6-2007

Population Assessment of Western Gray Whales in 2007

Justin G. Cooke
CEMS, Alexanderstr. 10, 79261 Gutach, Germany, jgc@cems.de

David W. Weller
Southwest Fisheries Science Center

Amanda L. Bradford
Washington Cooperative Fish and Wildlife Research Unit, School of Aquatic and Fishery Sciences, University of Washington

Alexander M. Burdin
Kamchatka Branch of Pacific Institute of Geography, Russian Academy of Sciences, Far East Division, Petropavlovsk, Kamchatka 683000, Russia

Robert L. Brownell Jr.
Southwest Fisheries Science Center, rlbcetacea@aol.com

Cooke, Justin G.; Weller, David W.; Bradford, Amanda L.; Burdin, Alexander M.; and Brownell, Robert L. Jr., "Population Assessment of Western Gray Whales in 2007" (2007). *Publications, Agencies and Staff of the U.S. Department of Commerce*. 69.
https://digitalcommons.unl.edu/usdeptcommercepub/69

Paper SC/59/BRG41 presented to the International Whaling Commission Scientific Committee, June 2007, Anchorage, Alaska, USA.

SC/59/BRG 41

Population Assessment of Western Gray Whales in 2007

Justin G. Cooke[1], David W. Weller[2], Amanda L. Bradford[3], Alexander M. Burdin[4,5]
and Robert L. Brownell, Jr.[2]

[1]CEMS, Alexanderstr. 10, 79261 Gutach, Germany. Email: jgc@cems.de
[2]Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037-0271, USA
[3]Washington Cooperative Fish and Wildlife Research Unit, School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195-5020, USA
[4]Kamchatka Branch of Pacific Institute of Geography, Russian Academy of Sciences, Far East Division, Petropavlovsk, Kamchatka 683000, Russia
[5] Alaska SeaLife Center, Seward, AK USA;University of Alaska Fairbanks, Fairbanks, AK USA

ABSTRACT

A population assessment of the western gray whale (*Eschrichtius robustus*) was conducted using photo-identification data collected off Sakhalin Island under the joint Russia-U.S. programme from 1994 to 2006. This is an update of the assessments by Reeves *et al* (2005) and Cooke *et al.* (2006) which used data up to 2003 and 2005 respectively, fitted to the same, individually-based population model. New median estimates of key population parameters (with 90% Bayesian confidence intervals) are 0.982 (0.972 - 0.991) for the non-calf annual survival rate; 0.76 (0.66 - 0.85) for the survival rate from calf to yearling; 2.9% *per annum* (1.9% – 4.0%) for the average annual rate of population increase over 1994-2006; 0.45 (0.37 - 0.52) for the female sex ratio and 121 whales (112 - 130) for the 1+ (non-calf) population size in 2007. The updated assessment is more optimistic than the Reeves *et al* (2005) mainly because of the reduced calving intervals observed in recent years, implying a higher reproductive rate. The modal calving interval has shortened from 3 years up to 2002 to 2 years post-2002. This is consistent with reduced disturbance from industrial activity during 2002-04. Forward projections of the population model to 2050, assuming no additional mortality or disturbance to reproduction, indicate a high probability (>99%) of population increase. Four whales (all female) have been killed in fishing nets on the Pacific coast of Japan during the past 24 months. Projections of the female population incorporating this level of extra mortality indicate a high (>25%) probability of population decline and a substantial (>10%) risk of extirpation by 2050. It is important to avoid any further human-caused deaths in this depleted population.

1. INTRODUCTION

The western gray whale population is Critically Endangered and its continued ability to survive is of concern. Hunted to such low numbers by the mid 20th century that some thought it to be extinct, the population remains highly depleted today (Reeves *et al*., 2005; Weller *et al*., 2007). The International Whaling Commission (IWC) and the World Conservation Union (IUCN) have each expressed serious concern about the status of this population and have called for urgent measures to be taken to help ensure its protection (IWC, 2004; Reeves *et al*., 2005).

While the breeding ground for the western population has yet to be determined, but is suspected to be off southern China, the main feeding ground is known to be in the coastal waters off northeastern Sakhalin Island. The potential impact on the population arising from the exploration and extraction of oil and gas resources in the main feeding ground has been a source of concern (Reeves *et al.*, 2005). Recently the deaths of four female gray whales entrapped in fishing nets on the Pacific coast of Japan between May 2005 and January 2007 highlight the existence of other threats to this population (Kato *et al.*, 2005; Brownell *et al.* 2007).

A joint Russia-U.S. research program on western gray whales off Sakhalin Island, Russia, was initiated in 1995 as part of the Marine Mammal Project under Area V: Protection of Nature and the Organization of Reserves within the U.S.-Russia Agreement on Cooperation in the Field of Environmental Protection (Weller *et al*., 2007). Data from this ongoing Russia-U.S. collaborative study have highlighted the fragile state of the western gray whale population and are used for the analysis of this paper.

Using data collected under this programme, the Independent Scientific Review Panel (ISRP) appointed in 2004 by IUCN to examine the potential impact of the Sakhalin II oil and gas project on the western gray whale and related wildlife, conducted a population assessment of the western gray whale using the data collected through to 2003 (Reeves *et al.*, 2005).

Gray whales, like other large whales, have a multi-year calving cycle, with one or more resting years between successive calvings. Multi-stage models that take account of an individual female's reproductive stage (immature, calving, resting) have been successfully fitted to photo-identification data for right whales in the northern and southern hemispheres (Caswell *et al.,* 1999; Best *et al.,* 2001; Cooke *et al.*, 2001). The ISRP adapted the right whale stage-structure approach for application to western gray whales. The purpose of the population model was to provide a framework for further interpreting the photo-identification data so as to estimate key parameters, such as survival rates, and to determine whether the population is increasing or decreasing. The population model was also used to project the population forward under a range of scenarios. Such projections provide information relevant for determining a conservation strategy for the population.

This paper presents an update of this assessment using data collected through to 2006. A report of the 2006 field season is provided by Weller *et al.* (2007).

2. MATERIAL AND METHODS

2.1. Photoidentification and sex-determination data

Photo-identification data have been collected in the Piltun area of northeastern Sakhalin by the joint Russia-US programme from 1994 to the present, with the exception of 1996 (Weller *et al.*, 2007). Data from the seasons up to and including 2006 were available for this analysis. A total of 158 distinct individual whales (73 males, 51 females and 34 animals of unknown sex) have been catalogued. An edition of the catalogue including data from 1994-2005 has been published (Weller *et al.* 2006).

A total of 59 calves have been identified, of which 52 could be assigned to an identified mother. 32 calves were male, 15 female and 12 of unknown sex. Sex determinations have been by biopsy, except that one unbiopsied whale was identified as female on the basis of an accompanying calf. Twenty-three individual females, none of known age, have been observed with a calf. Twenty-nine inter-birth intervals have been observed, consisting of fifteen 2-year intervals, ten 3-year intervals, three 4-year intervals and one 5-year interval (Table 1). The apparent 4 and 5-year intervals may be genuine intervals, or may be the result of failing to observe an intermediate calving, failure to assign a calf to its mother, or the loss of a calf before it could be observed and recorded.

No animals of known age have yet been observed to have a calf. The oldest known female of known age known to be alive in 2006 was eight years old. On this bas is it was assumed for this analysis that the minimum age at first calving is nine years.

Table 1. Lengths of observed calving intervals by end year

	Length of interval (years)				
Total	5	4	3	2	Interval ends
1				1	1997
1			1		1998
0					1999
1			1		2000
4			4		2001
3		2	1		2002
4			1	3	2003
6	1		1	4	2004
5				5	2005
4		1	1	2	2006
29	1	3	10	15	Totals

Shaded cells represent intervals that are unobservable because they would have begun in years where little or no data were collected

The following information on each identified whale were used for this analysis:

- the year first seen, and whether first seen as an accompanied calf, as an unaccompanied calf, or as a non-calf;
- the subsequent years in which the individual was seen, and the subset of years in which it was seen with a calf;

- sex, if known.

2.2. Population model

The Population model is illustrated in Fig. 1 and described in more detail in the ISRP report (Reeves *et al.*, 2005) and in SC/57/BRG22 (Cooke *et al.*, 2005). The male population is divided into just three stages: calves (weaned and unweaned) and animals aged 1+. On the assumption that reproduction is not limited by the number of males, more detail is not needed for the males. The female population is divided into: calves (weaned and unweaned); age classes 1 through 4; immature animals aged 5+; mature animals which are resting or receptive (before their first calf or between calves); mature animals which have been resting for at least one year; and calving mothers (divided into those still accompanying their calf and those who have already weaned it). The time resolution of the model is one year, and the stages refer to the state of animals during the summer study season off Sakhalin Island.

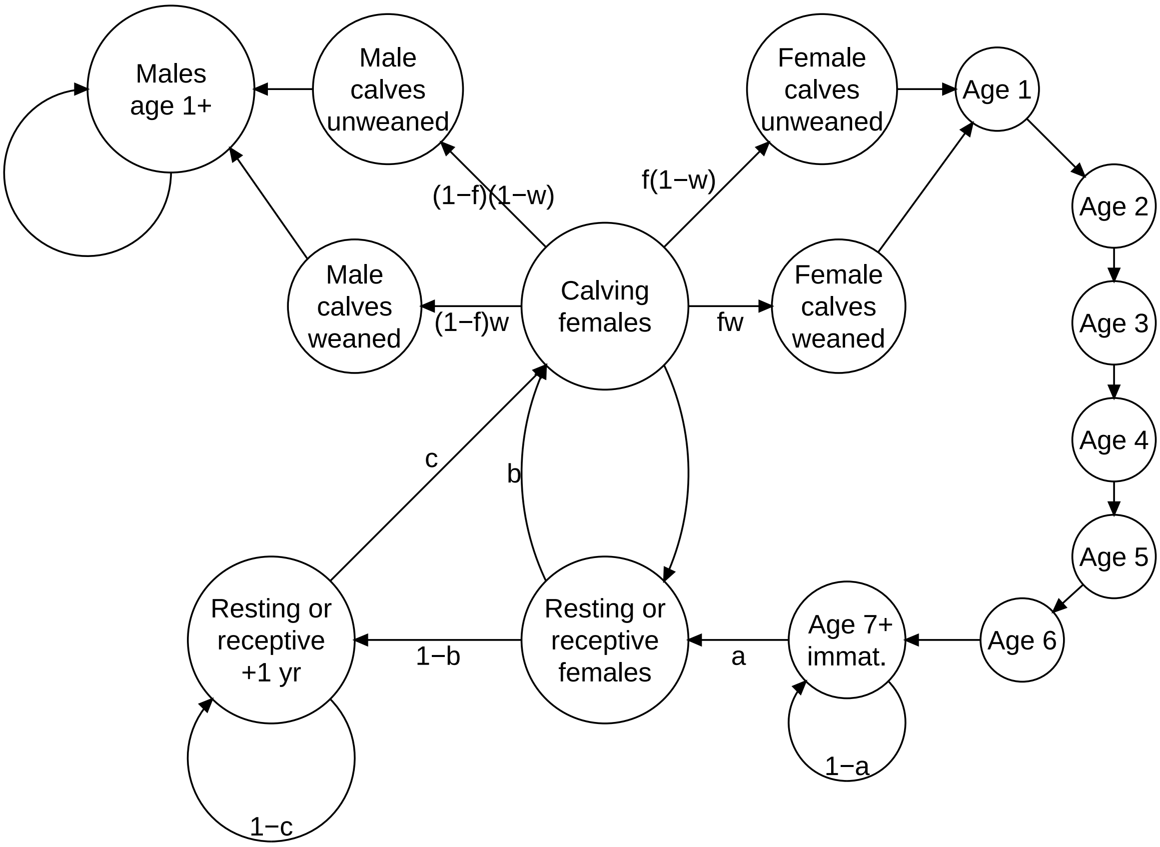

Fig. 1. Structure of population with transition probabilities/rates between classes (exluding mortality).

The distinction between weaned and unweaned calves has no demographic significance but is necessary for fitting the data because some calves have already separated before the Piltun study season and cannot be assigned to a mother.

Once a female has reached age 7, it is assumed thereafter to have a constant annual probability *a* of becoming mature. On maturity it then enters the first Resting/Receptive class where it has an annual probability *b* of having a calf the following year, and a probability $1 - b$ of entering the second Resting/Receptive class (females which have been resting for at least one year). After resting for a year, the whale has a probability *c* of having a calf the following year, and a probability $1-c$ of resting for a further year. The youngest age a female can become mature is 8 years and the youngest age it can have a calf is 9 years. After having a calf, females return to the Receptive/Resting class. The probabilities *b* and *c* of "having a calf" actually refer to the probability that a calf is born and survives the migration to the study area. The minimum interval between calves in the data and the model is two years.

The calving probabilities *b* and *c* are allowed to vary randomly from year to year, as in the ISRP assessment.
Since *b* and *c* must take values between zero and one, their variation is modelled on the logit scale. We write:

$$b_t = \frac{\exp(\beta + \sigma v_t)}{1 + \exp(\beta + \sigma v_t)} \qquad c_t = \frac{\exp(\gamma + \sigma v_t)}{1 + \exp(\gamma + \sigma v_t)}$$

where β is a parameter determining the median calving probability without resting, γ is a parameter determining the median calving probability after resting, and σ determines their inter-annual variance. For each year, ν_t is an independently distributed standard normal random variable which expresses the extent to which the favourability of external circumstances for reproduction differ from the average. The external factors that affect reproduction are still largely unknown, and we make no assumptions about their nature, apart from assuming that the variation in their effects on reproduction can be modelled as specified here.

The model has just two survival parameters: the calf survival probability *Sj* for calves to age 1; and the non-calf survival probability *S*. The "calf" survival rate *Sj* represents survival from the animal's first summer season to the next summer season (*i.e.* age 6-18 months). Calf mortality before the first summer season is subsumed into the calving probability, which reflects the probability of producing a calf that survives to the first summer season.

2.5. Fitting the model to the data

The data used for fitting the model consisted of the observation histories of each of the 158 individuals. Each observation history consists of the list of years in which the individual was seen, with the indication of whether the individual was a calf or had a calf in the given year. The sex of the individual, where known, was also used. The fitting of the model to the data is Bayesian, as detailed in Annex F of the ISRP report (Reeves *et al*., 2005). The prior distributions of the parameters as specified in Table 1 are combined with the likelihood according to Bayes' rule to produce the joint posterior distribution of parameters and population states in the years 1994-2006. A Monte Carlo Markov Chain algorithm was used to compute a random sample from the posterior distribution.

The formulation of the likelihood function reflects the assumptions made about the relationship between the whales' actual biographies and the data. Because survey effort has been variable, we do not assume that all whales are present in the study area every year, nor that they are necessarily identified in every year that they are present, nor do we assume that the probability that a whale is identified in a season is constant from year to year. Calves tend to separate from their mothers as the season progresses, and we do not always determine the mother of an observed calf. We therefore do not assume that whales seen without calves did not have a calf in the season. The probability of observing a whale in a given year is allowed to depend on the sex and life stage of the whale (e.g. immature, calving, resting) and to vary annually, as described by Reeves *et al.* (2005).

2.4. Additional mortalities

One female, apparently a yearling, died in a net in Tokyo Bay in May 2005 (Kato *et al.*, 2005). Two more whales (a mother and a female calf) were taken in a net near Enoshima, Oshika peninsula, northeastern Honshu, Japan in July 2005, while an additional female (of unknown life stage but apparently not a calf) was found in a trap net in Yoshihama Bay in January 2007 (Brownell *et al*. 2007). In the absence of genetic samples and photographs from these animals, it was not possible to determine whether the three non-calf animals were previously known individuals from Sakhalin, but we assume that these whales are from the population feeding off the northeastern coast of Sakhalin Island.

Given that only three mortalities, all strandings, had been recorded on the Pacific coast of Japan in the preceding 20 years (Kato *et al.* 2005) it seems reasonable to treat this recent spate of deaths as additional mortality, not covered by the average natural mortality rate estimated for 1994-2005.

The losses were accounted for in the population model by deducting, for each known death, one animal chosen randomly from the population component or components from which the dead animal could have come, after excluding animals subsequently seen alive.

2.5. Projections

Stochastic projections of the population forward to 2050 were generated by sampling randomly from the posterior distribution of parameter values and population states in 2006. Each sampled population state was simulated forwards on an individual whale basis as described by Reeves *et al* (2005). For each year forward to 2050, the 1st, 5th, 10th, 25th and 50th percentiles of the distribution of population sizes was extracted from the sample of simulations for the following population components: total non-calf (aged 1+) population; reproductively mature females; and aged 1+ females.

Two sets of projections were generated. The base case scenario assumed no additional sources of mortality apart from the 4 whales taken in 2005-07. The alternative scenario assumed that female population continues to be subject to an additional mortality averaging 2 animals per year, this being the average rate over the last 24 months, as of the time of writing. The extra mortality was drawn randomly without replacement from the female population in each year from 2008 onwards, prior to the field season. Although it is not necessarily considered likely that this level of extra mortality will continue, the purpose of the scenario is to investigate the consequences of this level of mortality for the population.

3. RESULTS

3.1. Parameter estimates

Estimated distributions for the key population parameters in the base-case model are shown in Table 2. The median parameter estimates are 0.982 for the non-calf adult survival rate, 0.76 for the "calf" survival rate (i.e. survival from first to second summer season), 0.45 for the sex ratio (female proportion) and 2.9% per annum for the rate of population increase over the data series (1994-2006). Approximate Bayesian 90% confidence limits are 0.972-0.991 for the adult survival rate, 0.66-0.85 for the calf survival rate, 0.37-0.52 for the female sex ratio and 1.9%-4.0% for the annual rate of population increase. The median estimate for the non-calf population size in 2007 is 121 animals (90% confidence interval 112-130). The median estimate of the number of mature females in 2007 is 28 with 90% confidence limits 24 to 33.

The distribution of the estimates of annual maturation probability of age 7+ females is not much more concentrated than its prior range (0.2-1.0). This implies that the data contain little no information on this parameter. This is because no known-age western gray females have yet been observed to have a calf. If this series of western gray whale surveys is continued, then we would expect to start to see known age females reproducing over the next few years, which will substantially improve estimation of this parameter. The oldest known-age female observed in 2006 was eight years old. However, the data cannot exclude the possibility that young mothers breed cryptically, e.g. by weaning their calves early, before arrival at Piltun.

The distributions for most of the other population parameters are clustered well within the prior ranges, hence are not constrained by the assumed prior ranges. However, the data do not seem to place a well-defined upper bound on the variance of the annual calving probabilities.

3.2. Projections

The results of the base-case projections (no additional mortality or disturbance to reproduction) for four components of the population are shown in Figs 2a-d. The median projections show a substantial increase in the population by 2050. Even the 1st percentile of population sizes shows an increase, which implies a greater than 99% chance of a population increase to 2050, if the assumptions of this scenario hold. The projected population in 2050 is still substantially below estimated pre-whaling population levels (Weller *et al*, 2002).

Under the assumption that the level of offtake (through net entrapment) of the past 24 months continues, the female population is predicted to decline with high (25-50%) probability, and with a substantial (10-25%) probability of extirpation by 2050 (Fig. 3).

4. DISCUSSION

The results of this modelling exercise demonstrate the utility of the data collected during the ongoing joint Russia-US programme in terms of estimating key population parameters and to draw inferences about the current status of the population and its likely future trend under different scenarios.

This assessment is more optimistic than the ISRP assessment (Reeves *et al.*, 2005), which used data only up to 2003. The new median estimate of the 1+ population size in 2004 is 110 animals, compared with 102 animals in 2004 in the ISRP assessment. In addition, the population is estimated to have increased from 110 to 121 animals between 2004 and 2007. These estimates compare with ordinary mark-recapture abundance estimates (not incorporating population structure) of 98 whales (95% CI=89-110) in 2002 and 99 (95% CI = 90-109) in 2003 (Wade *et al*. 2003; Weller *et al*., in prep).

The main cause of the more optimistic assessment appears to be the shortening of calving intervals observed in the most recent years (Table 1). The modal calving interval has reduced from 3 to 2 years and the proportion of 2-year intervals has increased. Of the observed intervals ending in 2004-2006, 11 out of 16 were two years in length.

The current estimate of annual non-calf survival rate, at 0.983 (95% CI 0.972-0.991) is higher than the value of 0.951 (95% CI 0.917-0.972) obtained by Bradford *et al.* (2006) using data from 1997-2003. The difference appears to be partly caused by the re-sighting, post-2003, of some of the potential mortality candidates implied by the lower survival estimate. However, when using the model of this paper, omitting the post-2003 data resulted in only a small reduction in the estimated non-calf survival rate. The differences between the models used in the two analyses also play a role. In particular, the model used by Bradford *et al.* allows an arbitrary number of new whales to enter the population each year, such that a low survival rate can be consistent with an increasing population. The model of this paper assumes that new whales come from reproduction within the population. With some experimentation, we found that we could obtain a median survival estimate close to that of Bradford *et al.* by doing *both* of: (i) omitting post-2003 data; *and* (ii) adjusting the population model to allow for additional reproduction of a kind that would escape detection. It is expected that as more data accumulate, the estimates of demographic parameters will become less sensitive to assumptions.

A key assumption underlying this and previous analyses is that the entire population visits the Piltun study area, albeit not necessarily every year. If there is a component of the western gray whale population that never visits Piltun, then the population estimates of this paper will not include it. Vertyankin *et al.* (2004) report sightings of gray whales off S.E. Kamchatka, some of which, but perhaps not all, may belong to the Piltun population. Vertyankin *et al.* speculate that the feeding ranges of eastern and western gray whales may overlap near Kamchatka, but in the absence of a comprehensive photo-id catalogue of eastern gray whales, this is hard to confirm.

The good numbers of calves present during 2003-05 presumably reflect conditions during 2002-04. It is not possible to assign a specific cause to the variations in calf production, but the data are consistent with calf production tending to be good in years with little disturbance, because the 2002-04 seasons were apparently relatively quiet with little or no seismic surveying or construction work (IISG, 2006). Offshore construction work for the Sakhalin II project resumed in 2005 and continued in 2006 and 2007 (WGWAP, 2007). If calf production is negatively impacted by disturbance due to construction work, then lower calf production might be expected in 2006-2008. Four calves were observed in 2006, and the median estimate calf production was 8 (90% CI 5-12). This is the lowest estimated calf production since 1999. The projected calf production in 2007 is 12 (90% CI 4-23), assuming that there have been no negative impacts of recent construction work.

The recent increased level of net-caused mortality is a source of concern in such a small population. If this level of mortality continues, the population is projected, with high (>25%) probability, to decline towards extirpation. Every effort should be made to avoid a recurrence of these mortality events and to minimise or eliminate human-caused mortalities in this depleted population.

REFERENCES

Best, P.B., Brandão, A. and Butterworth, D.S. 2001. Demographic parameters of southern right whales off South Africa. *J. Cetacean Res. Manage.* (Special Issue 2):161-169.

Bradford A.L., Wade P.R., Weller D.W., Burdin A.M., Ivashchenko Y.V., Tsidulko G.A., VanBlaricom G.R., and Brownell R.L. Jr. 2006. Survival estimates of western gray whales *Eschrichtius robustus* incorporating individual heterogeneity and temporary emigration. *Mar. Ecol. Prog. Ser.* 315:293-307.

Brownell R.L., Kasuya T. and Weller D.W. 2007. Entrapment of gray whales in Japanese fishing gear: population threats. Paper SC/59/BRG38.

Caswell, H., Fujiwara, M. and Brault, S. 1999. Declining survival probability threatens the North Atlantic right whale. *Proc. Natl Acad. Sci. USA* 96:3308-3313.

Cooke, J.G., Rowntree, V.J. and Payne, R.S. 2001. Estimates of demographic parameters for southern rght whales (*Eubalaena australis*) observed off Península Valdés, Argentina. *J. Cetacean Res. Manage.* (Special Issue 2):125-132.

Cooke, J.G., Weller, D.W., Bradford, A.L., Burdin, A.M., and Brownell, R.L. 2005. Estimates and projections of the western gray whale population using an individually-based population model. Paper SC/57/BRG22.

Cooke, J.G., Weller, D.W., Bradford, A.L., Burdin, A.M., and Brownell, R.L. 2006. Population assessment of western gray whales in 2006. Paper SC/58/BRG30.

Interim Independent Scientists Group (IISG) 2006. Report of the Interim Independent Scientists Group (IISG) on mitigation measures to protect western gray whales during Sakhalin II construction operations in 2006, Vancouver, British Columbia, 3-5 April 2006. International Union for Conservation of Nature (IUCN), Business and Biodiversity Program. http://www.iucn.org/themes/marine/sakhalin/ISRP_Followup/IISG April 2006.htm.

International Whaling Commission. 2004. Resolution on Western North Pacific Gray Whales. Annual Report of the IWC 2004, p. 66.

Kato, H., Ishikawa, H., Mogoe, T. and Bando, T. 2005. Occurrence of a Gray Whale, *Eschrichtius robustus,* in the Tokyo Bay, April – May 2005, with its Biological Information. Paper SC/57/BRG18.

Reeves, R.R., Brownell, R.L., Burdin, A., Cooke, J.C., Darling, J.D., Donovan, G.P., Gulland, F.M.D., Moore, S.E., Nowacek, D.P., Ragen, T.J., Steiner, R.G., VanBlaricom, G.R., Vedenev, A. and Yablokov, A.V. 2005. Report of the Independent Scientific Review Panel on the Impacts of Sakhalin II Phase 2 on Western North Pacific Gray Whales and Related Biodiversity. IUCN, Gland, Switzerland and Cambridge, UK. 123pp. http://www.iucn.org/themes/marine/sakhalin/isrp/index.htm.

Vertyankin V.V., Nikulin V.C., Bednykh A.M. and Kononov A.P. 2004. Sighting of gray whales (*Eschrichtius robustus*) near southern Kamchatka. pp. 126-128 in *Marine Mammals in the Holarctic*, Collection of Scientific Papers of Conference, Koktebel, Ukraine, October 11-17, 2004 (in Russian).

Wade, P.R., Burdin, A.M., Bradford, A.L., Brownell, R.L., Jr. and Weller, D.W. 2003. Abundance estimates of western gray whales (*Eschrichtius robustus*) off northeastern Sakhalin Island, Russia. Paper SC/55/BRG18.

Weller D.W., Burdin, A.M., Würsig, B., Taylor, B.L., and Brownell, R.L. Jr. 2002. The western gray whale: a review of past exploitation, current status, and potential threats. *J. Cetacean Res. Manage.* 4:7-12.

Weller, D.W., Bradford, A.L., Tsidulko, G.A., Ivashchenko, Y.V., Lang, A.R., Kim, H.W., Burdin, A. M. and Brownell, R.L., Jr. 2006. A catalog of photo-identified western gray whales from Sakhalin Island, Russia. Paper SC/58/BRG2 + CD.

Weller, D.W., Bradford, A.L., Lang, A.R., Kim, H.W., Krukova, N., Tsidulko, G.A., Burdin, A.M. and Brownell, R.L., Jr. 2007. Status of western gray whales off northeastern Sakhalin Island, Russia, in 2006. Paper SC/59/BRG19.

Weller, D.W., Bradford, A.L., Wade, P.R., Burdin, A.M. and Brownell, R.L., Jr. In Preparation. Population abundance and growth rate of western gray whales off northeastern Sakhalin Island, Russia.

Western Gray Whale Advisory Panel (WGWAP). 2007. Report of the 2nd Meeting. http://www.iucn.org/themes/marine/sakhalin/meetings_2.html.

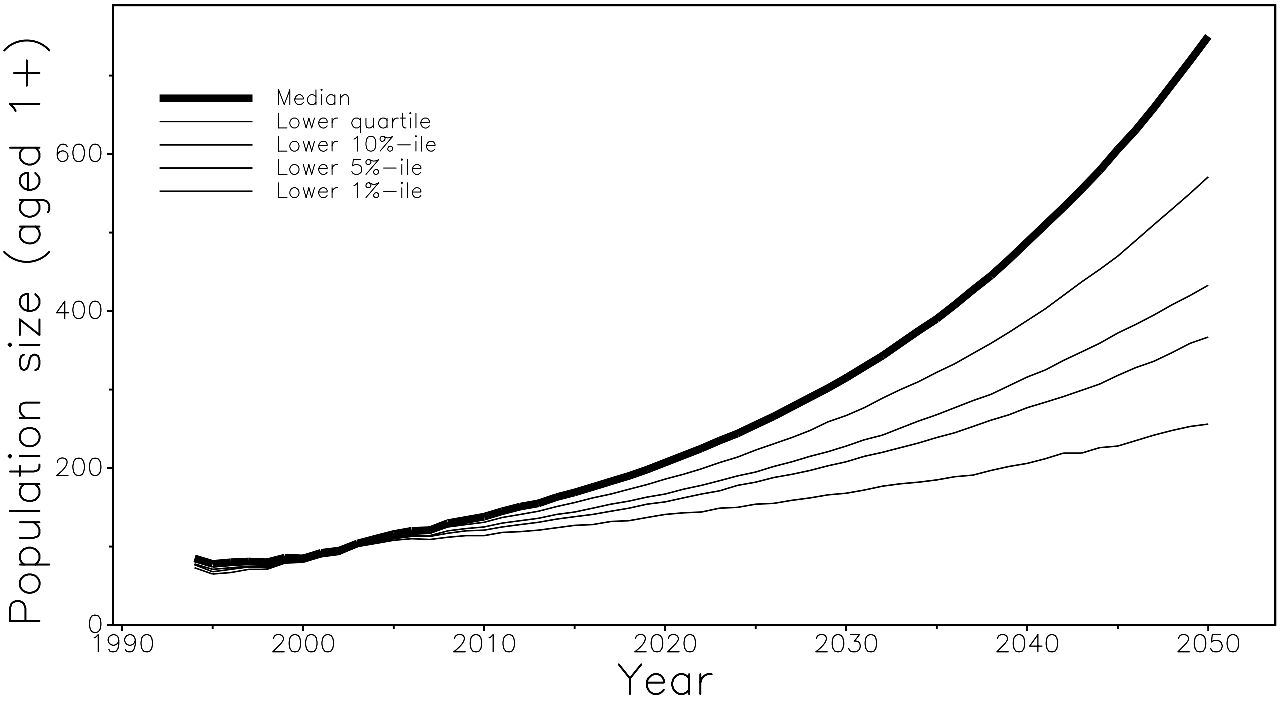

Fig. 2a. Western Gray Whale population trajectories 1994-2050: 1+ population

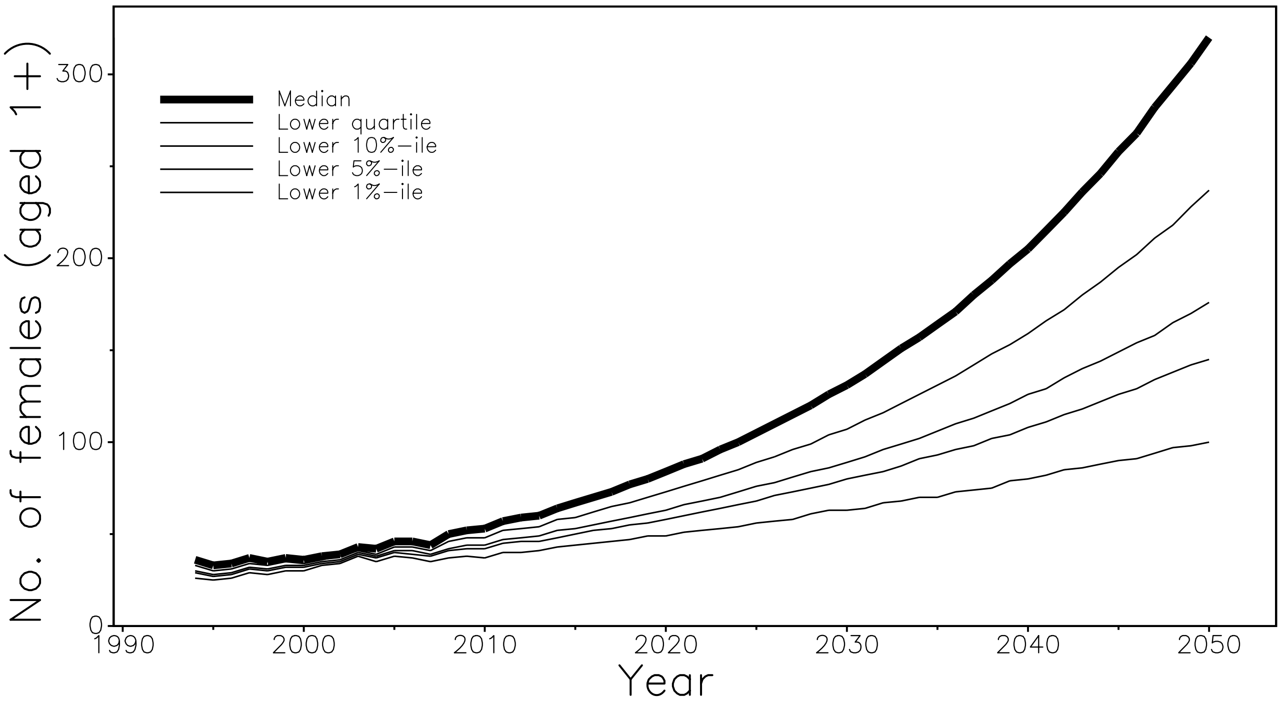

Fig. 2b. Western Gray Whale population trajectories 1994–2050: female 1+ population

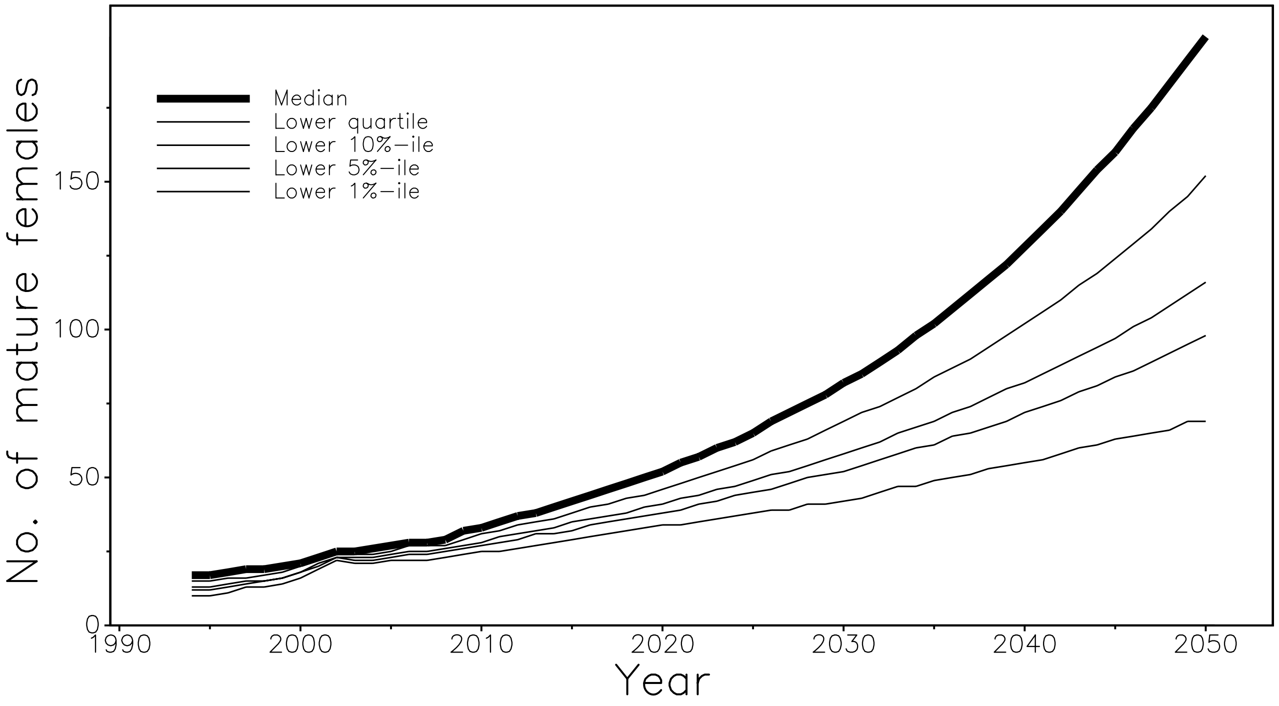

Fig. 2c. Western Gray Whale population trajectories 1994–2050: mature females

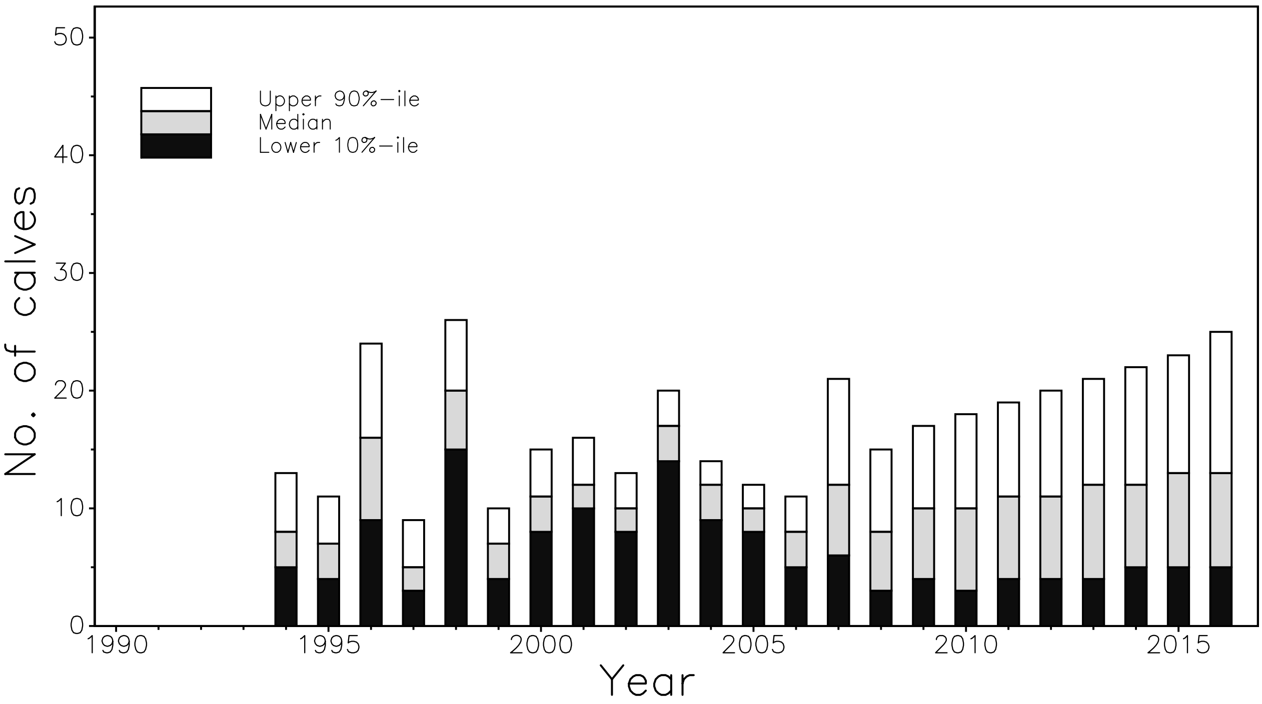

Fig. 2d. Western Gray Whale population trajectories 1994–2015: calves

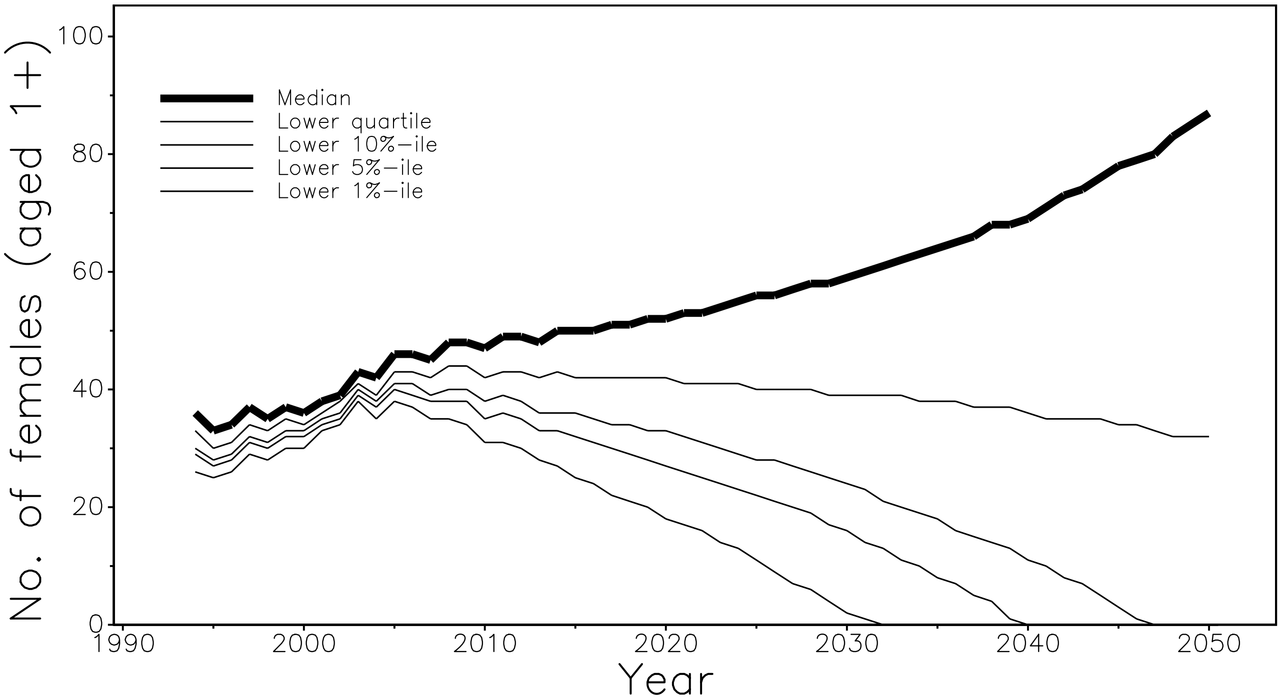

Fig. 3. Western Gray Whale population trajectory (1+ females) 1994–2050
Assuming annual additional mortality at recent level (2 animals/yr)

Table 2. Parameters of the models, prior ranges and percentiles of posterior distributions

	Prior range		Percentiles of posterior								
Parameter	Min	Max	1	5	10	25	50	75	90	95	99
Population model parameters											
Population 1994 P_0	50	250	57	62	65	69	75	81	86	89	96
Annual survival non-calf S	0	1	0.967	0.972	0.974	0.978	0.982	0.986	0.989	0.991	0.993
Calf survival Sj	0	1	0.614	0.660	0.682	0.721	0.761	0.799	0.833	0.851	0.881
Female sex ratio f	0	1	0.343	0.374	0.390	0.417	0.445	0.475	0.500	0.515	0.548
Maturation probability a	0.2	1	0.214	0.236	0.256	0.349	0.488	0.640	0.792	0.859	0.930
Median calving prob. b	0	1	0.221	0.311	0.363	0.438	0.517	0.600	0.672	0.721	0.797
Median calving prob. c (rested)	0	1	0.396	0.485	0.537	0.645	0.760	0.865	0.934	0.963	0.989
Calving prob SD σ	0	2	0.076	0.206	0.315	0.534	0.838	1.260	1.629	1.780	1.951
Derived parameter											
Annual rate of increase *1994-2005*			0.015	0.019	0.021	0.025	0.029	0.033	0.038	0.040	0.045
Observation model parameters											
Probability weaned w	0	1	0.060	0.078	0.092	0.116	0.148	0.181	0.212	0.235	0.284
Sight prob SD τ	0	2	0.323	0.378	0.406	0.467	0.543	0.638	0.735	0.808	0.982
Median sampling prob. Cows&Calves	0	1	0.409	0.472	0.500	0.548	0.599	0.649	0.690	0.714	0.760
Median sampling prob. immatures	0	1	0.330	0.378	0.406	0.458	0.527	0.600	0.678	0.725	0.795
Median sampling prob. Resting	0	1	0.479	0.531	0.559	0.606	0.654	0.705	0.746	0.771	0.813
Median sampling prob. Males 1+	0	1	0.501	0.543	0.561	0.592	0.628	0.667	0.697	0.714	0.745