Assessing the Bering-Chukchi-Beaufort Seas stock of bowhead whales using abundance data together with data on length or age

ANDRÉ E. PUNT

University of Washington, School of Aquatic and Fishery Sciences, Box 355020, Seattle, WA 98195, USA

Contact e-mail: aepunt@u.washington.edu

ABSTRACT

The 1998 assessment of the Bering-Chukchi-Beaufort (B-C-B) Seas stock of bowhead whales (*Balaena mysticetus*) was conducted using a Bayesian estimation framework. That assessment ignored information on the length-frequency and age-composition of the harvests and the detailed length-frequency information from photogrammetry studies. The modelling framework used to assess the B-C-B Seas bowhead whales is therefore extended to make use of these data. The results indicate that selectivity is not uniform, as assumed in previous assessments, but rather domed-shaped, with young animals most vulnerable to harvest. The length-frequency, proportion, age-composition and abundance data are inconsistent to some extent. Fitting the model to the age-composition data leads to the most pessimistic estimates of stock status and productivity. The results of projections based on these assessments in which strike limits are set using the *Bowhead Strike Limit Algorithm* (*SLA*) suggest that none of the data sets are such that the scenarios considered when testing the *Bowhead SLA* should now be considered implausible.

KEYWORDS: BOWHEAD WHALE; ARCTIC; ABORIGINAL WHALING; AGE DATA; LENGTH DATA; MODELLING; ABUNDANCE ESTIMATE

INTRODUCTION

The 1998 assessment of the Bering-Chukchi-Beaufort (B-C-B) Seas stock of bowhead whales (*Balaena mysticetus*) was based on fitting the age- and sex-structured population dynamics model, Baleen II (de la Mare, 1989; Punt, 1999b), to data on population counts and the proportion of calves and mature animals in the population in 1988/89 (IWC, 1999). This assessment was based on Bayesian techniques, using the 'backwards' (Butterworth and Punt, 1995; Punt and Butterworth, 1999) and 'full pooling' (Poole and Raftery, 1998) methods.

The Scientific Committee (SC) of the International Whaling Commission (IWC) has recommended a *Strike Limit Algorithm* (*SLA*) for the B-C-B Seas stock of bowhead whales (IWC, 2003a). This implies that it is no longer necessary to conduct regular traditional stock assessments to provide management advice for setting catch limits. However, it is nevertheless worthwhile to continue to conduct assessments to evaluate whether the scenarios on which the *Bowhead SLA* was based remain plausible given the implications of recent data and analyses.

In this context, there are several potential sources of information that have not been included explicitly in recent assessments of the B-C-B Seas bowhead whales. In particular: (1) the information on length-at-age (George *et al.*, 1999; J. Zeh, pers. comm.); (2) the length-frequency of the early harvests (e.g. Bockstoce and Botkin, 1983; Bockstoce and Burns, 1993); (3) the length-frequency of the recent harvests (e.g. Braham, 1995; Punt *et al.*, 2003; Suydam and George, 2004; George, pers. comm.); (4) the length-frequency of the population in recent years (e.g. Angliss *et al.*, 1995; Koski *et al.*, 2006); and (5) the estimates of abundance from photogrammetry (e.g. da Silva *et al.*, 2000; Schweder, 2003) were not included in the likelihood function used when estimating model parameters during the 1998 assessment.

Some of these data have been examined before. For example, George *et al.* (1999) speculated that the 'gap' in the age-frequency distribution (roughly between ages 70 and 135) may be due to the large removals during the period of commercial whaling (approximately 1848–1910). Additionally, Bockstoce and Burns (1993) noted that 'the largest whales were taken in the earliest years of the fishery, although paradoxically, one or two very big whales were taken in the last years', and Schweder and Ianelli (2000) noted that the formulation of the Baleen II model applied for the 1998 assessment is unable to mimic the age-frequency data adequately. Schweder (2003) noted that the estimate of abundance based on the photo-identification data is consistent with the estimates of abundance from visual and acoustic methods. The analyses of this paper do not use the photo-identification estimate of abundance as it is only a single datum. Likewise, the early length-frequency information is ignored because lengths[1] are available for only 333 of the 3,198 animals in the database constructed by Bockstoce and Botkin (1983).

Schweder and Ianelli (2000), in common with all assessments of the B-C-B bowhead stock in recent years, assumed that the harvest is taken randomly from the animals aged one and older. In contrast, Punt *et al.* (2003) showed that the length-frequency of the catch varies by village and that the fraction of the catch taken by each village has changed over time.

Age- and length-composition data are used in conventional fisheries stock assessments for two main reasons: (a) to estimate the strength of recent cohorts; and (b) to determine the selectivity pattern of the harvest[2]. The sample sizes for the B-C-B Seas bowhead whales are much too small to expect that it will be possible to estimate even patterns in historical recruitment adequately. However, the length-frequency information can potentially inform assumptions regarding the selectivity pattern of the harvest. This paper therefore develops a variant of the Baleen II model that can include age- and length-composition data as well as proportion and abundance data in a single modelling framework and in which the selectivity pattern of the harvest need not be uniform above some pre-specified age. The

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[1] Actually the number of barrels of oil produced.

[2] Selectivity in this context is the combined effect of hunter behaviour and the availability of whales of different sizes/ages to the hunters.

estimation is based on the 'backwards' approach to Bayesian analysis which was used for the 1998 assessment of the B-C-B Seas bowhead whales and on which the trials used to evaluate alternative *SLAs* for this stock were conditioned (e.g. IWC, 2003a).

METHODS

Basic formulation

Each data source is included separately in the assessment using a length-based Synthesis approach (Smith and Punt, 1998; Methot, 2000). The population dynamics model underlying the analyses is identical to the standard Baleen II model, except that account is taken of length-specific selectivity. The probability of harvesting an animal of age *a* and sex *s* during year *y*, $p^s_{y,a}$, depends on the relative frequency of animals of age *a* and sex *s* in the population and the selectivity on animals of age *a* and sex *s*, i.e.:

$$p^s_{y,a} = \frac{S^s_a N^s_{y,a}}{\sum_{a'} S^s_{a'} N^s_{y,a'}} \qquad (1)$$

where

$N^s_{y,a}$ is the number of animals of age *a* and sex *s* at the start of year *y*,

S^s_a is selectivity as a function of age and sex (S^s_0 is set equal to zero for all of the analyses of this paper to reflect the fact that calves are not harvested):

$$S^s_a = \frac{\sum_L S_L X^s_{a,L}}{\max_{a'} \sum_{L'} S_{L'} X^s_{a',L'}} \qquad (2)$$

S_L is selectivity as a function of length,

$X^s_{a,L}$ is the proportion of animals of sex *s* and age *a* in length-class *L* i.e.:

$$X^s_{a,L} = \int_{\bar{L}-\Delta L}^{\bar{L}+\Delta L} \frac{1}{\sqrt{2\pi}\sigma^s \ell} \exp\left(-\frac{(\ell n\ell - \ell n\ell^s_a)^2}{2(\sigma^s)^2} \right) d\ell \qquad (3)$$

$\bar{L}$ is the average of the upper and lower limits of size-class *L*,

ΔL is half the width of a length-class (taken here to be 25cm),

ℓ^s_a is the length of a bowhead of age *a* and sex *s* and

σ^s is (approximately) the coefficient of variation of length-at-age for animals of sex *s*.

Data to estimate selectivity-at-length are only available for recent years, so selectivity is assumed to be uniform for the period 1848–1914.

Length-at-age for animals aged 1 and older is based on the Schnute (1981) formulation i.e.:

$$\ell^s_a = \left((\ell^s_1)^{\beta^s} + ((\ell^s_{40})^{\beta^s} - (\ell^s_1)^{\beta^s}) \frac{1-\exp[-\kappa^s(a-1)]}{1-\exp[-\kappa^s\, 39]} \right)^{1/\beta^s} e^{\varepsilon}$$

$$\varepsilon \sim N(0;(\sigma^s)^2) \qquad (4)$$

where

κ^s is a growth rate parameter for animals of sex *s*,

β^s is a shape parameter for animals of sex *s* and

σ^s determines the extent of variation about the mean length-at-age for animals of sex *s*.

The estimable parameters of this growth model are the lengths at ages 1 and 40 (ages chosen to encompass the bulk of the ages represented in the length-at-age data set), κ, β and σ. The mean length of a calf is set to 4.54m, the mean length of calves in the data set analysed by Koski *et al.* (2006). This assumption is, however, inconsequential for the analyses of this paper because the population dynamics model is fitted to data for animals aged 1 and older only.

The values for the parameters of Eq. (4) are determined by maximising the following likelihood function:

$$L = \prod_s \prod_a \prod_i \frac{1}{\sqrt{2\pi}\sigma^s \tilde{L}^{s,i}_a} e^{-\frac{(\ell n\tilde{L}^{s,i}_a - \ell n\ell^s_a)^2}{2(\sigma^s)^2}} \qquad (5)$$

where

$\tilde{L}^{s,i}_a$ is the observed length of the *i*th animal of age *a* and sex *s* in the data set on length-at-age.

The measurements of the lengths of animals in the catch (and hence in the data set on which the growth model is based) exceed the actual lengths of these animals owing to the impact of stretching. Therefore, when fitting the growth model (and for all other uses of the catch length data), the lengths are multiplied by 0.918 (George *et al.*, 2004a).

Likelihood function

As noted above, there are several potential sources of data that could be used in an assessment of the B-C-B Seas stock of bowhead whales. The data used in the analyses of this paper are: (a) the annual catches (Table 1); (b) the estimates of abundance from visual and acoustic surveys at Point Barrow, Alaska (Table 2); (c) the information on the fraction of calves and mature animals in the population in 1988-89[3]; (d) the length-frequency from the surveys during 1985-1994; and (e) the age-composition of the catches during 1973-92.

The indices of abundance are based on data collected from visual and acoustic surveys at Point Barrow, Alaska (see George *et al.*, 2003; 2004b for a brief summary of the history and methods of the studies). Estimates of the number of animals passing within the 4km visual range from the observation 'perch' from which whales are counted are combined with estimates of the proportion of whales which passed within this range using a model in which the proportion within visual range is treated as a random effect (Zeh and Punt, 2005). The contribution of the abundance data to the negative of the logarithm of the likelihood function (ignoring constants independent of the model parameters) is:

$$-\ell nL_1 = 0.5 \sum_{y_1} \sum_{y_2} (\ell n\hat{N}_{y_1} - \ell nN^{obs}_{y_1})^T \Sigma^{-1}_{y_1,y_2} (\ell n\hat{N}_{y_2} - \ell nN^{obs}_{y_2}) \qquad (6)$$

where

N^{obs}_y is the N_4/P_4 estimate for year *y*,

$\hat{N}_y$ is the model estimate of 1+ abundance for year *y*[4] and

Σ is the variance-covariance matrix for the logarithms of the estimates of abundance.

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[3] The data used actually relate to the period 1985-94, but are fitted to the model predictions for 1988-89. This is appropriate given the slow dynamics of the B-C-B Seas bowhead stock.

[4] The estimates of N_4/P_4 actually include some, but not all, calves. Sensitivity tests (not shown here) indicate that the results of assessments are not sensitive to whether the N_4/P_4 estimates are treated as indices of 0+ or 1+ abundance.

Table 1

B-C-B Seas bowhead whale kill, 1848-2004. Values in parenthesis are the catches used in the 1998 assessment where these catches differ from those used in the present assessment.

Year	Total kill	Year	Total kill	Year	Total kill	Year	Total kill
1848	18	1888	160	1928	30	1968	27
1849	573	1889	127	1929	30	1969	32
1850	2,067	1890	136	1930	17	1970	48
1851	898	1891	284	1931	32	1971	25
1852	2,709	1892	346	1932	27	1972	44
1853	807	1893	180	1933	21	1973	51
1854	166	1894	234	1934	21	1974	42
1855	2	1895	117	1935	15	1975	32
1856	0	1896	118	1936	24	1976	74
1857	78	1897	130	1937	53	1977	72
1858	461	1898	309	1938	36	1978	15
1859	372	1899	234	1939	18	1979	20
1860	221	1900	148	1940	20	1980	32
1861	306	1901	55	1941	38	1981	26
1862	157	1902	162	1942	26	1982	14
1863	303	1903	116	1943	14	1983	16
1864	434	1904	86	1944	8	1984	16
1865	590	1905	105	1945	23	1985	14
1866	554	1906	69	1946	20	1986	22
1867	599	1907	96	1947	21	1987	29
1868	516	1908	123	1948	8	1988	28
1869	382	1909	61	1949	11	1989	25
1870	637	1910	37	1950	23	1990	41
1871	138	1911	48	1951	23	1991	47
1872	200	1912	39	1952	11	1992	46
1873	147	1913	23	1953	41	1993	51
1874	95	1914	61	1954	9	1994	39 (38)
1875	200	1915	23	1955	36	1995	56 (57)
1876	76	1916	23	1956	11	1996	42 (45)
1877	270	1917	35	1957	5	1997	62
1878	80	1918	27	1958	5	1998	51
1879	266	1919	33	1959	2	1999	47
1880	480	1920	33	1960	33	2000	42
1881	435	1921	9	1961	17	2001	65
1882	242	1922	39	1962	20	2002	45
1883	42	1923	12	1963	15	2003	37
1884	160	1924	41	1964	24	2004	43
1885	377	1925	53	1965	14		
1886	168	1926	35	1966	24		
1887	240	1927	14	1967	12		

The summations in Eq. (6) are restricted to the years for which estimates of N_4/P_4 are available (Table 2).

The age-composition of the catches for 1973-1992 (Table 3) is assumed to be multivariate normally distributed about the model predictions (Schweder and Ianelli, 2000). Schweder and Ianelli (2000) constructed the age-compositions in Table 3 by first modelling the relationship between length and age based on data for 42 bowhead whales reported in George *et al.* (1999) and then allocating the observed lengths in the catch from 1973-92 (Braham, 1995) to ages using this relationship. The uncertainty associated with the age-compositions was determined by bootstrapping the construction of the age-at-length data. There are, however, some concerns with the basis for the age-composition information provided by Schweder and Ianelli (2000) as detailed below.

(1) Schweder and Ianelli (2000) ignored sex when constructing their age-compositions because George *et al.* (1999) did not identify a statistically significant difference between male and female growth. However, the sample size available to George *et al.* (1999) to estimate growth (42 animals) was small in comparison to the age-length data set on which the analyses of this paper was based. This larger sample size supports different growth curves for males and females. One consequence of ignoring sex when creating the age-composition data was that the fraction of very old (100+) animals was over-estimated (all animals aged to be 100+ were males; the two oldest females were 38 and 69 respectively);

(2) Schweder and Ianelli (2000) mis-interpreted the meaning of animals in George *et al.* (1999) that had negative standard errors.

The age-compositions reported by Schweder and Ianelli (2000) have not been updated for this paper because a primary reason for conducting the analyses reported herein, was to determine the reasons for the inability of the Baleen II model to mimic these data.

Studies attempting to document the length structure of B-C-B Seas bowhead stock using photographic survey methods were conducted near Point Barrow, primarily by scientists from the National Marine Mammal Laboratory, but also by other researchers (Withrow and Angliss, 1992; 1994; Angliss *et al.*, 1995). The surveys were conducted from about mid-April to early June in 1985, 1986 and 1989-92. Less extensive spring surveys were conducted in 1989 and during 1994. A variety of papers have documented the

Table 3

Age-composition data (fraction of the catch in each of six age-groups). Source: Schweder and Ianelli (2000).

Age-range	Estimate	SE	Correlation matrix					
0-20	0.667	0.029	1	-0.55	-0.56	-0.88	-0.83	-0.30
21-40	0.110	0.018	-0.55	1	0.64	0.44	0.06	-0.54
41-60	0.073	0.008	-0.56	0.64	1	0.71	0.25	-0.49
61-80	0.053	0.006	-0.88	0.44	0.71	1	0.76	0.11
81-100	0.035	0.005	-0.83	0.06	0.25	0.76	1	0.62
100+	0.063	0.019	-0.30	-0.54	-0.49	0.11	0.62	1

Table 2

Estimates, CVs (actually standard errors of the logarithms) and the correlation matrix for the indices of abundance for the B-C-B Seas stock of bowhead whales. Source: Zeh and Punt (2005).

Year	Estimate	CV	Correlation matrix										
1978	4,765	0.305	1.000										
1980	3,885	0.343	0.118	1.000									
1981	4,467	0.273	0.056	0.050	1.000								
1982	7,395	0.281	0.094	0.084	0.035	1.000							
1983	6,573	0.345	0.117	0.104	0.049	0.084	1.000						
1985	5,762	0.253	0.070	0.062	0.020	0.078	0.062	1.000					
1986	8,917	0.215	0.072	0.064	0.017	0.092	0.064	0.113	1.000				
1987	5,298	0.327	0.124	0.110	0.052	0.088	0.110	0.065	0.067	1.000			
1988	6,928	0.120	0.028	0.025	0.013	0.017	0.024	0.009	0.007	0.026	1.000		
1993	8,167	0.071	0.001	0.001	0.001	0.000	0.001	-0.001	-0.002	0.001	0.000	1.000	
2001	10,545	0.128	0.008	0.007	0.005	0.001	0.007	-0.004	-0.008	0.008	0.003	0.000	1.000

methods employed (e.g. Koski *et al.*, 2006), but briefly the surveys were conducted from fixed-wing aircraft with search effort focused along open water areas, especially near the land-fast ice edge. A variety of ways exist for analysing the data from these surveys. Two of these are considered in this paper: (a) the approach of Angliss *et al.* (1995); and (b) the 'base case' analysis of Koski *et al.* (2006)[5]. The length-frequency data can be included in the assessment either as the actual length-frequency (Fig. 1) or as the proportion of calves and mature animals (Table 4). The 1998 assessment was based on the second of these alternatives only.

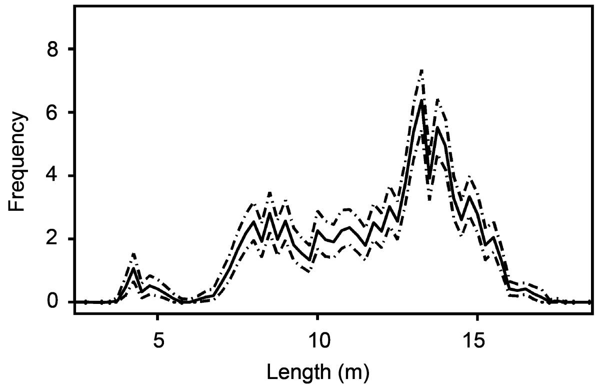

Fig. 1. The photogrammetry-based length-frequency distribution. The lengths are grouped in 25cm length bins. The solid lines denote the estimates on which the analyses of this paper are based and the dashed lines are bootstrap 95% confidence intervals.

Table 4

Proportion of calves and mature animals.

Scenario	P_c	σ_{p_c}	P_m	σ_{p_m}
Koski *et al.* (2006)	0.0339	0.0040	0.3975	0.0100
1998 assessment (IWC, 1998)	0.052	0.0164	0.411	0.0286

The contribution of the fraction of the population that consists of calves and mature animals ('the proportion data') to the negative of the logarithm of the likelihood function is based on the assumptions that these fractions are normally-distributed (Koski *et al.* (2006) data) or *t*-distributed (Angliss *et al.*, 1995 data) i.e.:

$$-\ell nL_2 = \frac{1}{2\sigma_{p_c}^2}(p_c - p_c^{obs})^2 + \frac{1}{2\sigma_{p_m}^2}(p_m - p_m^{obs})^2 \qquad (7a)$$

$$-\ell nL_2 = \frac{6}{2}\ell n(1+\frac{1}{5}\{\frac{p_c - p_c^{obs}}{\sigma_{p_c}}\}^2) + \frac{6}{2}\ell n(1+\frac{1}{5}\{\frac{p_m - p_m^{obs}}{\sigma_{p_m}}\}^2) \qquad (7b)$$

where

p_c^{obs}	is the observed fraction of the population that consisted of calves in 1988/89[3],
σ_{p_c}	is the standard deviation of p_c^{obs},
p_c	is the model-estimate of the fraction of the population that consisted of calves in 1988/89,
p_m^{obs}	is the observed fraction of the population that consisted of mature animals in 1988/89[3],
σ_{p_m}	is the standard deviation of p_m^{obs} and
p_m	is the model-estimate of the fraction of the population that consisted of mature animals in 1988/89.

The survey length-frequency data are assumed to be multinomially distributed about the model predictions i.e.:

$$-\ell nL_3 = -\omega\sum_L \rho_L \ell n(\hat{\rho}_L / \rho_L) \qquad (8)$$

where

ω	is the effective sample size,
ρ_L	is the observed fraction of the length-frequency distribution that is in (25cm) length-class *L* (Fig. 1) and
$\hat{\rho}_L$	is the model-estimate of the fraction of the length-frequency distribution that is in length-class *L* i.e.:

$$\hat{\rho}_L = \frac{\sum_{y=1985}^{1994}\sum_{s}\sum_{a>1} X_{a,L}^{s}\, N_{y,a}^{s}}{\sum_{y'=1985}^{1994}\sum_{s'}\sum_{a'>1} N_{y',a'}^{s'}} \qquad (9)$$

The base-case value for ω is taken to be 2,000 which corresponds roughly to the effective sample size of the proportion-at-length data in Koski *et al.* (2006).

Parameters and priors

The parameters of the population dynamics model are: (a) the total (1+) pre-exploitation size of the resource, K_{1+}; (b) $MSYR_{1+}$; (c) $MSYL_{1+}$; (d) the age-at-sexual-maturity, a_m; (e) the survival rate of adults in the absence of exploitation, $s_{adult} = \exp(-M_{adult})$; (f) the survival rate of juveniles in the absence of exploitation, $s_{juv} = \exp(-M_{juv})$; and (g) the greatest age at which juvenile natural mortality applies, a_T. Rather than placing a prior on s_{juv}, a prior is instead placed on the pregnancy rate in the limit of zero population size, f_{max} and the system of equations that relate f_{max}, $MSYR_{1+}$, $MSYL_{1+}$, s_{juv}, and s_{adult} is solved for s_{juv} and the parameters of the density-dependence function (see Punt (1999b) for details). If the value for s_{juv} is larger than that for s_{adult}, the set of parameters is ignored (implemented by assigning the parameter vector a likelihood of zero).

A prior is not placed on K_{1+}. Instead, a prior is placed on the 1993 1+ population size and the value for K_{1+} calculated so that if the population is projected from unexploited equilibrium in 1848 to 1993, the 1993 1+ population size equals the generated value for N_{1993}^{1+}. This 'backwards' approach to parameterising the Baleen II model formed the basis for the 1998 assessment of the B-C-B bowhead stock.

In principle, selectivity-at-length could be estimated as part of the model-fitting process. However, this would make the calculations prohibitively time consuming given the approach used to sample parameter vectors from the posterior distribution (the Sample-Importance-Resample, SIR, algorithm). Instead, selectivity-at-length is pre-specified using the length-frequency of recent harvests and the length-frequency of the surveys conducted at Point Barrow. Specifically, the length-specific selectivity pattern on which the analyses are based is determined by taking the ratio of the numbers caught (in 1m length-classes) to the

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[5] Koski *et al.* (2006) provide several length-frequency distributions based on varying the assumptions of their analysis method. Results (not shown here) indicate that the outcomes from the assessment are not notably sensitive to changing these assumptions.

numbers observed during the surveys (also in 1m length-classes) i.e.:

$$S_L = \frac{C_L / V_L}{\max\limits_{L'}(C_{L'} / V_{L'})} \qquad (10)$$

where

C_L is the total catch of animals in 1m length-class L during 1984-95 (the years that encompass those on which the length-frequency distributions are based) (Fig. 2) and

V_L is the fraction of the numbers observed during the surveys in 1m length-class L, based on the surveys conducted during 1985-94 (see Fig. 1).

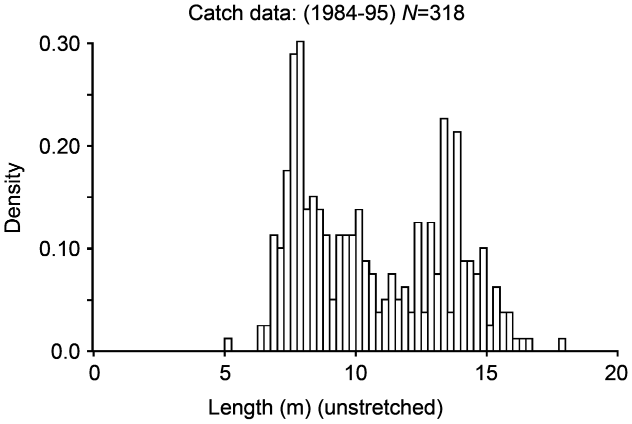

Fig. 2. The catch length-frequency distribution used when defining selectivity-at-length.

Table 5

The prior distributions (IWC, 1998).

Parameter	Prior distribution
$MSYL_{1+}$	U[0.4, 0.8][a]
$MSYR_{1+}$	U[0.01, 0.7][b]
a_T	DU[1, 9][c]
a_m	N(20,3^2), truncated at 13.5 and 26.5[d]
S_{adult}	N(1.059, 0.0378^2) truncated at 0.995 with no constraint on the maximum age[e]
S_{juv}	Constrained by the population dynamics equation to be less than S_{adult}
$f_{\max}$	$1/f_{\max} \sim$ U[2.5, 4][f]
N_{1993}^{1+}	N(7,800, $1{,}300^2$)[g]

[a] Selected to encompass the range of values commonly assumed when conducting assessments of cetacean populations.

[b] Based on reported estimates of the current rate of increase (ROI) for cetacean populations (IWC, 1994); the upper limit is somewhat lower than the upper confidence limit for ROI, while the lower limit is consistent with the range of values used to develop the Aboriginal Whaling Management Procedure.

[c] Selected by the Scientific Committee (SC) of the IWC (IWC, 1995) although there is little information on the value of this paper (Givens *et al.*, 1995).

[d] Based on a best estimate of 20 years and lower confidence intervals for the age-at-maturity of 14 years (IWC, 1995).

[e] See main text for details.

[f] Selected by the SC of the IWC (IWC, 1995).

[g] Selected by the SC of the IWC (IWC, 1995) based on the prior distribution assumed for the Bayes empirical Bayes estimate of abundance (Raftery and Zeh, 1991).

Table 5 lists the priors on which the analyses of this paper are based. These priors are the same as those used for the 1998 assessment, except that the prior placed on the survival rate of adults is set to a truncated normal distribution that mimics the posterior distribution for adult survival rate obtained by Zeh *et al.* (2002). Assuming a maximum survival rate of 0.995 (corresponding to an average age of 200) leads to the prior for adult survival of $N(1.059, 0.0378^2)$ bounded between 0 and 0.995. The 1998 assessment included a case in which there was a maximum lifespan of 100 years (IWC, 1999; Punt, 1999a). However, this case is considered implausible given that the age-composition data include animals aged to be 100+ (Table 3).

Scenarios

Table 6 lists the scenarios considered in this paper. None of the analyses that involve fitting to the survey length-frequency data also involve fitting to the proportion data because the proportion data are based on the survey length-frequency data (see Koski *et al.*, 2006). Similarly, analyses that use the age-composition data ignore the length-frequency data and the proportion data.

RESULTS AND DISCUSSION

Growth curve estimation

The estimates of the values for the parameters of the growth model are listed in Table 7. The results in Table 7 are based on the full (10-parameter, 5 parameters per sex) model. The decision to base the growth curves on which the assessment is based on the full model was supported by application of likelihood ratio tests in which various sub-models were compared; all of the sub-models provided fits that were significantly poorer than the full model at the 5% significance level. Fig. 3 shows the fit of the growth model to the data on length-at-age and Fig. 4 shows the length-at-age distributions obtained using Eq. (4) and the estimates of the parameters of the growth model in Table 7. As expected, the 95% confidence intervals for the data encompass the bulk of the data and the solid lines mimic the central tendency of the data well.

Length-specific selectivity

Selectivity-at-length (Fig. 5) is defined using 1m length-classes even though the population dynamics model uses 25cm size-classes. This is because the sample sizes for some of the 25cm size-classes are very small (see Figs 1 and 2), which would have resulted in highly variable (and hence unrealistic) estimates of selectivity-at-length. The survey and catch length-frequencies are pooled into minus- and plus-groups at 8m and 16m respectively. This reduces the impact of growth during the first years of life and also avoids fitting the model to very small proportions.

Selectivity-at-length is greatest for the smallest (and hence youngest) animals and is relatively constant for animals from 12m. Selectivity-at-length (and hence selectivity-at-age) is markedly different from the ‘uniform from age one’ assumption that underlies past stock assessments of this stock, and most other stocks, of baleen whales, and as well as the operating model used to evaluate *SLAs* for the B-C-B Seas bowhead whales.

Assessment results

Comparison of models that account for and ignore length-specific selectivity

Alternative models for the B-C-B bowhead whales have, in the past, been compared using Bayes factors (Brandon and Wade, 2006). This approach is used to compare models based on the two selectivity patterns. According to the guide to interpreting Bayes factors developed by Kass and Raftery (1995), there is ‘positive’ support (Bayes Factor >3 but <20) for the analysis in which selectivity is based on Fig. 5 when

Table 6

The data-scenarios considered in the analyses of this paper.

Abbreviation	Abundance data	Koski *et al.* (2006) proportions	1998 proportions	Survey length data	Catch-at-age data
With Koski *et al.* (2006) proportions	Yes	Yes	No	No	No
With 1998 proportions	Yes	No	Yes	No	No
With length data	Yes	No	No	Yes	No
With age data	Yes	No	No	No	Yes

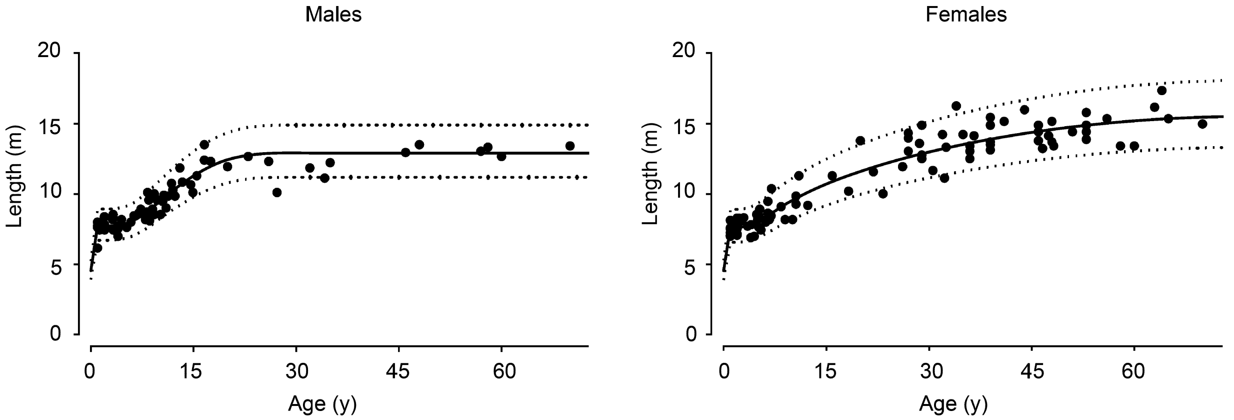

Fig. 3. Fits of the growth model to the data on length-at-age. The solid line is the maximum likelihood estimate and the dotted lines indicate the 95% confidence intervals for an individual data point (i.e. the combined impact of the uncertainty associated with the mean length-at-age and the individual variation about the mean length-at-age). Data points for ages 75 and older are omitted from this figure for improved clarity.

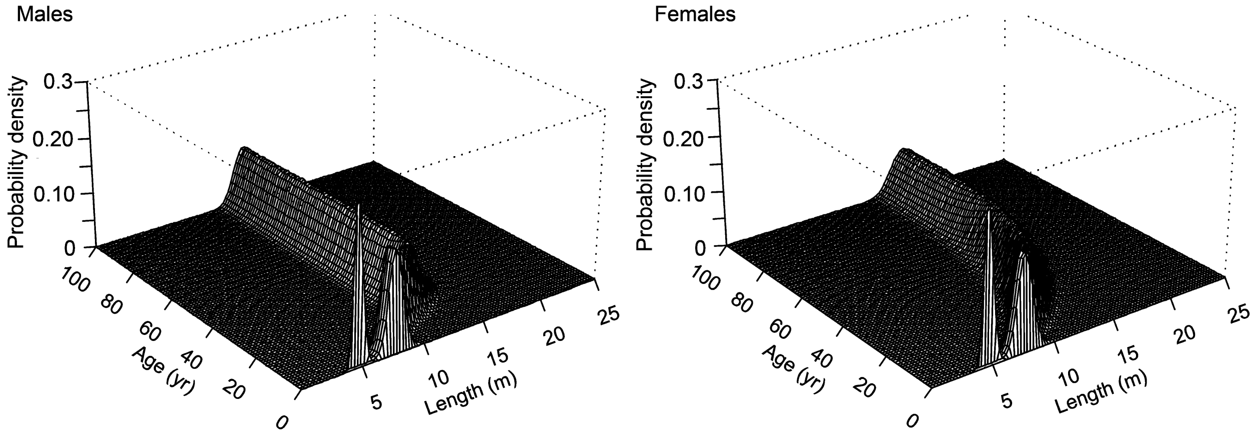

Fig. 4. The point estimates of the length-at-age distributions.

Table 7

Values for the parameters of the growth equation.

Parameter	Males	Females
l_1(m)	7.73	7.64
l_{40} (m)	12.91	13.98
κ (yr^{-1})	1.021e-8	9.608e-8
β	9.131	15.892
σ	0.0734	0.0781

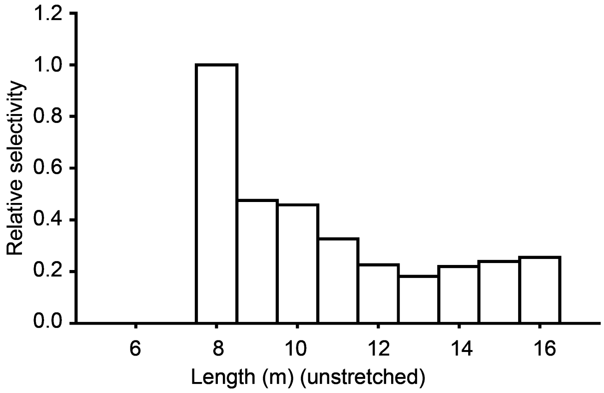

Fig. 5. Selectivity-at-length for the B-C-B stock of bowhead whales.

the model is fitted the length-frequency data and ‘very strong’ support for this analysis when the model is fitted to the age-composition data (Bayes factor >150; see Fig. 6). Thus, it seems as if a key reason for the earlier inability to mimic the catch age-composition data (Schweder and Ianelli, 2000) was due to the assumption of uniform selectivity harvesting when this is not actually the case. The data provide little ability to discriminate between the two selection patterns (uniform selectivity and the selectivity based on Fig. 5) when the model is fitted to the proportion data (Bayes factor < 3). The latter result is not surprising because this is a case in which the model is fitted to data aggregated over age and length. As a result, there is not much information on the pattern of abundance within fairly large groups of ages. The remaining analyses of this paper are based on the model in which the selectivity pattern is given by Fig. 5 (henceforth referred to as the 'base-model').

Results for base-model

Table 8 lists the results (posterior medians, means and 95% probability intervals) for the base-model in terms of the values for the following seven quantities of management interest.

K_{1+} – the pre-exploitation size of the 1+ component of the population.

P^{1+}_{2004} / K_{1+} – the ratio (expressed as percentage) of the size of the 1+ component of the population at the start of 2004 to K_{1+}.

P^{f}_{2004} / K^{f} – the ratio (expressed as percentage) of the size of the mature female component of the population at the start of 2004 to the corresponding pre-exploitation size.

$P^{1+}_{2004} / MSYL_{1+}$ – the ratio (expressed as percentage) of the size of the 1+ component of the population at the start of 2004 to *MSYL*.

$MSYR_{1+}$ – *MSYR* for uniform selectivity harvesting of the 1+ component of the population, expressed as a percentage.

RY (2004) – the replacement yield for 2004 (the catch during 2004 so that the population size at the start of 2005 equals that at the start of 2004).

Slope – the annual rate of increase of the 1+ population from 1978 to 1993, expressed as a percentage[6].

Fig. 7 provides diagnostic statistics (the fits to the age-composition data, the length frequency data, the abundance indices, and the proportion data) for the analyses that fit to: (a) the Koski *et al.* (2006) proportion data; (b) the length frequency data; and (c) the age-composition data.

The results of the assessment are quite sensitive to the choice of data set. Specifically, the productivity of the resource (expressed in terms of $MSYR_{1+}$ and the '*slope*' statistic) is lower when the model is fitted to the length or age data (posterior medians for $MSYR_{1+}$ ~ 1.3-2.0% compared to 2.7-2.9% when the model is fitted to the proportion data).

The model mimics the trend in the abundance data best when it is not fit to the length or age data, suggesting that there is conflict between these data sources. In contrast, the abundance and proportion data are totally consistent (Fig. 7a). The model does not mimic the age-composition data adequately unless it is fitted to these data (Figs 7a and 7b, upper left panels). Specifically, the model predicts that a much larger fraction of the catch should be animals aged 0-20 years (Fig. 7a) and 20-40 years (Fig. 7b) than is actually the case and that a much lower fraction of the catch should be animals aged 100+. Similarly, only the analysis that fits to the length frequency data mimics these data well; the fit to the length data for the case in which the model is fit to the proportion data is particularly poor as it severely underpredicts the abundance of animals 12m and longer (Fig. 7a).

The B-C-B Seas stock of bowhead whales is assessed to be above or approaching *MSYL* at present (Table 8). However, the exact status of the stock remains uncertain because, for example, the ratio of current to pre-exploitation population size is higher (markedly so in terms of the 1+ component of the population) if the length and age data are

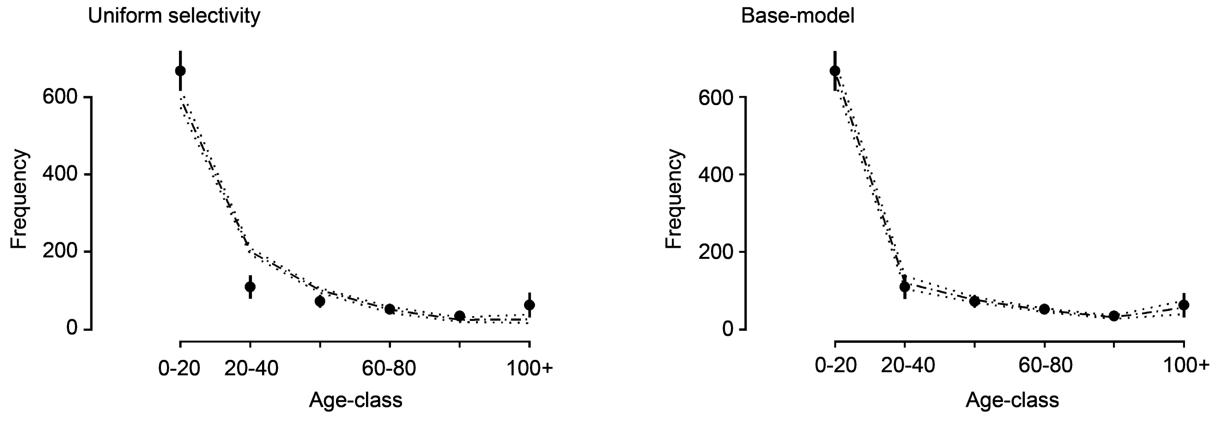

Fig. 6. Posterior distributions (medians and 90% probability intervals) for the catch age-compositions based on models fitted to the age-composition data. Results are shown for the analysis in which selectivity is uniform and for the base-model.

Table 8

Estimates of seven management-related quantities for the B-C-B Seas stock of bowhead whales. The point estimates given are posterior medians, followed by posterior means in round parenthesis. Posterior 90% probability intervals are given in square parenthesis. The analyses in this table are based on the base-model.

	K_{1+}	*RY* (2004)	P^{1+}_{2004} / K_{1+}	P^{f}_{2004} / K^{f}	$P^{1+}_{2004} / MSYL_{1+}$	$MSYR_{1+}$	*Slope*
With Koski *et al.* (2006) proportions	11,261 (11,411)	143 (135)	86.6 (85.3)	53.5 (54.4)	127.0 (125.7)	2.90 (2.91)	2.60 (2.59)
	[9,943 13,432]	[76 171]	[69.0 96.8]	[43.8 68.7]	[110.1 136.0]	[1.96 3.83]	[1.80 3.31]
With length data	14,067 (14,101)	134 (133)	66.1 (66.1)	48.8 (48.9)	123.6 (123.6)	1.96 (1.95)	1.60 (1.58)
	[13,219 15,119]	[124 141]	[58.3 74.4]	[42.3 55.9]	[112.1 135.2]	[1.66 2.23]	[1.36 1.76]
With age data	15,662 (15,658)	138 (140)	57.5 (58.0)	40.0 (40.2)	81.9 (82.2)	1.31 (1.34)	1.23 (1.25)
	[14,138 17,118]	[109 182]	[49.7 68.2]	[35.5 45.7]	[68.0 97.0]	[1.04 1.73]	[0.94 1.66]
With 1998 proportions	11,710 (11,941)	162 (157)	85.2 (83.3)	52.7 (53.4)	117.3 (114.9)	2.70 (2.70)	2.60 (2.60)
	[10,174 14,491]	[85 212]	[63.5 96.7]	[42.5 67.0]	[91.0 131.0]	[1.65 3.76]	[1.59 3.60]

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[6] The slope statistic is based on the years 1978-93 for comparability with the assessment conducted in 1998.

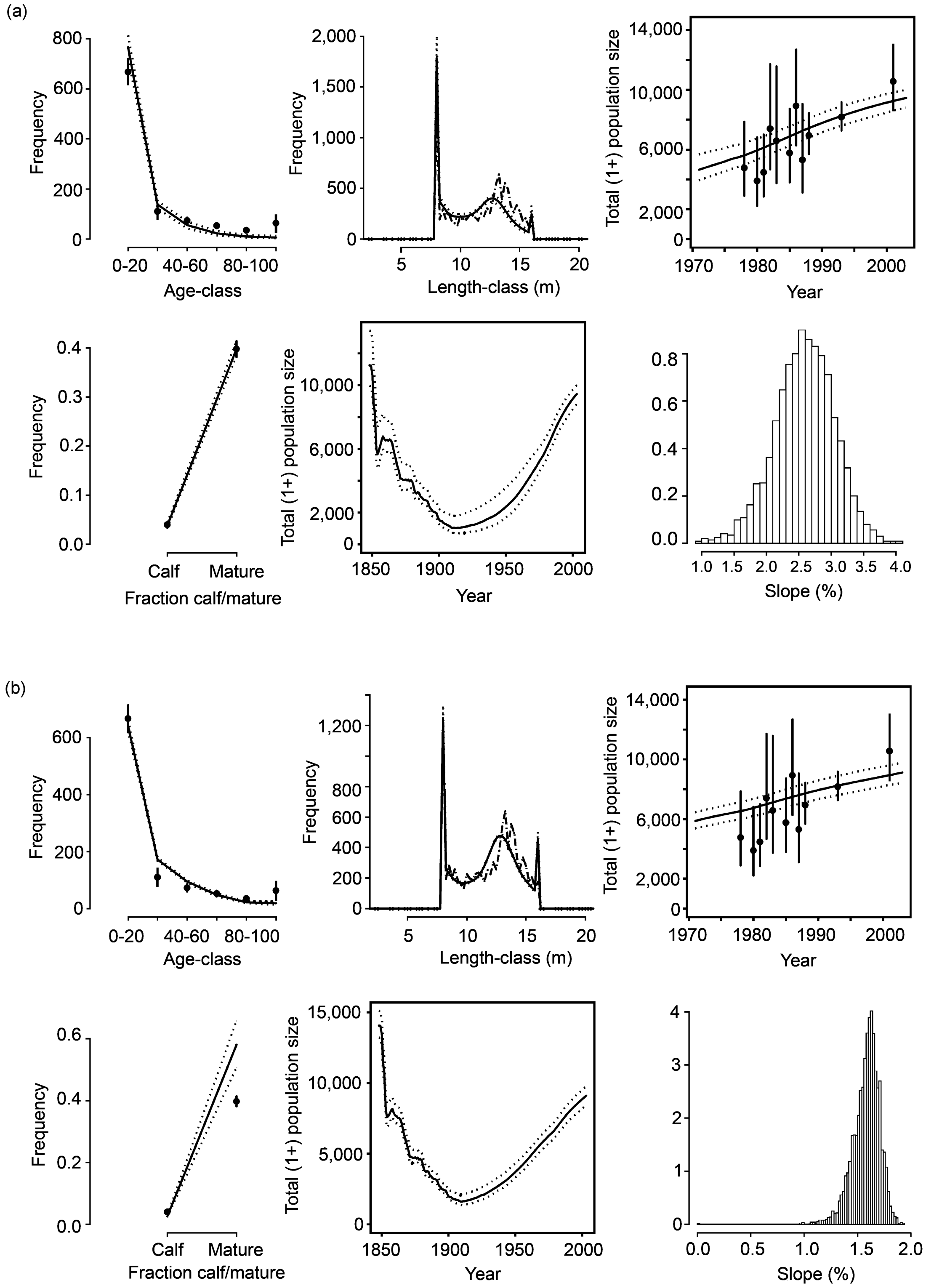

Fig. 7. Diagnostic statistics (fits to the age-composition, length frequency, abundance, and proportion data), the posterior distribution for the time-trajectory of 1+ population size, and the posterior distribution for the 'slope' statistic. Results are shown for analyses that fit to: (a) the Koski *et al.* (2006) proportion data; (b) the length frequency data; and (c) the age-composition data. The solid lines are posterior medians and the dotted lines indicate posterior 90% intervals. The dashed line in the upper centre panel indicates the observed length-frequency distribution.

ignored when conducting the assessment. The ratio of current population size to $MSYL_{1+}$ is more robust than the ratio of current to unexploited population size, except for the case in which the assessment is based on the age-composition data (Table 8).

Sensitivity to weights

The results of an assessment often depend on the weight assigned to the various data sources when these data sources are contradictory. Fig. 8 explores the sensitivity of the posterior distribution for $MSYR_{1+}$ to reducing the effective sample size assumed for the length-frequency data and to changing the emphasis placed on mimicking the age-composition data (implemented by multiplying the standard deviations in Table 3 by various constants).

A marked reduction in the median of the posterior distribution for $MSYR_{1+}$ occurs even if a relatively small (~100) effective sample size is assigned to the length frequency data (Fig. 8; left panel); increasing this effective sample size beyond 100 leads to narrower probability

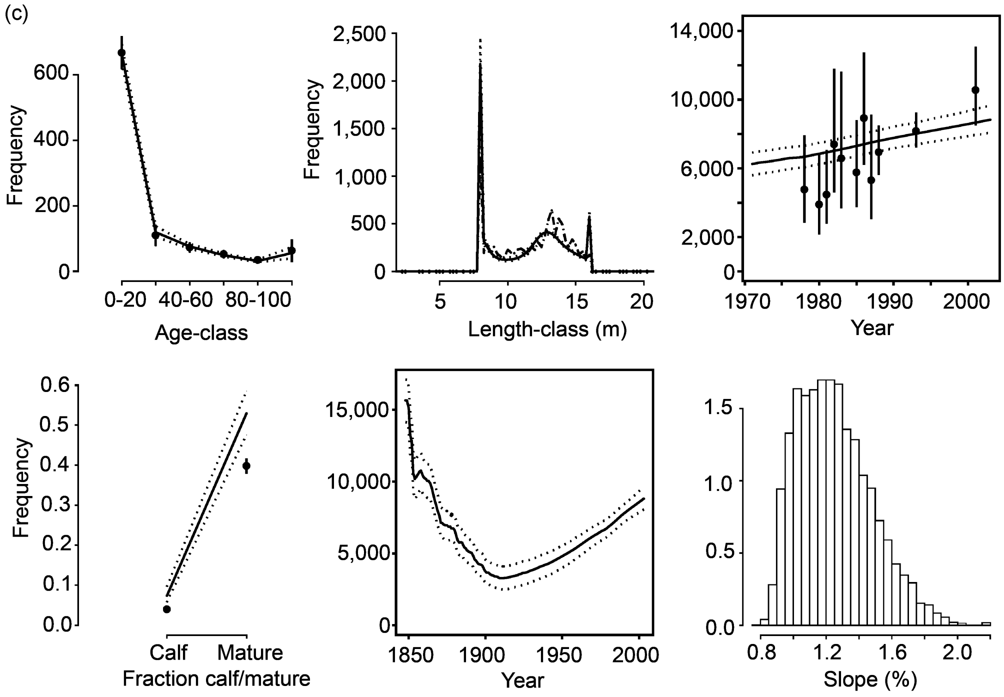

Fig. 7 *continued.* Diagnostic statistics (fits to the age-composition, length frequency, abundance, and proportion data), the posterior distribution for the time-trajectory of 1+ population size, and the posterior distribution for the 'slope' statistic. Results are shown for analyses that fit to: (a) the Koski *et al.* (2006) proportion data; (b) the length frequency data; and (c) the age-composition data. The solid lines are posterior medians and the dotted lines indicate posterior 90% intervals. The dashed line in the upper centre panel indicates the observed length-frequency distribution.

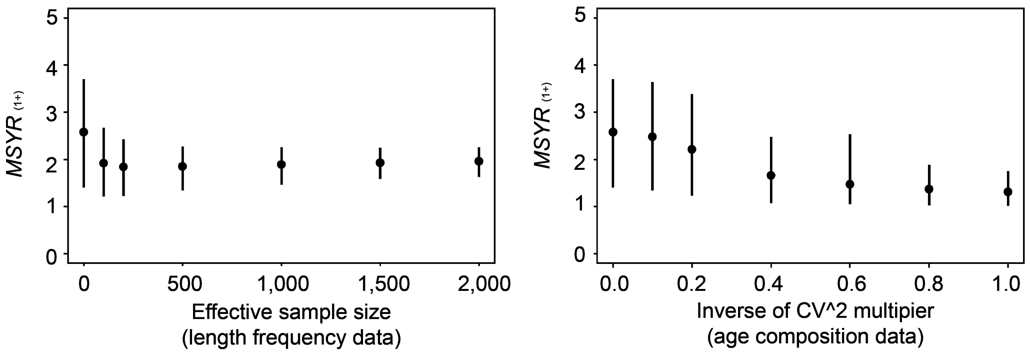

Fig. 8. Posterior distributions (medians and 95% probability intervals) for $MSYR_{1+}$ for different assumed effective sample sizes for the length-frequency data and for different levels of emphasis on the age-composition data.

intervals, as would be expected. In contrast to the case for the length frequency data, there is no obvious CV multiplier at which the median of the posterior for $MSYR_{1+}$ changes markedly (Fig. 8; right panel). In contrast, the median for $MSYR_{1+}$ continues to decline almost continuously with increasing emphasis on the age-composition data.

Management implications

From a management viewpoint, none of the lower 5th percentiles of the posterior distributions for the 2004 replacement yield are less than the current strike limit of 68 (Table 8). However, a more appropriate way to determine the management implications of the results of this paper is to evaluate the performance of the *Bowhead SLA* (IWC, 2003a) when the operating model is parameterised in terms of the results outlined above. Table 9 therefore presents the values for five of the mandatory performance measures selected by IWC (2003a) for simulation trials in which the final need level is set to 134 and in which it is set to 201 for a variety of specifications related to the assumed form of selectivity and the data used when conditioning the trials.

The conservation-related performance measures (D1 – Final depletion, and D10 – Relative increase) are higher when selectivity is not uniform (presumably because less of the catch is taken from the mature age-classes; Fig. 5). However, the differences are not particularly marked, except possibly for the lower 5th percentiles of the final depletion distribution. There is almost no impact from the choice of selectivity pattern on need satisfaction. The results are again more sensitive to the choice of data used when conditioning than to the form of the selectivity pattern. As expected, final depletion and need satisfaction are lowest when the operating model is conditioned using the age data because these data imply the lowest productivity (Table 8). However, the results for even this case are not poorer than when the *Bowhead SLA* is used to manage a population for which $MSYR_{1+}$=1% (see IWC, 2003b for full details).

General discussion

This paper shows that it is possible to 'integrate' more sources of data into the assessment of the B-C-B Seas bowhead stock than has been done to date. This process of

Table 9

Performance measures for the *Bowhead SLA* for trials in which the biological parameters are based on the results of the assessments of the population. Results are shown for final need levels of 134 and 201.

	Final depletion; 1+ population (D1)			Relative increase; 1+ population (D10)			Average need satisfaction (N9-20 years)			Average need satisfaction (N9-100 years)			Mean downstep (N12)		
Scenario	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Final need = 134															
Uniform selectivity															
With Koski *et al.* (2006) proportions	0.816	0.930	0.972	1.010	1.100	1.280	1.00	1.00	1.00	0.85	0.98	1.00	0.000	0.004	0.020
Base-model															
With Koski *et al.* (2006) proportions	0.842	0.937	0.969	1.020	1.110	1.260	1.00	1.00	1.00	0.86	0.99	1.00	0.000	0.003	0.021
With length data	0.724	0.786	0.844	1.110	1.190	1.320	1.00	1.00	1.00	0.87	0.99	1.00	0.000	0.003	0.019
With age data	0.659	0.854	0.940	1.300	1.490	1.660	0.99	1.00	1.00	0.89	1.00	1.00	0.000	0.000	0.018
With 1998 proportions	0.871	0.950	0.978	1.010	1.140	1.410	1.00	1.00	1.00	0.86	0.99	1.00	0.000	0.002	0.018
Final need = 201															
Uniform selectivity															
With Koski *et al.* (2006) proportions	0.776	0.921	0.970	1.000	1.090	1.240	0.96	1.00	1.00	0.73	0.88	0.95	0.004	0.010	0.033
Base-model															
With Koski *et al.* (2006) proportions	0.822	0.931	0.967	1.020	1.100	1.210	0.96	1.00	1.00	0.73	0.88	0.95	0.003	0.010	0.035
With length data	0.667	0.755	0.829	1.040	1.140	1.300	0.95	1.00	1.00	0.73	0.88	0.94	0.004	0.011	0.029
With age data	0.639	0.813	0.919	1.240	1.430	1.580	0.94	1.00	1.00	0.72	0.91	0.96	0.002	0.007	0.030
With 1998 proportions	0.834	0.941	0.977	1.010	1.130	1.370	0.96	1.00	1.00	0.73	0.90	0.96	0.003	0.009	0.030

integration allows an examination to be conducted to determine whether some of the available data sources are contradictory (i.e. imply different impressions of stock status and productivity). The results of this paper highlight that there is some inconsistency among the proportion data, the length frequency data, the age-composition data and the abundance estimates. The age-composition data are least compatible with the other data, and suggest the least amount of recovery and the lowest levels of productivity of the B-C-B Seas bowhead stock. However, the quantitative results for the case in which the model is fitted to the age-composition data should be interpreted with caution owing to the problems in how the age-compositions were constructed by Schweder and Ianelli (2000). Nevertheless, all of the analyses considered in this paper confirm that the B-C-B Seas bowhead stock has been recovering steadily over the last few decades (Fig. 7), even though the present analyses suggest that the certainty associated with the rate of increase in the past may have been over-estimated.

The assumption underlying past assessments that selectivity is uniform above age one appears to be violated for this stock (Fig. 5). Rather, it appears that hunters take smaller (younger) animals rather than larger (older) animals. Whether this pattern is due to preference or differences in the availability of different age-classes cannot be assessed conclusively with the available information, but subsistence hunters have expressed a preference for smaller animals that are easier to manoeuvre to shore and they were encouraged to take smaller animals by the IWC for several years (e.g. Donovan, 1982; IWC, 1995). However, with respect to the estimated status of the population, the consequences of differences in selectivity among age-classes are minor compared to the choice of which sources of data are to be included in the assessment.

A number of factors could not be accounted for in the analyses of this paper. Specifically, no account of the uncertainty associated with estimating selectivity-at-length was taken because no attempt was made to treat selectivity-at-length as estimable. In principle, selectivity-at-length could be treated as parameters of the model and included when calculating the posterior distributions. Unfortunately, the number of selectivity parameters is quite large (see Fig. 5) and attempting to allow for their uncertainty using the SIR algorithm to sample from the posterior distribution would lead to prohibitively long computation times. In principle, uncertainty regarding the selectivity parameters could be accounted for if a different approach was used to sample from the posterior distributions (e.g. by using an MCMC algorithm).

Selectivity is assumed to be uniform prior to 1914. In contrast, Bockstoce and Burns (1993) noted that ‘the largest whales were taken in the earliest years of the fishery, although paradoxically, one or two very big whales were taken in the last years’. Although the sample sizes for length frequency for the early harvests are low, it may be possible in future to develop a selectivity pattern for those harvests which is more realistic than the current assumption of uniform selectivity harvesting. This might help to fit the length-frequency data for the largest animals although the management implications of historical selectivity differing from uniform above age one are likely to be fairly minor.

Finally, although the results of the assessment suggest that selectivity is not uniform and that the various data sources are inconsistent to some extent, the results of the projections (Table 9) provide no evidence that the scenarios considered during the testing of the *Bowhead SLA* are insufficient to cover the plausible range.

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