An assessment of the eastern gray whale population in 2002

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INTRODUCTION

The eastern Pacific stock of the gray whale, *Eschrichtius robustus,* has been monitored since 1967. Since the last assessment of the population (Wade 2002), three additional surveys were carried out in 1997/98,2000/01 and 2001/02 (Rugh et al. 2002), making possible pre-assessment of the stock. The population has now been surveyed on its southbound migration in 23 out of 35 years from 1966/67 to 2001/02. Since 1994, a survey for calves has been done every year during the northbound migration in the late spring (Perryman et al. 2002)

Wade (in press) used an age and sex structured model, based on a simplified Leslie matrix with a density-dependent term for fecundity. In that assessment, the population survey data were used, but the calf estimates were not used. Wade *(SC/49/AS24)* introduced the first assessment that used the calf estimates in addition to the population estimates. If an age-structured model is used, the calf estimates can be added to the analysis by adding a term to the likelihood function that calculates the likelihood of observing those estimates of calves in each year given the model number of calves in those years. The calf surveys now provide eight estimates of the number of calves migrating north, for 1994 through 2000 (Perryman et al 2002) and 2001 (Perryman, unpublished). The analysis in Wade *(SC/49/AS24)* was therefore updated using all of the calf estimates and population estimates, through 2001/02. Identical Bayesian statistical methods as in Wade (2002, 1997) were used to estimate the model parameters by fitting the models to the total population abundance and calf abundance data.

METHODS

Population dynamics Model

The population model was the same as the density-dependent Leslie matrix model in Wade (2002). A simplified Leslie matrix (Leslie 1945, 1948) was used with a total of 4 variable parameters. Three were elements of the matrix: (1) s_c' the survival rate of the first age class ("calf" survival rate), (2) s_a , the survival rate of all other age classes ("adult survival rate"), *(3).1;,* the fecundity rate at time *t* (assumed identical for all mature age classes), and (4)*ASM,* the age of sexual maturity (with the first non-zero fecundity in the subsequent age class). The maximum age was fixed at 60 years.

This model was identical to a usual Leslie matrix model, except that the fecundity term was density dependent with a form similar to the generalized-logistic:

$$f_t = f_0 + (f_m - f_0)\left[1 - \left(\frac{N_t}{K}\right)^z\right]$$

where f_t = the realized fecundity in year t, f_m = the maximum fecundity rate, and f_0 = fecundity at a net recruitment of zero, which can be solved directly from the other parameters. This model is thus identical to the model in Breiwick *et al.* (1984). The population growth rate (λ) associated with a Leslie matrix using a fecundity value of f_t was referred to as λ_t, and the population growth rate associated with f_t=f_m was referred to as λ_{max}. Estimates of λ_{max} were expressed as λ_{max}-1.

The sequence of events in the model were as follows. At the beginning of a year, (1) the model population was compared to the abundance estimate from the southbound total population survey (if available in that year), (2) the population was projected one time-step, producing newborn calves, (3) the model number of calves was compared to the calf estimate from the northbound survey (if available in that year), and finally, (4) the harvest kills were subtracted from the population. This sequence was used because calves are mostly born after the southbound migration but before the northbound migration, and because the harvest takes place mostly in the summer and early fall. In each year the kills were distributed to each recruited age-class according to the age distribution in that year. Recruitment to the harvestable population was assumed to be knife-edge and to occur at age 5. Each population trajectory was initiated with the stable age distribution associated with that population size. In other words, the starting population size for a trajectory was used in Eq. 1 to find the value of f_t associated with that population size and the particular values for f_m, N_{eq}, and z used on that trajectory. Then the stable age distribution was found for the Leslie matrix composed of s, s_j, *ASM*, and that value of f_t.

Because the sex-ratio of the kill was not equal, two vectors of population size were projected, one .for each sex. The same survival rates were used in the Leslie matrix to project each vector. The sex ratio of calves was assumed to be 50:50; therefore the number of males in age-class 1 was set to be equal to the number of age-class 1 females at each time step. The population was assumed to have a 50:50 sex ratio in the beginning year.

Additional variance term

Wade (2002) showed that the use of an additional variance term, CV_{add}, provided a better fit to the data when compared with the Bayes factor (Kass and Raftery 1994). CV_{add} was parameterized as a coefficient of variation and was considered constant across years. CV_{add} was incorporated into the likelihood function in each year as an additive variance term to the abundance estimates, with the assumption that this additional variance has a Gaussian distribution. In other words, in any year, a new total CV was calculated as the square root of the sum of the squares of CV(t) and CV_{add-1}.

$$CV_{tot}(t) = \sqrt{CV^2(t) + CV^2_{add-1}}$$

where CV(t)=S(t)/N(t). The likelihood component from that year's abundance estimate was calculated as usual with the new total CV term (i.e., S(t)=N(t)$CV_{tot}(t)$).

A similar tenn was added for the analyses which used the calf estimates, adding another parameter to be estimated, CV_{add-2} where the total CV for the calf estimates were also calculated using Eq. 2.

Statistical methods

A Bayesian statistical method (e.g., Press 1989) was used to estimate the parameters of the models and other output quantities. The same technique was used as in Wade (2002, SC/48/AS8). The integration was again performed using the Sampling-Importance-Resampling routine of Rubin (1988). The calf data were added to the likelihood function, with the assumption of a Log-normal sampling distribution.

Prior Distributions

Prior distributions for the parameters are in Table 1. The only restriction on the calfe survival rate, s_c, was that it be less than s_a. The prior distributions for many of these parameters did not remain uniform on these ranges. A uniform distribution was set for λ_{max}. Then, values for f_{max}, *ASM*, and *s* were drawn from the prior distributions described above. From these values, s_c can be calculated (Breiwick *et al.* 1984). If s_c was less than s_a, this set of values was used. If s_c was > s_a, then f_{max}, *ASM*, and s_a were re-drawn from their uniform distributions but retaining the original value for λ_{max}. This resulted in non-uniform realized prior distributions for these parameters, which were stored, but retained the uniform prior distribution for λ_{max}. An explicit prior was not set for s_c because this would have resulted in two different prior distributions being established for λ_{max}, and because little information exist regarding s_c.

The prior distribution for *K* was set as uniform from 15,000 to 70,000. The lower bound was found through previous analyses (*e.g.*, Wade SC/48/AS8), to have very little probability in any of the posterior distributions. Therefore, the lower bound for the prior distribution is un-informative in the sense that any lower value could have been used instead without influencing the results (although computation time would increase because the value of n_1 would need to be increased). The upper bound was set to a somewhat arbitrary large value.

The prior distribution for the maximum sustained yield level (MSYL) was a uniform from 0.5K to 0.8K. Values were drawn from this distribution and then transformed into the appropriate value for z. This creates a non-uniform prior for *z*, but MSYL was the parameter of interest and so it was most appropriate to set a uniform distribution for it.

The prior distribution for CV_{add-1} was a uniform distribution found to span the range of posterior probability in all of the analyses. Again, this makes the prior for CV_{add} un-informative in the sense that the specific limits of this prior distribution do not affect the results. The prior distribution for CV_{add-2} was set in a similar way.

Posterior distributions

Posterior distributions for several output quantities of interest were calculated that were functions of the other parameters. The maximum sustained yield rate (MSYR) was calculated as the λ_t-1 value associated with the MSYL, defined in terms of the 1+ population. The maximum sustained yield (MSY) was calculated as the product of MSYR, MSYL and N_{eq} (because MSYL was parameterized as a fraction of N_{eq}). Current replacement yield (RY) was calculated directly as the model population size in 2002 minus the model population size in 2001. Another catch statistic was calculated, based on the quantity Q_1 described by Wade and Givens (1997) that was designed to meet the intent of aboriginal whaling management objectives. Q_1 was calculated as 0.9MSY for populations above the MSYL, as the minimum of 0.9MSY and the product N_t*MSYR for populations below the MSYL, and as zero for populations below P_{min}, the population size below which no aboriginal catches are allowed. P_{min} was assumed to be a value of $0.1*N_{eq}$. The quantity Q_0 from Wade and Givens (1997) was also calculated.

Prior distributions were also calculated for the output quantities of interest. These were simply the distributions of these parameters in the initial sample n_1. These represent the implied prior distributions for these parameters that results from the prior distributions specified for the parameters of the population dynamics models.

Available data.

Abundance surveys for the eastern Pacific stock of gray whales take place from December to February, so they are referred to by two years *(e.g.,* a survey from December 1995 to February 1996 is called the 1995/96 survey). Abundance estimates are available in Buckland and Breiwick (in press), Hobbs et al. (2002), Laake et al. (1994), and Rugh et al. (2002). Earlier estimates have been slightly revised and all the estimates used are shown in Table 2 (J. Breiwick, pers. comm.). The estimated number of calves in each year for 1980 and 1981 is from Poole (1984), from 1994 to 2000 is from Perryman *et al.* (2002), and the estimate for 2001 is from Perryman (unpublished). The catch history prior was obtained directly from the IWC (Table 3).

Four scenarios were run (1) using all the calf estimates, (2) using none of the calf estimates, (3) using all of the calf estimates except the 1980 and 1981 estimates, and (4) using all of the calf estimates plus an assumed value of 1100 in 2002. This last scenario is used because calf estimates were low the previous three years, Perryman et al. (2002) show a relationship between calf production and ice conditions in the Bering Sea the previous summer, and ice conditions were favorable in the summer of 2001, and therefore it is predicted that calf production will be higher in 2002. On-going surveys at the time of the analysis appear to have more sightings of calves than in the previous three years (Perrryman pers. comm.).

RESULTS

Over all the scenarios, current carrying capacity (K) was estimated to be between 19,000 and 35,000 (Table 4). λ_{max} was estimated to be 1.07 to 1.08, with intervals from about 1.04 to 1.11. The point estimates of current depletion level (N_{2002}/K) of the gray whale population were all either 99 or 100% of K, so the population is estimated to currently be at K (lower bounds of the intervals were as low as 71 %). There is essentially zero probability that the population is below MSYL.

The population trajectories show the population is estimated to have leveled off, and is no longer increasing (Figs 1-4). Using the calf estimate data does not substantially change the results, but makes the results more precise, particularly for K.

The point estimates for Q_l ranged from 605 to 669, with the lower 5th percentile of the posterior distributions ranging from 455 to 490 (Table 4). The point estimates for Q_0 was quite similar, not unexpected because Q_0 and Q_l are identical for populations estimated to be above MSYL, which is the case here.

DISCUSSION

The additional data collected over the last five years has increased the precision of the eastern gray whale assessment. The posterior distribution for K, the equilibrium population size (current carrying capacity) is much more precise than in Wade (2002) or Wade (1997). The major difference is the addition of three abundance surveys, four calf surveys, and the inclusion of the earlier calf estimates from Poole (1984). In the analysis that did not use the calf data, K is still estimated with greater precision, which illustrates the influence of the additional three abundance estimates. The calf data simply strengthens the same result.

The historic catch infonnation has been used to estimate historic population size by back-calculating from a recent abundance estimate. Between the start of commercial whaling and 1900, approximately 15,000 whales were estimated to have been harvested. Using this information, Henderson (1972) concluded that the population did not exceed 15,000-20,000 at the start of commercial whaling. However, Reilly (1981) and Butterworth *et al. (in press)* have shown that it is impossible to project back to a historic population size and have a trajectory consistent with the recent abundance trend without making a major untestable assumptions, such as commercial harvests were greater than estimated. Therefore, the previous estimates of historic population size may be questionable.

By making certain assumptions, Reilly (1981) was able to construct some sensible population trajectories, and concluded that a carrying capacity of 24,000 was in best agreement with the available information in his study. Butterworth *et al. (in press)* investigated a broader range of plausible scenarios to also construct a variety of sensible population trajectories, and they found that historic population sizes greater than 30,000 were possible under certain scenarios, particularly if it is assumed that historic catches, either commercial or aboriginal, were greater than estimated.

Other lines of evidence are consistent with the idea that gray whales are currently close to their carrying capacity. For example, Stoker *(in press)* concluded that the recent decline of amphipods in one of the major feeding areas of the gray whale could have been caused by gray whale predation. Reilly (1992) described a recent decline in gray whale pregnancy rates in the aboriginal catch data, although he cautions that sampling bias could have produced this result because of the known differences in pregnancy rates in different areas.

More recently, an increase in the number of strandings of gray whales was seen in 1999 and 2000 (Norman et al. 2000, LeBoeuf et al. 2000). Observations of "skinny" whales, along with the increased strandings, has led to speculation that the population is either experiencing poor environmental conditions, reached carrying capacity, or both (Moore et al. 2001). Populations at or near carrying capacity may be depleting their prey base. This is likely to make such populations more subject to changes in the environment, so it is expected that populations close to K might experience greater fluctuations than populations well below K.

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Table 1. Prior distributions for the model parameters. U=Uniform distribution, DU=Discrete uniform distribution, and LN=Log-normal distribution.

Parameter	Distribution
MSYL	U(0.50, 0.80)
K	U(15,000, 70,000)
λ_{max}	U(1.03, 1.12)
ASM	DU(5, 7)
S_a	U(0.965, 0.999)
S_c	<Sa
f_{max}	U(0.05, 0.25)
N_{1967}	LN(12921, 0.075)
CV_{add-1}	U(0.05, 0.25)
CV_{add-2}	U(0.20, 1.40)
IW	DU(60, 80)
IR	DU(2, 5)

Table 2. Abundance estimates used in the analysis, including population estimates made during the southbound migration, and calf estimates made during the northbound migration. Estimated coefficients of variation (CV) are also shown.

Year	Population estimate	CV	Calf estimate	CV
1967/68	12,921	0.075		
1968/69	12,070	0.049		
1969/70	12,597	0.051		
1970/71	10,708	0.045		
1971/72	9,760	0.054		
1972/73	15,099	0.046		
1973/74	14,696	0.050		
1974/75	12,955	0.051		
1975/76	14,520	0.055		
1976/77	15,304	0.044		
1977/78	16,879	0.065		
1978/79	13,104	0.048		
1979/80	16,363	0.051	691	0.051
1980/81			768	0.071
1981/82				
1982/83				
1983/84				
1984/85	21,444	0.055		
1985/86	20,113	0.046		
1985/86				
1987/88	20,869	0.044		
1988/89				
1989/90				
1990/91				
1991/92				
1992/93	17,673	0.058		
1993/94	23,110	0.055	945	0.072
1994/95			619	0.109
1995/96	22,263	0.076	1,146	0.067
1996/97			1,431	0.057
1997/98	26,635	0.090	1,388	0.068
1998/99			427	0.096
1999/00			279	0.129
2000/01	18,761	0.090	256	0.112
2001/02	17,414	0.090		

Table 3. Catches by year used in the analyses, from 1968 to 2000, using assumed values for 2001 and 2002.

Year	Male	Female
1968	67	134
1969	59	155
1970	26	125
1971	51	102
1972	22	160
1973	97	81
1974	94	90
1975	58	113
1976	69	96
1977	86	101
1978	94	90
1979	57	126
1980	53	128
1981	36	100
1982	56	112
1983	46	125
1984	59	110
1985	55	115
1986	46	125
1987	47	112
1988	43	107
1989	61	119
1990	67	96
1991	57	113
1992	0	0
1993	0	0
1994	25	19
1995	49	43
1996	19	24
1997	48	31
1998	63	60
1999	69	53
2000	62	51
2001	61	51
2002	61	51

Table 4. Estimates of 22 quantities for the eastern stock of north Pacific gray whales. The point estimates are posterior medians, with lower and upper 90% credibility intervals. Results are for 4 analyses: (1) all of the calf estimates, (2) none of the calf estimates, (3) all of the calf estimates except the 1980 and 1981 estimates from Poole (1984), and (4) all of the calf estimates plus an assumed estimate for 2002 of 1100.

	(1) All calf estimates			(2) No calf estimates		
Quantity	Median	Lower 90%	Upper 90%	Median	Lower 90%	Upper 90%
MSYR	4.705	3.390	6.175	5.147	2.971	6.744
MSYL	0.618	0.523	0.777	0.659	0.534	0.783
K	22610	19830	28470	21740	19480	35430
N_{2002}/K	99	84	101	100	71	102
$N_{2002}/MSYL$	158	128	175	148	124	174
RY	179	111	405	134	106	533
Q_0	608	463	794	670	483	884
Q_1	608	463	794	669	482	883
λ_{max}	1.079	1.051	1.116	1.076	1.044	1.113
ASM	6	5	7	6	5	7
S_c	0.831	0.538	0.976	0.797	0.441	0.972
S_a	0.989	0.972	0.998	0.988	0.969	0.998
f_{max}	0.208	0.119	0.247	0.212	0.123	0.247
N_{1967}	10920	9770	12260	10700	9411	12390
CV_{add-1}	0.128	0.090	0.181	0.127	0.090	0.183
CV_{add-2}	0.686	0.445	1.090	--	--	--
Z	1.560	0.430	7.300	2.330	0.580	7.800

	(3) No 1980/1981 calf estimates			(4) All calf estimates plus 2002		
Quantity	Median	Lower 90%	Upper 90%	Median	Lower 90%	Upper 90%
MSYR	4.825	3.619	6.328	4.707	3.297	6.241
MSYL	0.657	0.540	0.781	0.621	0.519	0.766
K	22110	19840	26880	22590	20020	30280
N_{2002}/K	100	89	102	99	79	101
$N_{2002}/MSYL$	151	128	175	156	129	173
RY_{2002}	146	111	356	187	110	431
$Q0_{2002}$	638	490	858	605	456	814
$Q1_{2002}$	638	490	858	605	455	814
λ_{max}	1.071	1.047	1.111	1.080	1.045	1.111
ASM	6	5	7	6	5	7
S_c	0.805	0.435	0.961	0.850	0.515	0.969
S_a	0.987	0.970	0.998	0.987	0.972	0.998
f_{max}	0.207	0.121	0.246	0.200	0.112	0.244
N_{1967}	10790	9499	12120	10970	9778	12430
CV_{add-1}	0.126	0.091	0.175	0.128	0.092	0.187
CV_{add-2}	0.738	0.487	1.175	0.661	0.453	1.067
Z	2.320	0.550	7.500	1.700	0.390	6.700

Figure 1. Estimated population quantities by year for the analysis using all the calf estimates.

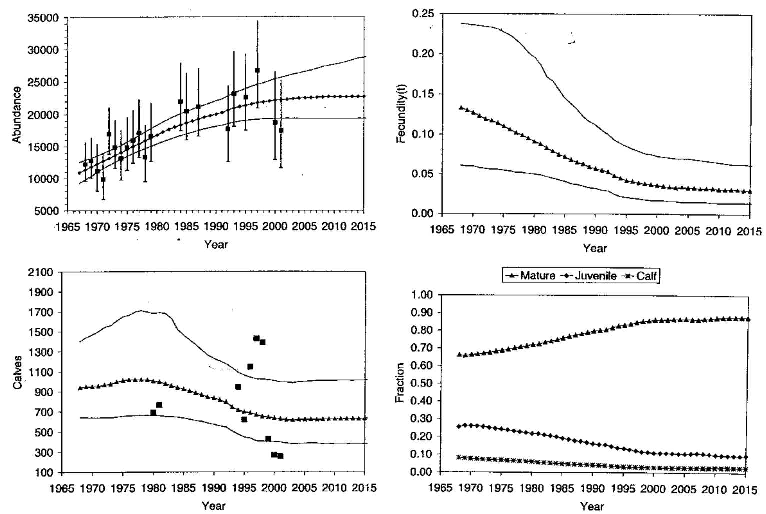
Upper left panel: median total population size through time (diamonds), with 95% credibility intervals (thin line), with abundance estimates (squares) with 95% intervals (calculated with the estimated additional variance, $CV_{add.I}$. Lower left panel: median number of calves (diamonds), with 95% credibility interval (thin line), and calf estimates (squares). Upper right panel: estimated fecundity in each year *(fJ,* with 95% credibility interval. Lower right panel: fraction of population that was in a mature age class (triangles), juvenile age class (diamonds), or in the calf age class (star), for each year.

Figure 2. Estimated population quantities by year for the analysis using none of the calf estimates. See Figure 1 for explanation of panels and symbols.

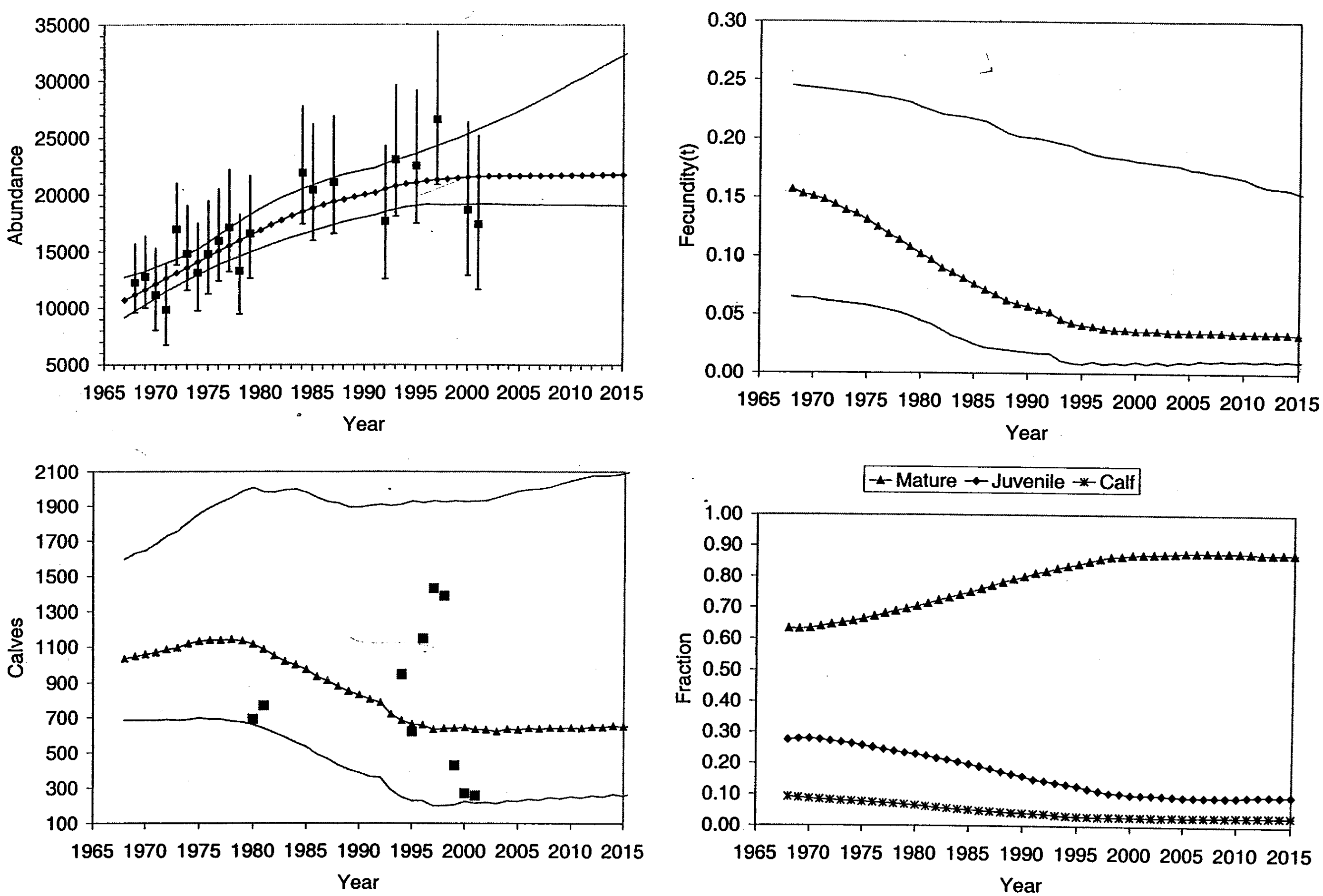
Figure 3. Estimated population quantities by year for the analysis using all of the calf estimates except the estimates from 1980 and 1981. See Figure 1 for explanation of panels and symbols.

Figure 4. Estimated population quantities by year for the analysis using all of the calf estimates plus an assumed estimate of 1100 for 2002. See Figure 1 for explanation of panels and symbols.

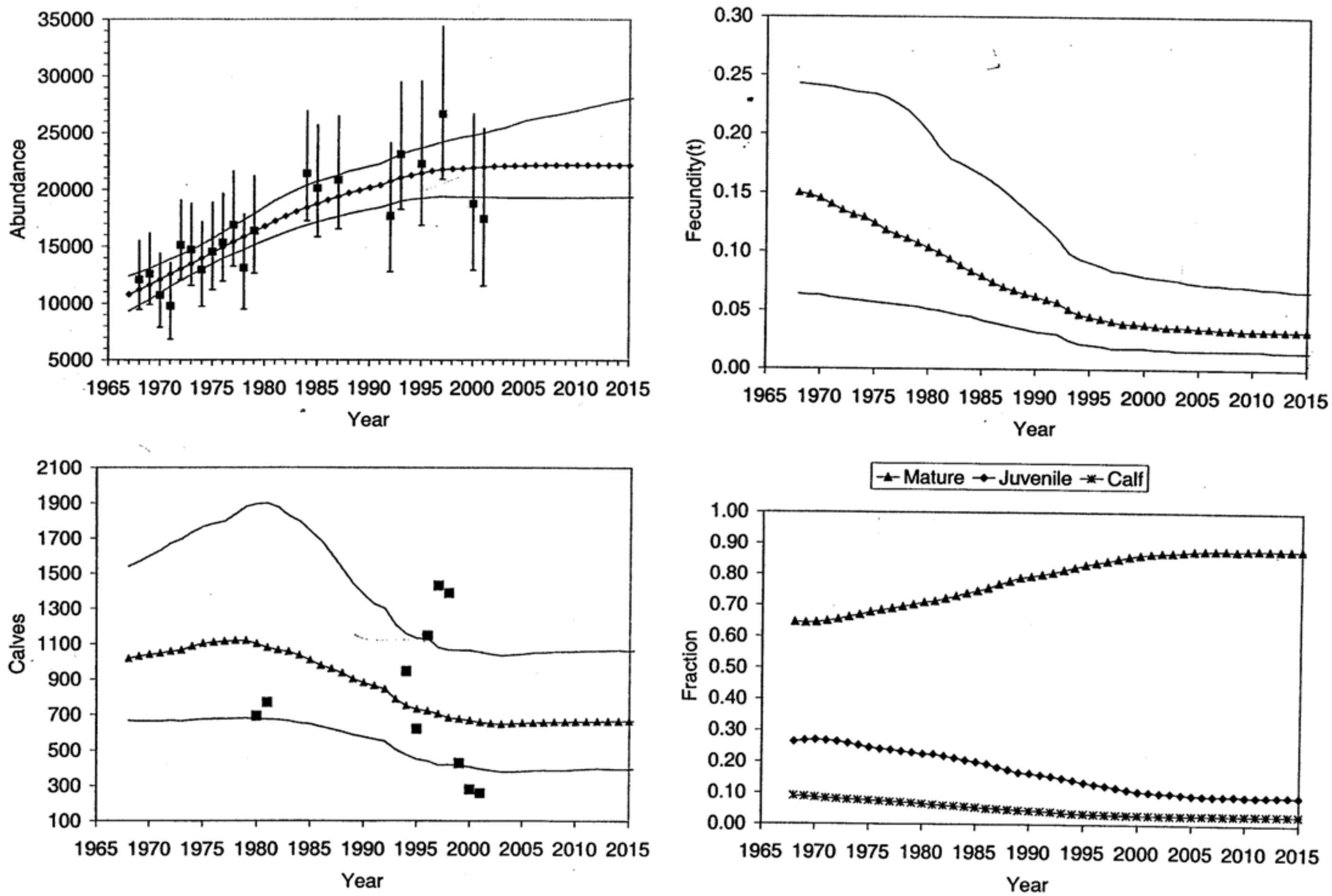
SC/54/BRG7 Figure 1. Using all the calf estimates.



SC/54/BRG7 Figure 2. Using none of the calf estimates.



SC/54/BRG7 Figure 3. Using all of the calf estimates except 1980 and 1981.



SC/54/BRG7 Figure 4. Using all of the calf estimates plus an assumed estimate of 1100 in 2002.