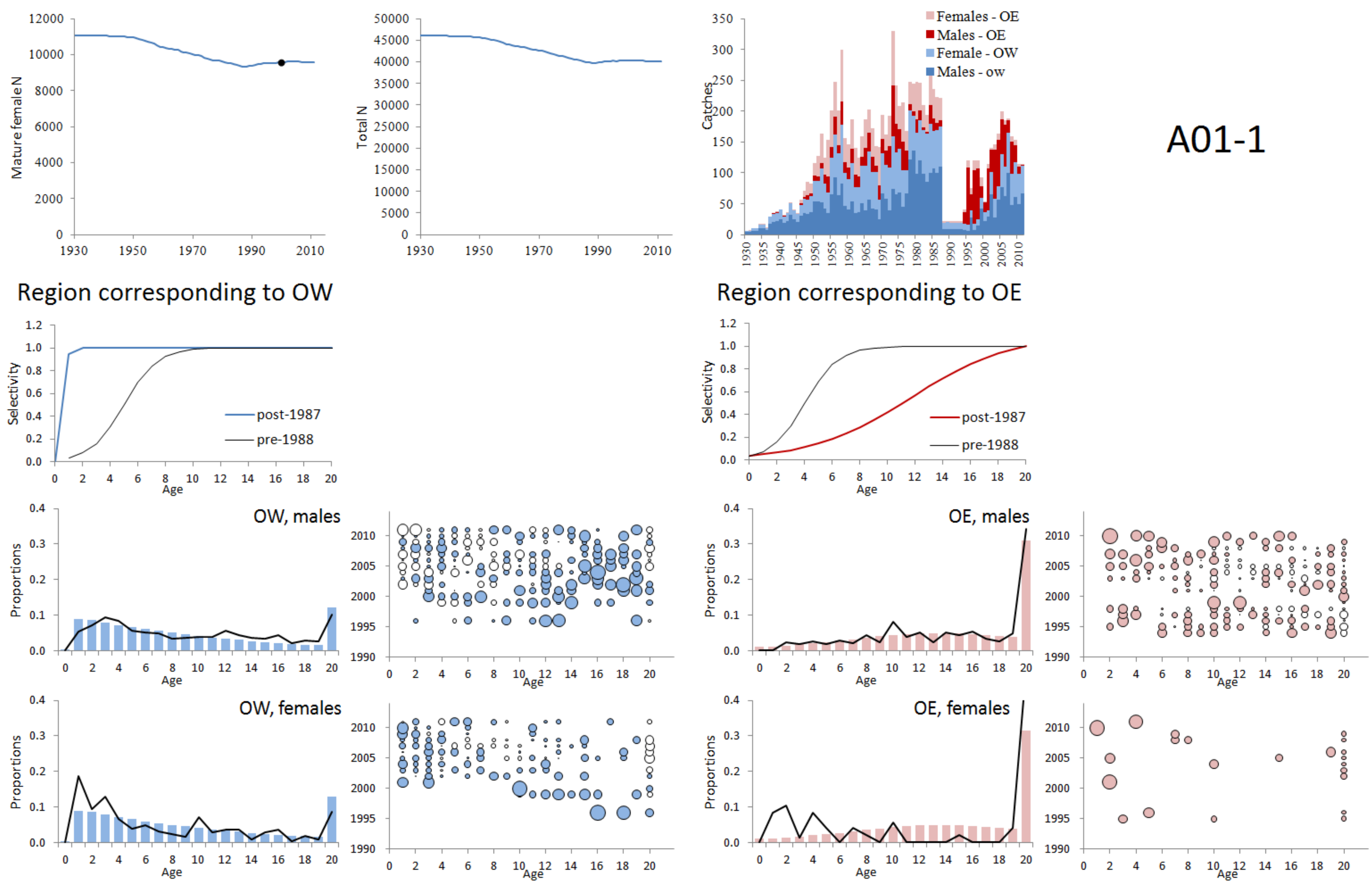

Figure 1: Results for A01_1.

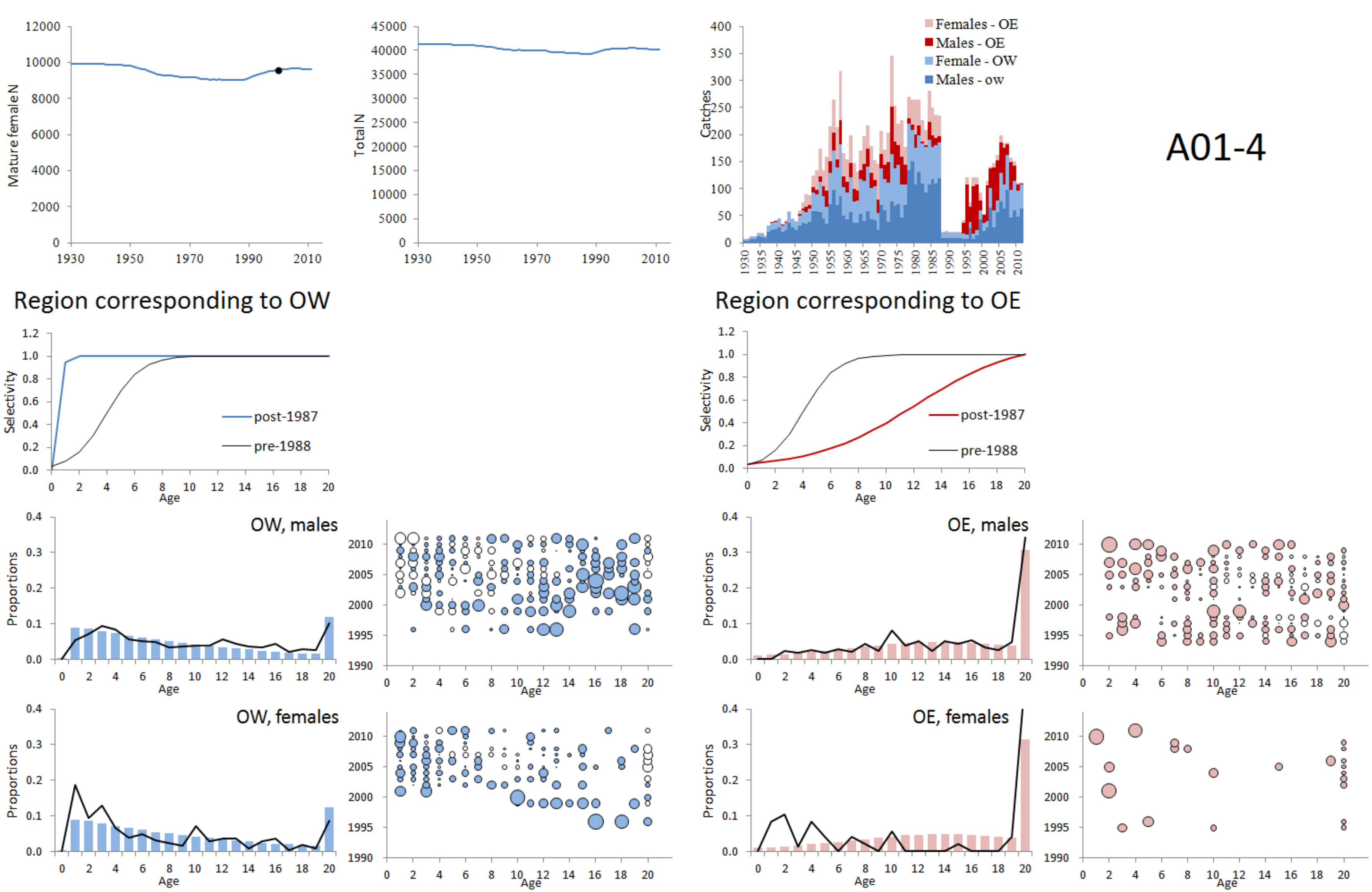

Figure 2: Results for A01_4.

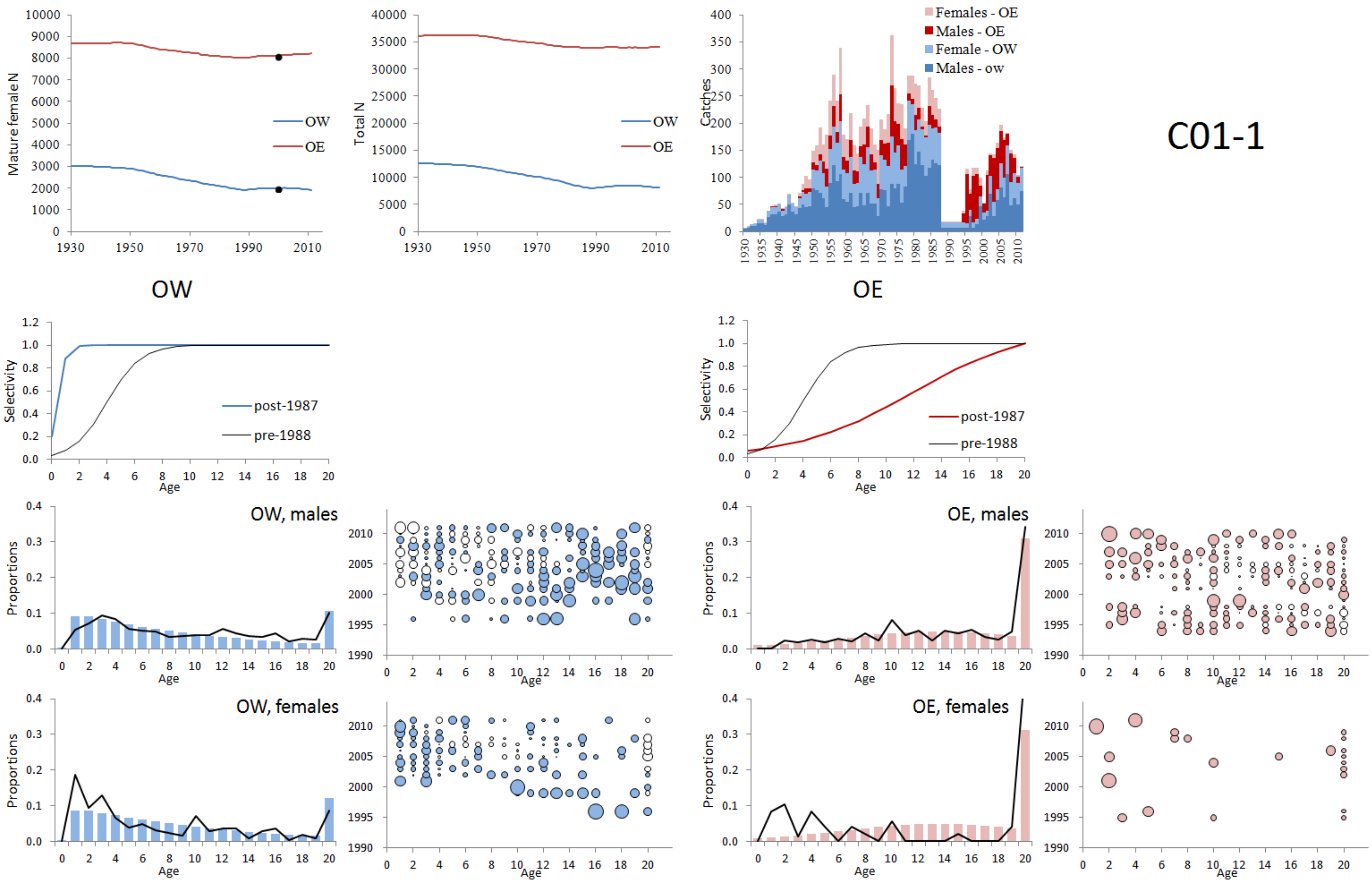

Figure 3: Results for C01_1.

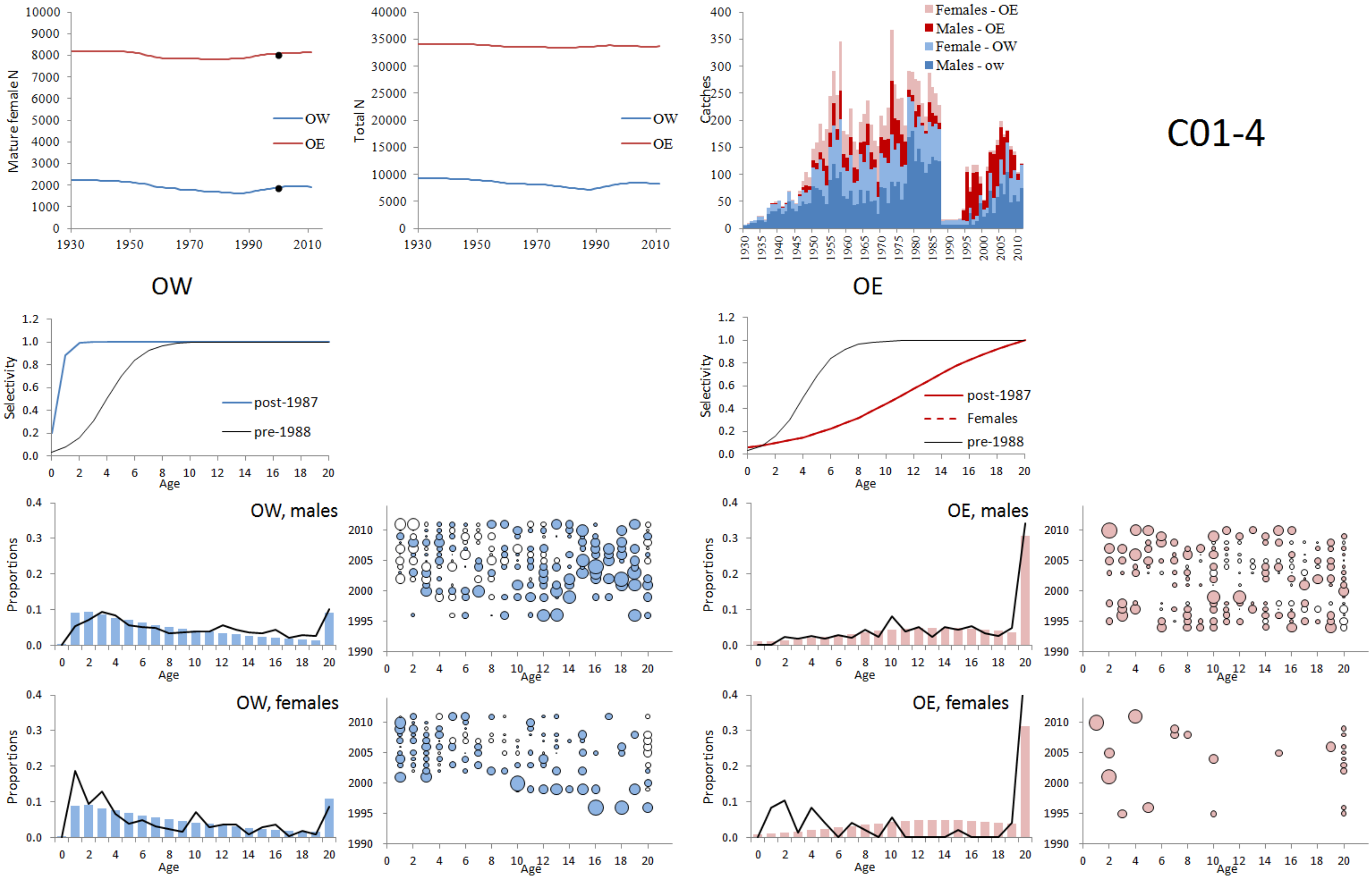

Figure 4: Results for C01_4.

Appendix A - The data

The catches assumed by regions/stocks for males and females separately are given in Table A1 (Cherry Allison, pers. commn). These catches are median outputs from trials A01_1/4 and C01_1/4 which are detailed in IWC (2014). For the one stock hypotheses, the catches for males and females have been split by region corresponding to OW and OE (see details given below), assuming the same OW:OE proportions as those in the corresponding C01_1 and C01_4 trials.

The numbers assumed for mature females in 2000 are provided in Table A2. They correspond to deterministic values for the associated trials, kindly provided by Cherry Allison.

Table A3 gives the males and females catches-at-age from JARPN surveys for the regions corresponding to OW and OE (Luis Pastene, pers. commn). Catches in sub-areas 8, 9 and 7E have been assigned to region/stock OE. Catches in sub-areas 11, 7CN and 7CS have been assigned to region/stock OW. Catches in sub-area 7WR have been assumed to come from region/stock OE if taken east of 145E and OW otherwise.

Table A4 lists the life history parameters used (IWC, 2014), taken to be the same for both stocks in the two-stocks hypothesis.

Table A1: Male and female minke catches assumed for each run (see above for source).

A01_1					A01_4					C01_1					C01_4				
Regions corresponding to:					Regions corresponding to:														
	OW		OE			OW		OE			OW		OE			OW		OE	
	♂	♀	♂	♀		♂	♀	♂	♀		♂	♀	♂	♀		♂	♀	♂	♀
1930	4	2	0	2	1930	4	0	3	0	1930	5	2	0	0	1930	5	2	0	0
1931	4	2	0	3	1931	4	0	2	1	1931	6	2	0	1	1931	6	2	0	1
1932	6	4	0	4	1932	7	0	5	0	1932	10	4	0	0	1932	10	4	0	0
1933	6	5	0	5	1933	7	0	5	0	1933	10	5	0	0	1933	10	5	0	0
1934	10	6	0	7	1934	11	0	6	1	1934	15	6	0	1	1934	15	6	0	1
1935	10	6	0	7	1935	10	1	6	1	1935	15	6	0	1	1935	15	6	1	1
1936	7	4	0	5	1936	8	0	4	1	1936	11	4	0	1	1936	11	4	0	1
1937	18	11	0	11	1937	20	0	12	0	1937	27	11	0	0	1937	27	11	0	0
1938	20	13	1	12	1938	23	1	14	0	1938	31	13	1	0	1938	31	13	1	0
1939	22	13	1	14	1939	24	2	14	2	1939	32	13	2	2	1939	32	13	2	2
1940	25	15	0	15	1940	28	0	16	0	1940	37	15	0	0	1940	37	15	0	0
1941	19	10	1	10	1941	20	2	12	1	1941	28	11	2	1	1941	27	11	2	1
1942	21	13	1	14	1942	23	2	14	2	1942	31	13	1	2	1942	31	13	2	2
1943	32	18	0	19	1943	36	0	20	1	1943	49	19	0	1	1943	49	19	0	1
1944	25	14	0	15	1944	28	0	16	1	1944	37	15	0	1	1944	37	15	0	1
1945	21	13	0	14	1945	24	0	14	1	1945	31	14	0	1	1945	31	14	0	1
1946	30	18	2	23	1946	32	2	19	7	1946	43	19	3	7	1946	42	18	3	7
1947	35	22	3	30	1947	37	4	23	11	1947	50	23	4	11	1947	49	22	5	11
1948	33	23	8	36	1948	35	10	22	23	1948	45	24	11	22	1948	44	23	13	24
1949	36	26	5	37	1949	38	6	26	17	1949	47	26	7	16	1949	46	25	7	17
1950	54	33	9	44	1950	59	11	33	22	1950	80	35	13	21	1950	78	34	14	22
1951	54	33	7	59	1951	58	8	32	36	1951	77	35	10	36	1951	75	34	11	38
1952	52	55	9	94	1952	56	10	56	52	1952	72	58	12	50	1952	71	57	13	53
1953	42	42	14	55	1953	44	17	43	30	1953	61	47	21	31	1953	60	46	23	33
1954	34	34	26	67	1954	34	29	32	63	1954	45	37	34	63	1954	44	35	37	68
1955	66	59	17	101	1955	70	21	59	65	1955	90	63	24	64	1955	89	62	26	68
1956	92	70	29	97	1956	98	34	72	60	1956	122	72	38	57	1956	119	71	41	60
1957	64	68	13	111	1957	69	15	69	61	1957	93	71	19	59	1957	93	71	20	62
1958	83	95	38	140	1958	86	44	96	91	1958	106	98	49	86	1958	104	97	53	92
1959	47	53	18	73	1959	49	21	53	42	1959	60	55	23	40	1959	59	54	25	43
1960	41	49	18	69	1960	43	20	50	41	1960	55	52	24	40	1960	54	52	25	43
1961	54	63	23	87	1961	56	27	64	52	1961	71	66	31	50	1961	70	65	33	53
1962	35	41	21	64	1962	36	23	41	47	1962	44	43	26	46	1962	43	42	28	48
1963	36	42	16	57	1963	37	18	41	35	1963	46	44	21	33	1963	45	43	22	36
1964	51	61	14	80	1964	53	17	64	37	1964	71	66	20	36	1964	71	66	22	38
1965	39	73	29	90	1965	39	32	75	51	1965	48	76	36	48	1965	47	76	38	51
1966	57	79	30	86	1966	59	33	82	42	1966	71	84	38	40	1966	70	84	40	43
1967	42	59	25	80	1967	42	28	58	50	1967	51	61	30	48	1967	49	60	32	51
1968	40	61	10	84	1968	42	11	63	36	1968	52	62	13	33	1968	51	62	14	35
1969	25	32	23	71	1969	24	25	31	65	1969	29	32	26	63	1969	27	31	28	66
1970	66	65	24	80	1970	69	27	67	43	1970	78	63	28	38	1970	76	63	29	40
1971	58	55	23	58	1971	60	26	57	29	1971	76	56	30	27	1971	75	56	32	28
1972	39	69	35	84	1972	39	38	72	55	1972	47	74	42	54	1972	46	75	45	58
1973	75	85	81	93	1973	76	87	88	94	1973	87	88	95	92	1973	86	88	98	95
1974	66	67	47	82	1974	68	51	69	65	1974	79	67	57	62	1974	78	67	58	64
1975	68	70	32	76	1975	71	36	73	40	1975	87	71	41	38	1975	86	71	43	39
1976	45	59	47	75	1976	46	51	61	68	1976	53	61	56	65	1976	53	61	59	68
1977	66	39	32	38	1977	69	36	39	33	1977	83	37	40	30	1977	82	36	42	31
1978	122	80	10	106	1978	135	11	85	38	1978	168	73	14	33	1978	168	75	14	34
1979	136	56	8	92	1979	150	10	58	46	1979	180	54	11	42	1979	181	54	12	43
1980	99	66	22	105	1980	107	25	68	65	1980	124	63	28	58	1980	124	63	29	60
1981	120	65	17	92	1981	131	20	66	48	1981	147	60	21	41	1981	147	60	22	43
1982	99	70	4	103	1982	110	4	74	39	1982	122	66	5	35	1982	123	67	5	36
1983	85	78	3	103	1983	93	4	83	29	1983	102	72	3	26	1983	102	74	4	26
1984	100	79	30	104	1984	108	33	82	58	1984	118	78	35	54	1984	119	78	36	55
1985	108	60	20	88	1985	117	22	60	51	1985	132	58	25	47	1985	132	57	25	48
1986	100	70	12	99	1986	109	13	71	43	1986	125	67	15	40	1986	126	67	15	41
1987	110	64	11	89	1987	119	12	66	37	1987	123	59	12	33	1987	124	59	12	33
1988	9	11	0	13	1988	8	0	10	2	1988	7	9	0	2	1988	6	8	0	2
1989	9	11	0	13	1989	9	0	11	2	1989	7	10	0	2	1989	6	9	0	2
1990	9	11	0	13	1990	8	0	10	2	1990	7	9	0	2	1990	6	9	0	2
1991	9	11	0	13	1991	8	0	11	1	1991	7	9	0	2	1991	6	9	0	1
1992	9	11	0	13	1992	8	0	11	1	1992	7	9	0	2	1992	6	9	0	1
1993	9	11	0	13	1993	8	0	10	2	1993	7	9	0	2	1993	7	9	0	2
1994	7	10	19	-4	1994	7	20	10	5	1994	7	9	18	4	1994	6	9	18	4
1995	6	10	93	-72	1995	6	93	9	12	1995	6	9	91	10	1995	6	8	91	10
1996	27	12	27	-6	1996	27	27	12	9	1996	29	11	29	9	1996	28	11	29	9
1997	7	10	88	-63	1997	7	88	10	15	1997	7	9	87	14	1997	7	9	87	14
1998	14	10	83	-60	1998	14	83	10	13	1998	14	10	82	12	1998	14	9	82	12
1999	42	17	19	13	1999	43	18	17	14	1999	47	17	21	15	1999	46	16	20	14
2000	21	15	16	0	2000	21	16	15	1	2000	22	13	16	1	2000	22	13	16	1
2001	29	11	67	-48	2001	29	67	11	8	2001	29	10	66	8	2001	29	10	67	8
2002	65	37	36	4	2002	64	36	37	3	2002	69	33	39	3	2002	69	33	39	3
2003	28	30	80	-42	2003	28	80	31	8	2003	28	26	81	7	2003	29	27	81	7
2004	57	22	74	-42	2004	56	74	22	10	2004	58	20	76	9	2004	58	20	76	9
2005	77	53	57	9	2005	77	56	53	13	2005	81	45	60	11	2005	82	45	60	11
2006	63	46	68	-14	2006	63	67	46	7	2006	63	37	68	6	2006	63	37	68	6
2007	100	65	21	46	2007	98	21	64	2	2007	106	52	22	2	2007	105	53	22	2
2008	48	51	52	7	2008	47	51	51	8	2008	48	43	53	7	2008	48	44	53	7
2009	61	56	28	36	2009	60	27	55	8	2009	61	46	28	7	2009	61	46	28	7
2010	49	49	12	41	2010	47	12	48	4	2010	49	40	12	3	2010	49	40	12	3
2011	33	30	34	14	2011	63	1	45	2	2011	24	74	25	44	2011	74	44	1	2

Table A2: Number of mature females in 2000 (Cherry Allisson, pers. commn).

		Year	Number of mature females
A01_1:	O	2000	9562
A01_4:	O	2000	9581
C01_1:	OW	2000	2000
	OE	2000	8119
C01_4:	OW	2000	1894
	OE	2000	8071

Table A3: Catch-at-age data from JARPN surveys for regions corresponding to OW and OE.

Region OW, males

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1996	0	0	2	0	0	1	2	0	1	2	0	1	3	3	0	0	0	0	0	1	2
1999	0	0	0	0	1	1	3	0	1	2	2	3	2	1	4	0	1	1	0	0	5
2000	0	0	0	2	1	1	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0
2001	0	0	0	2	0	1	0	0	0	0	2	1	1	1	1	0	0	0	1	1	4
2002	0	1	2	1	3	0	0	1	1	0	0	1	3	0	3	0	2	2	4	0	6
2003	0	1	2	2	0	0	0	0	1	0	0	0	1	0	0	1	1	0	0	1	0
2004	0	2	0	1	2	1	2	4	0	2	2	2	2	2	1	1	6	0	0	1	0
2005	0	2	2	4	7	3	0	4	1	1	2	3	1	1	0	6	0	3	1	2	3
2006	0	4	5	4	4	3	1	0	2	3	2	1	1	0	2	0	2	2	2	0	5
2007	0	2	2	4	6	6	4	0	2	4	1	3	4	0	0	2	3	4	2	2	5
2008	0	2	5	3	4	0	1	1	0	0	0	0	0	0	0	1	1	0	1	0	1
2009	0	5	2	3	4	3	1	1	1	0	2	0	1	1	1	1	1	0	0	0	6
2010	0	2	2	2	2	1	1	1	0	0	2	1	1	0	1	2	0	0	1	0	2
2011	0	1	1	3	4	4	3	2	5	4	0	1	1	4	2	0	1	0	0	2	3

Region OW, females

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1996	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	2
1999	0	0	0	0	0	0	0	0	0	0	1	1	2	3	1	2	1	0	0	1	1
2000	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1
2001	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	1	2	1	0	1	0	2	1	0	0	0	1	0	1	0	0	0	0	2
2003	0	2	2	2	1	2	0	2	0	0	1	1	1	0	0	0	0	0	0	0	1
2004	0	3	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
2005	0	4	5	4	2	0	2	4	0	1	1	2	1	1	0	2	1	0	1	0	1
2006	0	2	0	6	3	4	0	3	0	0	1	0	0	1	0	0	0	0	1	0	1
2007	0	5	5	5	2	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	1
2008	0	3	3	3	5	0	1	0	1	1	0	1	1	1	0	2	0	0	0	1	1
2009	0	6	4	1	2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
2010	0	6	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
2011	0	2	4	0	1	5	4	0	2	1	0	0	1	1	0	0	0	1	0	0	2

Region OE, males

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1994	0	0	0	0	0	0	1	0	1	1	1	0	0	0	1	0	2	0	0	2	2
1995	0	0	1	0	0	0	2	1	3	2	3	3	3	0	1	0	2	3	2	3	5
1996	0	0	0	1	0	0	0	0	1	0	0	1	0	0	1	1	1	0	0	1	3
1997	0	0	0	2	4	0	1	2	3	0	4	3	2	5	3	2	2	1	1	0	6
1998	0	0	1	2	1	0	1	0	1	0	3	2	3	2	2	1	1	3	0	1	10
1999	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1
2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
2001	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	1	4	0	1	12
2002	0	0	0	0	0	0	0	0	1	0	2	0	0	0	2	0	2	1	3	2	8
2003	0	0	1	1	2	1	1	2	3	0	1	0	2	2	5	2	2	1	0	0	18
2004	0	0	0	0	1	1	0	0	1	0	3	1	0	1	3	4	1	0	1	3	11
2005	0	0	1	1	0	2	1	2	0	1	0	1	1	1	1	1	1	1	2	2	8
2006	0	0	0	0	3	0	0	1	3	1	3	1	1	0	0	0	2	1	0	0	8
2007	0	0	1	1	0	1	0	0	1	2	1	1	0	0	0	0	0	0	1	1	7
2008	0	0	0	0	0	1	3	2	0	0	1	1	1	0	2	3	1	1	1	2	7
2009	0	0	0	0	0	0	1	0	0	0	2	0	1	0	1	0	0	0	0	0	4
2010	0	0	2	0	1	1	0	0	0	0	0	1	0	1	0	2	1	0	0	0	0

Region OE, females

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1995	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	4
1996	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2001	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2004	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
2005	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
2006	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
2008	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	2
2009	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3
2010	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2011	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A4: Life history parameter values (as defined for the trials detailed in IWC(2014)).

Parameter	Value	
Age at first parturition	5	
Age-at-50% maturity	7	
Steepness of the ascending limb of the maturity ogive	1.2	
Natural mortality:		
4-	0.085000	
5	0.077500	
6	0.072098	
7	0.066696	
8	0.061295	
9	0.055893	
10	0.050491	
11	0.045089	
12	0.039688	
13	0.034286	
14	0.028884	
15	0.023482	
16	0.018080	
17	0.012679	
18	0.007277	
19	0.001875	
20+	0.115000	
	MSYR=1%	MSYR=4%
Resilience parameter	0.12053	0.48523
Degree of compensation	2.38475	2.37389

Appendix B - The Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the SCAA followed by details of the contributions to the log-likelihood function from the different sources of data available. Quasi-Newton minimization is then applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder™ (Fournier *et al*. 2011) is used for this purpose).

B.1. Population dynamics

B.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N^{g,j}_{y+1,a} = \begin{cases} 0.5 b^{j}_{y+1} & \text{if } a = 0 \\ \left(N^{g,j}_{y,a-1} - C^{g,j}_{y,a-1}\right) S_{a-1} & \text{if } 1 \le a < m \\ \left(N^{g,j}_{y,m-1} - C^{g,j}_{y,m-1}\right) S_{m-1} + \left(N^{g,j}_{y,m} - C^{g,j}_{y,m}\right) S_{m} & \text{if } a = m \end{cases} \qquad \text{(B1)}$$

where

$N^{g,j}_{y,a}$ is the number of animal of gender *g* and age *a* in stock *j* at the start of year *y*,

$C^{g,j}_{y,a}$ is the catch (in number) of animal of gender *g* and age *a* in stock *j* during year *y*,

b^{j}_{y} is the number of calves born to females from stock *j* at the start of year *y*,

S_a is the survival rate $= e^{-M_a}$ where M_a is the instantaneous rate of natural mortality (assumed to be independent of stock and gender),

$m = 20$ is the maximum age (treated as a plus-group).

B.1.2. Births

Density-dependence is assumed to act on the female component of the mature population.

$$b^{j}_{y} = B^{j} N^{f,j}_{y} \left\{ 1 + A^{j} \left[1 - \left(N^{f,j}_{y} / K^{f,j} \right)^{z^{j}} \right] \right\} \qquad \text{(B2)}$$

where

B^{j} is the average number of births (of both genders) per year for a mature female in stock *j* in the pristine population,

A^{j} is the resilience parameter for stock *j* (see Table A4),

z^{j} is the degree of compensation for stock *j* (see Table A4),

$N^{f,j}_{y} = \sum_{a} f^{f,j}_{a} N^{f,j}_{y,a}$ is the number of mature' females in stock *j* at the start of year *y*,

a_m is the age-at-first parturition (see Table A4);

$f^{f,j}_{a}$ is the proportion of mature female of age *a* in stock *j*,

$K^{f,j}$ is the number of mature females in stock *j* in the pristine population.

B.1.3. Total catch and catches-at-age

The catch-at-age is given by:

$$C_{y,a}^{g,j} = F_y^{g,j} v_{y,a}^{g,j} N_{y,a}^{g,j} \qquad \text{(B3)}$$

where

$C_{y,a}^{g,j}$ is the catch-at-age, i.e. the number of animal of gender *g* and age *a* in stock *j* caught during year *y*,

$v_{y,a}^{g,j}$ is the commercial selectivity of an animal of gender g and age *a* in stock *j* for year *y*; when $v_{y,a}^{g,j} = 1$, the age-class *a* is said to be fully selected,

$F_y^{g,j} = \dfrac{C_y^{g,j}}{\sum_a v_{y,a}^{g,j} N_{y,a}^{g,j}}$ is the proportion of a fully selected age class that is caught , and

B.1.4. Initial conditions

For the first year (y_0) considered in the model (here 1930), the numbers-at-age are taken to be at unexploited equilibrium, i.e.:

$$N_{y_0,a}^{g,j} = \begin{cases} 0.5 B^j K^{f,j} & \text{for } a = 0 \\ N_{y0,a-1}^{g,j} S_{a-1} & \text{for } 1 \le a \le m-1 \\ N_{y0,m-1}^{g,j} S_{m-1} / (1 - S_m) & \text{for } a = m \end{cases} \qquad \text{(B4)}$$

B.2. The likelihood function

The model is fitted to estimates of mature female numbers and catch-at-age data to estimate model parameters. Contributions by each of these to the negative of the log-likelihood (- $\ell\text{n}L$) are as follows.

B.2.1 Estimates of mature female numbers

$$-\ell\text{n}\, L^{\text{abund}} = \sum_j \left\{ \ell\text{n}\sigma + \frac{\left(\varepsilon_y^j\right)^2}{2(\sigma)^2} \right\} \qquad \text{(B5)}$$

with

$$\varepsilon_y^j = \ell\text{n}\left(I_y^j\right) - \ell\text{n}\left(\sum_a f_a^{f,j} N_{y,a}^{f,j} \right) \qquad \text{(B6)}$$

where

I_y^j is the estimate of mature female numbers in year *y* and stock *j*, and

$\sigma = 0.01$ (i.e. sufficiently low to force an exact fit to I_y^j)

B.2.2. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of a multinomial error distribution is given by:

$$-\ell\text{n}\, L^{\text{CAA}} = \sum_{j,y,g} \sum_a -p_{y,a}^{g,j} \ln \left(\frac{\hat{p}_{y,a}^{g,j}}{\sum_{a'} \hat{p}_{y,a'}^{g,j}} \right) \qquad \text{(B7)}$$

where

$p_{y,a}^{g,j}$ is the observed number of whale of age *a* and gender *g* caught in year *y* in stock j,

$\hat{p}_{y,a}^{g,j}$ is the model-predicted number of whale of age *a* and gender *g* caught in year *y* in stock j,

where

$$\hat{p}_{y,a}^{g,j} = F_y^{g,j} v_{y,a}^{g,j} N_{y,a}^{g,j} \qquad \text{(B8)}$$

The standardised residuals are computed as:

$$\varepsilon_{y,a}^{g,j} = \frac{p_{y,a}^{g,j} \Big/ \sum_{a'} p_{y,a'}^{g,j} - \hat{p}_{y,a}^{g,j} \Big/ \sum_{a'} \hat{p}_{y,a'}^{g,j}}{\sigma_{y,a}^{g,j}} \qquad \text{(B9)}$$

with

$$\sigma_{y,a}^{g,j} = \frac{p_{y,a}^{g,j} \dfrac{\hat{p}_{y,a}^{g,j}}{\sum_{a'} \hat{p}_{y,a'}^{g,j}} \left(1 - \dfrac{\hat{p}_{y,a}^{g,j}}{\sum_{a'} \hat{p}_{y,a'}^{g,j}} \right)}{\sum_{a'} p_{y,a'}^{g,j}} \qquad \text{(B10)}$$

B.3. Harvesting selectivity

Fishing selectivities-at-age are estimated using a logistic form:

$$v_a^j = \left(1 + e^{(\Delta^j - a)/\delta^j} \right)^{-1} \qquad \text{(B11)}$$

The selectivities are taken to be the same for males and females. Pre-1988, the selectivities are taken to be the same for the two regions/stocks, with the parameters fixed: $\Delta^j = 4$ and $\delta^j = 1.2$ (i.e. as for the trials detailed in IWC (2014)). Post-1988, the selectivities are estimated separately for the two regions/stocks.