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Some examinations of uncertainties in the prey consumption estimates of common minke, sei and Bryde's whales in the western North Pacific

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ABSTRACT

The purpose of this study was to examine the uncertainties in the prey consumption estimates of common minke whale (*Balaenoptera acutorostrata*), sei whale (*B. borealis*) and Bryde's whale (*B. edeni*) in the western North Pacific in response to some recommendations from the JARPN II review workshop. The uncertainties of some parameters and consumption estimates by different models were examined, and suggestions for future collection of data and works were made. The differences in consumption rates estimated from different models increased with body mass. At this stage it is not possible to disregard the difference of energy contents among the preys. If the proportion of the energy intake during high feeding season (*P*) was between 70-90%, the range of *H index* (feeding index in high feeding season) in common minke, sei and Bryde's whales were estimated in the range 1.05-1.72, 1.19-1.80 and 1.19-1.80, respectively. Daily prey consumption was estimated using two different models (Equation 6 providing the smallest estimates and Equation 7 providing the largest estimate) and the *H index* above, by sex and maturity status for each of the whale species. The range of daily consumption estimates of mature female common minke, sei and Bryde's whales were 47-158kg, 102-491 and 132-577 kg, respectively. A comparison of these estimates by the two models with actual stomach content weight suggested that consumption by Equation 6) appears to be underestimated because consumption estimates by this equation is equal to just a single intake. The range of total prey consumption in the JARPN II research area for common minke whales was 90 thousands tons (95%CI: 54-150 thousands tones) by Equation 6 and 260 thousands tones (95%CI: 155-438 thousands tones) by Equation 7, respectively. The value of Equation 7 was 2.9 times larger than the value of Equation 6. The validity of different models for estimating the total consumption can be investigated with additional data collected by JARPN II. In this way it might be possible in the near future to provide estimates with narrow range.

KEYWORDS: COMMON MINKE WHALE; BRYDE'S WHALE, SEI WHALE, NORTH PACIFIC; JARPN II; CONSUMPTION RATES

INTRODUCTION

In January 2009 IWC/SC conducted the Expert Workshop to review the ongoing JARPN II Programme (IWC, 2009). The results presented on the first objective of JARPN II (Feeding ecology and ecosystem studies) were discussed by the Independent Expert Panel (IEP) into two sections: prey consumption and prey preference of whales, and ecosystem modelling. Regarding to the prey consumption rate estimates presented to the workshop (Tamura *et al.*, 2009) one of the major concern of the IEP related to the lack of full treatment of uncertainty. As part of the treatment of uncertainty the IEP recommended that the analyses of the JARPN II data should: (a) incorporate the use of several reasonable models and include the range of possible results in reporting the work; (b) use that range in subsequent analyses (including any ecosystem modelling) that employ these daily/annual consumption estimates and (c) undertake sensitivity analyses for the range of parameter values used in the consumption equations (IWC, 2009).

The objective of this study is to examine the uncertainty in several components involved in estimating the amount and types or prey consumed by whales. This examination was assisted by a recent review of whale consumption estimates by Leaper and Lavigne (2007). Following the recommendations from the IEP several models for estimating daily prey consumption in whales were examined and evaluated. This involved an examination of several parameters used in these models. Also the data and information regarding parameters involved in the extrapolation from daily, individual whale consumption rates to annual, population level rates were examined. Some suggestions are made for decreasing the uncertainties of some parameters and consumption rate estimates.

RESULTS AND DISCUSSION

Estimation of daily prey consumption

Examination of different consumption models for large baleen whales

The daily prey consumption estimates by Tamura *et al*. (2009) was based on a single model (Sigurjónsson and Víkingsson, 1997, Equation 7 below). In this section different models are examined to investigate uncertainty in the estimates due to the use of different models. This examination followed the review of consumption estimates by Leaper and Lavigne (2007). The models are represented by the following equations:

(1) $R = AM^{B}$

Where *R* is the consumption rate in kg per day, *A* and *B* are constants and *M* is body mass in kg.
Kleiber (1975) suggested that *A* and *B* were 293.1 and 0.75, respectively.

(2) $BMR = 293.1M^{0.75}$

Where BMR is energy requirement in kJ per day. Lavigne (1996) proposed the following formula based on Equation 2 above:

(3) $ADMR = \beta(293.1M^{0.75})$

ADMR (Average Daily Metabolic Rate) is equivalent to the average *FMR* (Field Metabolic Rate). For cetaceans, βis often assumed to be in the range of 2-5. Some studies have used β=2.5 (*e.g*. Kenney *et al*., 1997). This value was also adopted for the present analysis

(4) $R = 0.42\ M^{0.67}$ (Innes *et al*., 1986)

(5) $R_{i,s} = 0.1\ _{i,s}M^{0.8}$ (Trites *et al*., 1997)

R is the daily prey consumption (expressed by kg) and *M* is body mass in kg. The *i* is each species and *s* is the sex.

(6) $FMR = 2529.2\ M^{0.524}$ (Boyd, 2002)

(7) $FMR = 863.6M^{0.783}$ (Sigurjónsson and Víkingsson, 1997)

(8) $FMR = 80\ M$ (Blix and Folkow, 1995)

FMR is the daily prey consumption (expressed in KJ d^{-1}) and *M* is body mass in kg.

(9) $R = 1.66M^{0.559}$ (Reilly *et al*., 2004)

R is the daily prey consumption (expressed in kg) and *M* is body mass in kg. However, this equation leads the mean daily prey consumption during the feeding period in the Antarctic. We did not consider this model in our analysis.

Leaper and Lavigne (2007) considered that the appropriate consumption estimates is between the high end by Equation 4 and at the low end by Equation 6. The estimate of consumption by Equation 7 was considered by these authors at the upper range of reasonable values.

For the comparative analysis in this paper Equations 3 to 8 were considered. It should be noted here that the estimates from Equations 4 and 5 depend only on the body mass data (expressed in kg). The estimates from Equations 3, 6, 7 and 8 require body mass data (expressed in kg) and energy content of prey (expressed in kJ kg^{-1}).

For the comparative analysis it was assumed that the energy content of prey and assimilation efficiency was 5,450 kJ kg^{-1} (commonly used value for fish prey e.g. Sigurjónsson and Víkingsson, 1997) and 80% (Lockyer, 1981a), respectively.

Table 1 and Figure 1 shows the daily prey consumption (in kg) estimated by Equations 3 to 8 in relation to body mass. Among the equations the highest value of consumption (by body mass) was 2.6 to 5.1 times larger than the lowest one. Differences become larger as body mass increase.

The highest estimates were calculated by Equation 4 for body mass < 5,500kg and by Equation 7 for body mass > 6,000kg. On the other hand the lowest estimates were almost from Equation 6. If the body mass was 1,000kg, the difference of estimates was 35 kg (feeding consumption per body mass = 3.5%) among these equations. However, if the body mass was 35,000kg, the difference of consumption estimates was 576 kg (feeding consumption per body mass = 1.6%) among these equations. Leaper and,Lavigne (2007) concluded that both theoretical and empirical evidence indicate that values of B of Kleiber equation greater than 0.75 were not appropriate for large whales.

It is not possible at this stage to evaluate the appropriateness of each of the models. Therefore for the subsequent examinations in this study the two models represented by the equations giving the smallest and largest estimates (Equations 6 and 7, respectively) will be used.

Energy contents of prey species

Data on energy content of prey species is required for the daily prey consumption estimates using Equations 3, 6, 7 and 8.

Stomach contents analyses show large variations in the diet of baleen whales in the western North Pacific (Kasamatsu and Tanaka, 1992; Tamura 1998; Tamura and Fujise, 2002). In the North Atlantic the energy content of the prey species varies from 900kcal kg^{-1} (3,760 kJ kg^{-1}) in the case of *Parathemisto* spp. to as high as 3,000kcal kg^{-1} (12,540 kJ kg^{-1}) in the case of herring (Markussen *et al*., 1992). The study on prey consumption under JARPN II is based on Equation 7, which requires data on energy content of preys. For this aim the mean caloric value of copepod (*Neocalanus cristatus*), krill (*Eupahusia pacifica*), Japanese sand lance (*Ammodytes personatus*), Japanese anchovy (*Engraulis japonicus*), Pacific saury (*Cololabis saira*), walleye pollock (*Theragra chalcogramma*) and Japanese flying squid (*Todarodes pacificus*) were calculated using bomb caloric meter (results are shown in Table 2). There are differences in energy content among those prey species as well within the species according to body length. For example the difference in energy content between large and small Pacific saury was 2.5 times (Table 2). This implies that energy content of Pacific saury will change through its life cycle. The life span of Pacific saury is 1.5 years, with a maximum length of 40cm. Fish growth to 24-29cm at 0.5-year old and to 30cm when they reach 1-year old. They move northwards in summer for feeding, and southwards in late-autumn for reproduction.

For common minke and sei whales the energy contents of their prey species varies from 3,556kJ kg^{-1} when they feed on krill to as high as 13,138kJ kg^{-1} when they feed on large Pacific saury. For Bryde's whale the energy content of their prey species varies from 3,556kJ kg^{-1} when they feed on krill to as high as 6,420kJ kg^{-1} when they feed on large Japanese anchovy.

For estimating daily prey consumption using Equations 3, 6, 7 and 8, differences in energy content among the preys, and within a prey species according to body length and maturity status, can not be disregarded. As mentioned above, under the JARPN II research the actual energy content of each prey species of baleen whales in the western North Pacific was obtained using bomb caloric meter. However, these energy contents are based only on a single individual by prey species. The data are insufficient and more individuals should be analyzed by prey species and also to take into account seasonal variations. The limited number of individuals currently analyzed for energy content might bring some uncertainty to the results and effort will be made to analyze a large number of individuals.

One of the parameters used for estimating daily prey consumption in the JARPN II study is the prey composition in each sub area and month. Table 3 shows the prey composition of each baleen whale species, by sub-area and month. Table 4 shows the energy contents of three baleen whale species estimated from stomach content, by sub-area and month. These values were estimated on the basis of information of prey composition in stomach contents and energy content of preys. Some uncertainty could be involved in the information in Table 4 as data are insufficient for some months in some sub areas and because the limited information on energy content of prey species as noted above. However it is expected that more precise values will be obtained through the accumulation of further data.

Body mass (M), sex and sexual maturity of whales

Body mass is one of the important parameters in the equations for estimating daily prey consumption. Furthermore under the JARPN II research, prey consumptions are estimated by sex and sexual maturity status of the whales. Therefore the accuracy of such parameters is important.

In JARPN II males of common minke, Bryde's and sei whales are defined as sexually mature by testis weight (larger side) of more than 290g, 560g and 1,090g, respectively (Bando *et al*., unpublished data). Female are defined as sexually mature by the occurrence of at least one corpus luteum or albicans in their ovaries. These criteria are practical ones and confirmed biologically (Bando *et al*, personal communication). The composition of whales based on sex and sexual maturity status is shown in Table 5. It is suggested that there is little uncertainty in the information contained in this table.

Under JARPN II the body mass data (< 22,000kg) are obtained directly by using the large electronic weighing system. If the body mass was over 22,000kg, total weight is obtained by the sum of the weight of body parts. It is suggested that there is little uncertainty in measuring body mass in this way. Table 6 shows the body mass of each whale species, by sex and sexual maturity and by sub-area and period. It should be noted that additional body mass data are need to take into account seasonal variations. Current data on body mass might bring some uncertainty to the results. Seasonal (monthly) variation in body mass will be investigated in the near future.

Daily prey consumption in the high feeding season

Ratio of low feeding/high feeding intake (r) and index of high feeding season (H index)

Baleen whales are generally known to migrate between feeding grounds in high latitudinal waters in summer and the breeding grounds in low latitudinal waters in winter.

The ratio of high to low feeding seasons and the proportion of the energy intake per year during the high feeding season are assumed without actual data. This could bring some uncertainty to the estimations. For example Lockyer (1981a) indicated that around 83% of the annual energy intake in Southern Hemisphere balaenopterid species is ingested during the summer season (*P*). If the number of days of high feeding season (*HD*) is 120 days and the rest of the days (245) is low feeding season (*LD*), the ratio of low feeding/high feeding intake (*r*) is 0.10. Leaper and Lavigne (2007) estimated the *r* to be from 0.34 (Antarctic minke whales) to 0.62 (North Atlantic minke whales) based on other sources.

The *r* was calculated as following:

$$r = ((365(1-P)) / (365-HD))/ (365P/HD)$$

P is the proportion of the annual energy intake ingested in the feeding season.

Table 7 and Figure 2 show the relationship between *r* and *HD* for a range of *P* 70-90%. The gray portion in Figure 2 corresponds to the estimated range of *r* in Antarctic minke and North Atlantic common minke whales as estimated by Leaper and Lavigne (2007). Based on this analysis in this study the range of *r* was assumed as 0.10-0.62.

The daily prey consumption in the high feeding season was assumed as a feeding index of high feeding season (*H index*). If the *HD* is 120 days and P is 80%, the *H index* is 2.43. The *H index* was calculated as follow:

$$H\ index = 365P/HD$$

Table 7 and Figure 3 shows the relationship between H index and HD for *P*=70-90%. Figure 3 also indicates the feeding season period for the baleen whale species under study in JARPN II.

If the *r* is assumed to be 0.6 (Folkow *et al*., 2000), our assumptions on feeding period will be met. It should be noted however, that in order to calculate *r* more precisely, it is important to assess the energy storage of the baleen whales during feeding season in the future.

Ratio of high feeding season (days) in a year (*HD*)

During the JARPN II research period (from May to September), sei and Bryde's whales distributed and fed on prey in the research area (Hakamada *et al*., 2009; Konishi *et al*., 2009; Tamura *et al*., 2009). Common minke whales distributed and fed on prey in the research area during April to October (Tamura *et al*., 2009a; 2009b).

The estimated number of common minke and sei whales distributed in the survey area in the late season was less than that in the early season. In the case of the Bryde's whales the estimated number in the late season was much larger than that in the early season (Hakamada *et al*., 2009).

Miyashita *et al.* (1995) mapped the cetacean distribution based on Japanese sighting data (1964-1990). Common minke whales distributed in the JARPN II research area during April to October; sei whales during April to September and Bryde's whales during June to September. Unfortunately, there were limited research activities during winter (from November to March).

Previous studies reported that common minke whales distributed in Sanriku region from February to June, and in Kushiro region from June to October (Omura and Sakiura, 1956). Based on data of stomach contents by the *Miwa-Maru* between 1973-1975 research expedition, it was suggested that common minke whale fed until September and October (Kasamatsu and Hata, 1985). Hatanaka and Miyashita (1997) proposed feeding migration routes of Okhotsk –West Pacific stock common minke whale (O stock). Their proposal was that young animals migrate into coastal area in sub area 7 in April and then disperse to northern area; mature males appear widely from coastal area to offshore area in May; mature females move the Okhotsk Sea in April and May and then move further middle and northern Okhotsk Sea.

Based on sighting data from 1965 to 1972 sei whales distribute in the western North Pacific from April to September (Masaki, 1977). Based on the catch data of Japan and USSR from 1970 to 1974 Bryde's whales distribute in the western North Pacific from May to October (Ohsumi, 1977).

Based on the previous information briefly summarized above it is assumed that the high feeding season (days) of the three baleen whale species investigated under JARPN II is the following:

Common minke whale: 214 days (between April and October) and possibly 31 additional days (March)
It was divided into early (April-June; 91days plus March; 31 days) and late (July-October; 123days) periods.

Sei whale: 183 days (between April and September) and possibly 31 additional days (October)
It was divided into early (April-June; 91days) and late (July-September; 92 days plus October; 31 days) periods.

Bryde's whale: 184 days (between May and October) and possibly 31 additional days (April)
It was divided into early (May-June; 61days plus April; 31 days) and late (July-October; 123 days) periods.

Folkow *et al*. (2000) assumed that the minke whales stayed in feeding area for six months (183 days) in North Atlantic waters. Antarctic minke whale were estimated to spend 90 days in the feeding grounds, mature female spend 120 days (Lockyer, 1981a, b). Hinga (1979) assumed that baleen whales spend 120 days in the Antarctic feeding area.

Figure 3 showed the relationship between *H index* and *HD* for *P* assumed between 70-90%. The values of the *H index* for the *HD* summarized above for common minke, sei and Bryde's whale are in the range of 1.05-1.72, 1.19-1.80 and 1.19-1.80, respectively. These indexes were used for estimating seasonal consumption in the JARPN II research area.

Numbers of whales distributed in the sub areas and research period
The estimated numbers of whales in each sub area and period was estimated by Hakamada *et al*. (2009). The estimates were 7,338 and 2,976 for the common minke, 7,744 and 5,406 for sei whales, 1,677 and 9,797 for the Bryde's whales in the early and late periods, respectively. The population of baleen whales is sometimes segregated by sex and sexual maturity status. For example mature males of common minke whale distribute dominantly in the research area, especially in offshore sub-areas 8 and 9. The numbers of whales distributed in each sub-area and period is shown in Table 8, by sex and sexual maturity status. Estimates were based on data in Table 5.

Evaluation of two models and the total prey consumption in the research area

The daily consumption estimates by sex and maturity status

Estimates of daily prey consumption by sex and sexual maturity status were made using Equations 6 and 7. In order to estimate the 95% confidence interval of daily prey consumption, parametric bootstrap was conducted, with 1000 re-sampling of body mass, energy contents of prey and *HF* were generated assuming that body mass was normally distributed and that energy contents of prey and *HF* were uniformly distributed between maximum and minimum value.

Results of the estimates are shown in Table 9. The range of daily prey consumption estimates of mature females in common minke, sei and Bryde's whales were 47-158kg, 102-491 and 132-577 kg, by Equations 6 and 7, respectively. The estimate of Equation 7 was 2.6 to 4.4 times larger than the estimate of Equation 6.

Comparison between estimates from models and actual stomach content weight

The estimates from the two models above were compared to observed stomach contents weight. The information of observed stomach contents weight in each sex and reproductive status of each whale species is shown in Table 10. For common minke and sei whales the energy contents of the prey species varies from 3,556kJ kg-1 when feed on krill to as high as 13,138kJkg-1 when feed on large Pacific saury. For Bryde's whale, the energy contents of the prey species varies from 3,556kJ kg-1 when feed on krill to as high as 6,420kJ kg-1 when feed on large Japanese anchovy. The lowest and highest values of energy contents of prey in each whale species, was used. The range of *H index* in common minke, sei and Bryde's whales were 1.05-1.72, 1.19-1.80 and 1.19-1.80, respectively. Results are shown in Figure 4. It should be noted that these stomach content data represented the quantity of a single feeding. It should be also noted here that recent studies based on data logger system suggest that some baleen whale species dive many times for feeding in a single day (*e.g.* Fiedler *et al*., 1998; Acevedo-Gutierrez *et al*., 2002). For sei whales in particular, there is a possibility that the observed stomach contents are far less than total daily consumption, because they often feed on prey through skimming. They appear to feed continuously in the feeding grounds.

The consumption by Equation 6 seems to be underestimated because consumption estimates by this equation is similar to the intake of a single time only. It is important to investigate the diurnal change of actual stomach contents of whales in a day. If the average number of times of prey intake per day become known, it might be possible to narrow the range of daily consumption using the data of observed stomach contents weight. Tagging technology of data logger will provide such data. These information will assist into a thoroughly evaluation of the different models for JARPN II data.

The total prey consumption in the research area

The two models were also used to estimate the total prey consumption of minke whales in the research area. In order to estimate the 95% confidence interval of total prey consumption, parametric bootstrap was conducted with 1000 re-sampling of body mass, *HF* and estimated numbers distributed of whales in each sub area and period were generated assuming that body mass was normally distributed, and that *HF* were uniformly distributed between maximum and minimum value, and estimated numbers distributed of whales in each sub area and period were log-normally distributed. The energy contents of prey and the estimated numbers distributed of whales in each sub area in March and April it assumed as the same value as in May. The energy contents of prey and the estimated numbers of whales distributed in each sub area in October is assumed as the same value as in September.

Results are shown in Table 11. Based on two models the range of total prey consumption in the research area of common minke whales were estimated to be 90 thousands tons (95%CI: 54-150 thousands tones) by Equation 6 and 260 thousands tons (95%CI: 155-438 thousands tones) by Equation 7, respectively. The value of Equation 7 was 2.9 times larger than the value of Equation 6. It should be noted again that consumption by Equation 6 could be underestimated by the reasons given above. The validity of different models for estimating the total consumption can be investigated with additional data collected by JARPN II. It might be possible in the near future to provide estimates with narrow range.

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Table 1. Daily prey consumption estimates of whales using several models.

Body mass	Eqn. 3 (β =2.5) $BMR = \beta(293.1M^{0.75})$		Eqn. 4 $R = 0.42M^{0.67}$		Eqn. 5 $R_{i,s} = 0.1M_{i,s}^{0.8}$		Eqn. 6 $FMR = 2529.2M^{0.524}$		Eqn. 7 $FMR = 863.6M^{0.783}$		Eqn. 8 $FMR = 80M$	
kg	kg	% of M	kg	% of M	kg	% of M	kg	% of M	kg	% of M	kg	% of M
1,000	30	3.0	54	5.4	31	3.1	22	2.2	44	4.4	18	1.8
1,500	41	2.7	70	4.7	43	2.9	27	1.8	61	4.1	28	1.8
2,000	50	2.5	85	4.3	55	2.7	31	1.6	76	3.8	37	1.8
2,500	59	2.4	99	4.0	65	2.6	35	1.4	91	3.6	46	1.8
3,000	68	2.3	112	3.7	76	2.5	39	1.3	105	3.5	55	1.8
3,500	76	2.2	124	3.6	86	2.4	42	1.2	118	3.4	64	1.8
4,000	85	2.1	136	3.4	95	2.4	45	1.1	131	3.3	73	1.8
4,500	92	2.1	147	3.3	105	2.3	48	1.1	144	3.2	83	1.8
5,000	100	2.0	158	3.2	114	2.3	50	1.0	156	3.1	92	1.8
5,500	107	2.0	168	3.1	123	2.2	53	1.0	168	3.1	101	1.8
6,000	115	1.9	178	3.0	132	2.2	55	0.9	180	3.0	110	1.8
6,500	122	1.9	188	2.9	140	2.2	58	0.9	192	2.9	119	1.8
7,000	129	1.8	198	2.8	149	2.1	60	0.9	203	2.9	128	1.8
7,500	135	1.8	207	2.8	157	2.1	62	0.8	214	2.9	138	1.8
8,000	142	1.8	216	2.7	166	2.1	64	0.8	225	2.8	147	1.8
8,500	149	1.8	225	2.7	174	2.0	66	0.8	236	2.8	156	1.8
9,000	155	1.7	234	2.6	182	2.0	68	0.8	247	2.7	165	1.8
9,500	162	1.7	243	2.6	190	2.0	70	0.7	258	2.7	174	1.8
10,000	168	1.7	251	2.5	198	2.0	72	0.7	268	2.7	183	1.8
11,000	181	1.6	268	2.4	214	1.9	76	0.7	289	2.6	202	1.8
12,000	193	1.6	284	2.4	229	1.9	80	0.7	310	2.6	220	1.8
13,000	205	1.6	300	2.3	244	1.9	83	0.6	330	2.5	239	1.8
14,000	216	1.5	315	2.2	259	1.9	86	0.6	349	2.5	257	1.8
15,000	228	1.5	330	2.2	274	1.8	89	0.6	369	2.5	275	1.8
16,000	239	1.5	344	2.2	289	1.8	93	0.6	388	2.4	294	1.8
17,000	250	1.5	359	2.1	303	1.8	96	0.6	407	2.4	312	1.8
18,000	261	1.5	373	2.1	317	1.8	98	0.5	425	2.4	330	1.8
19,000	272	1.4	386	2.0	331	1.7	101	0.5	444	2.3	349	1.8
20,000	283	1.4	400	2.0	345	1.7	104	0.5	462	2.3	367	1.8
21,000	293	1.4	413	2.0	359	1.7	107	0.5	480	2.3	385	1.8
22,000	304	1.4	426	1.9	372	1.7	109	0.5	498	2.3	404	1.8
23,000	314	1.4	439	1.9	386	1.7	112	0.5	515	2.2	422	1.8
24,000	324	1.4	452	1.9	399	1.7	114	0.5	533	2.2	440	1.8
25,000	334	1.3	464	1.9	412	1.6	117	0.5	550	2.2	459	1.8
26,000	344	1.3	477	1.8	425	1.6	119	0.5	567	2.2	477	1.8
27,000	354	1.3	489	1.8	439	1.6	122	0.5	584	2.2	495	1.8
28,000	364	1.3	501	1.8	451	1.6	124	0.4	601	2.1	514	1.8
29,000	373	1.3	513	1.8	464	1.6	126	0.4	618	2.1	532	1.8
30,000	383	1.3	525	1.7	477	1.6	129	0.4	634	2.1	550	1.8
31,000	393	1.3	536	1.7	490	1.6	131	0.4	651	2.1	569	1.8
32,000	402	1.3	548	1.7	502	1.6	133	0.4	667	2.1	587	1.8
33,000	411	1.2	559	1.7	515	1.6	135	0.4	684	2.1	606	1.8
34,000	421	1.2	570	1.7	527	1.6	137	0.4	700	2.1	624	1.8
34,400	425	1.2	575	1.7	532	1.5	138	0.4	706	2.1	631	1.8
35,000	430	1.2	582	1.7	540	1.5	140	0.4	716	2.0	642	1.8

Table 2. The caloric value of dominant prey species in western North Pacific, as estimated by JARPN II

Species	Size	Body length	Body mass	Current KJ/kg
Copepoda (*Neocalanus cristatus*)				3,849
Krill（*Eupahusia pacifica*）				3,556
Sand lance (*Ammodytes personatus*)				7,699
Japanese anchovy (*Engraulis japonicus*)				
	Small	86 mm	7 g	5,523
	Large	125 mm	18 g	6,402
Pacific saury (*Cololabis saira*)				
	Small	158 mm	16 g	5,272
	Large	300 mm	145 g	13,138
Walleye pollock (*Theragra chalcogramma*)		192 mm	66 g	6,234
		430 mm	624 g	6,192
Japanese flying squid (*Todarodes pacificus*)		206 mm	200 g	6,611

Table 3-1. Prey composition of common minke whales sampled in JARPN II.

Sub-area 7

Species	May	June	July	Aug.	Sept.
Copepods	-	-	0.01	-	-
Krill	14.3	16.7	-	59.7	1.9
Anchovy	85.7	24.4	71.3	-	12.5
B.L < 80 mm					
B.L > 80 mm					
Saury	-	-	0.05	39.4	79.3
Mackerels	-	-	18.4	-	-
Walleye pollock	-	58.9	10.3	-	-
Japanese flying squid	-	-	-	-	6.3
Sardine	0.01	-	0.01	-	0.02
Other fish	-	-	-	0.9	-

Sub-area 8

Species	May	June	July	Aug.	Sept.
Copepods	-	0.3	-	-	-
Krill	24.9	0.6	2.2	-	-
Anchovy	66.6	66.1	12.8	-	-
B.L < 80 mm					
B.L > 80 mm					
Saury	1.3	32.8	83.5	92.4	-
Mackerels	5.4	0.1	-	-	-
Japanese flying squid	-	-	1.3	7.6	-
Sardine	-	0.01	-	-	-
Salmonids	1.9	-	-	-	-
Other fish	-	-	0.2	-	-
Other squid	-	0.1	-	-	-

Sub-area 9

Species	May	June	July	Aug.	Sept.
Copepods	29.5	6.8	-	-	-
Krill	7.7	2.3	10.5	0.8	-
Anchovy	-	31.0	0.4	24.9	8.5
B.L < 80 mm					
B.L > 80 mm					
Saury	18.6	59.9	85.1	56.8	91.5
Mackerels	37.4	-	-	0.2	-
Walleye pollock	-	-	0.1	0.01	-
Japanese flying squid	-	-	-	0.002	-
Sardine	-	-	-	0.001	-
Pacific pomfret	-	-	3.7	0.4	-
Salmonids	5.6	-	-	0.5	-
Min. armed squid	-	-	-	15.6	-
Attka mackerel	-	-	-	0.8	-
Other fish	1.3	-	0.2	0.1	-

Table 3-2. Prey composition of sei whales sampled in JARPN II.

Sub-area 7

Species	May	June	July	Aug.	Sept.
Copepods	-	-	9.7	-	-
Anchovy	-	99.99	89.5	-	-
B.L < 80 mm	-			-	-
B.L > 80 mm	-			-	-
Sardine	-	0.01	-	-	-
Saury	-	-	0.8	-	-
Mackerels	-	0.003	-	-	-

Sub-area 8

Species	May	June	July	Aug.	Sept.
Copepods	0.1	2.1	2.8	-	-
Krill	42.0	25.1	53.3	-	-
Anchovy	4.8	70.1	43.2	-	100.0
B.L < 80 mm				-	
B.L > 80 mm				-	
Saury	0.1	0.8	0.7	-	-
Mackerels	53.0	1.9	-	-	-
Japanese flying squid	-	-	0.01	-	-

Sub-area 9

Species	May	June	July	Aug.	Sept.
Copepods	53.6	30.8	16.7	11.4	69.7
Krill	33.7	6.8	30.1	11.8	-
Anchovy	4.9	58.7	44.5	62.0	1.3
B.L < 80 mm					
B.L > 80 mm					
Sardine	-	-	-	1.1	-
Saury	0.1	2.9	2.9	13.7	-
Mackerels	7.7	0.6	5.4	-	29.0
Japanese flying squid	-	0.3	0.5	-	-

Table 3-3. Prey composition of Bryde's whales sampled in JARPN II.

Sub-area 7

Species	May	June	July	Aug.	Sept.
Krill	88.9	75.3	35.0	6.5	5.6
Anchovy	11.1	22.0	61.6	93.5	94.4
B.L < 80 mm		77.4%	55.6%	45.1%	90.8%
B.L > 80 mm		22.6%	44.4%	54.9%	9.3%
Mackerel	-	2.8	3.4	-	-

Sub-area 8

Species	May	June	July	Aug.	Sept.
Krill	-	37.0	34.6	-	-
Anchovy	-	30.1	65.3	100.0	-
B.L < 80 mm		95.6%	71.8%	53.0%	
B.L > 80 mm		4.4%	28.2%	47.0%	
Mackerel	-	32.9	0.1	-	-
Japanese flying squid	-	0.002	-	-	-

Sub-area 9

Species	May	June	July	Aug.	Sept.
Krill	-	17.7	4.9	6.9	-
Anchovy	-	73.2	95.1	64.5	100.0
B.L < 80 mm		46.0%	58.3%	1.0%	
B.L > 80 mm		54.0%	41.8%	99.0%	
Mackerel	-	9.1	-	-	-
Oceanic lightfish	-	0.02	-	28.7	-

Table 4. The energy contents estimated from stomach contents based on prey composition in each sub area and month, and energy content data of prey species.

Sub area 7

Species	May (KJ)	June	July	Aug.	Sept.
Minke whale	5,995	5,807	6,388	7,357	11,789
Sei whale	5,532	5,532	5,424	5,424	5,424
Bryde's whale	3,797	4,116	5,102	5,846	5,496

Sub area 8

Species	May (KJ)	June	July	Aug.	Sept.
Minke whale	5,787	8,587	11,966	12,642	12,642
Sei whale	5,194	5,542	4,861	4,861	6,366
Bryde's whale	5,096	5,096	5,050	5,936	5,936

Sub area 9

Species	May (KJ)	June	July	Aug.	Sept.
Minke whale	6,689	10,198	11,835	10,233	12,561
Sei whale	4,077	5,576	5,285	6,695	4,623
Bryde's whale	5,603	5,603	5,781	6,209	6,393

Table 5. The composition of whales in western North Pacific based on sex and maturity status.

Common minke

	Sub-area 7		Sub-area 8		Sub-area 9	
Sex maturity	Early	Late	Early	Late	Early	Late
IM	24.2	19.7	13.3	10.9	13.2	6.4
MM	64.0	61.4	75.9	80.4	73.7	86.8
IF	7.5	10.2	7.2	0.0	5.3	0.5
MF	4.3	8.7	3.6	8.7	7.9	6.4
N	186	127	83	46	38	220

Sei

	Sub-area 7		Sub-area 8		Sub-area 9	
Sex maturity	Early	Late	Early	Late	Early	Late
IM	25.0	16.7	15.1	10.3	15.4	14.6
MM	25.0	50.0	27.4	32.8	32.3	37.3
IF	50.0	8.3	8.2	13.8	14.6	13.7
MF	0.0	25.0	49.3	43.1	37.7	34.4
N	4	12	73	58	130	212

Bryde's

	Sub-area 7		Sub-area 8		Sub-area 9	
Sex maturity	Early	Late	Early	Late	Early	Late
IM	18.2	25.0	20.6	27.3	10.9	16.7
MM	9.1	26.7	20.6	24.7	23.9	16.7
IF	25.8	19.0	14.7	13.0	21.7	13.0
MF	47.0	29.3	44.1	35.1	43.5	53.7
N	66	116	34	77	46	54

Table 6. The body mass based on sex and maturity status of each whale species.

Species	Sex and reproductive status	Body mass (kg)	S.D. (kg)	Min (kg)	Max (kg)
Minke	Immature male	2,600	900	1,100	5,200
	Immature female	2,200	900	1,000	4,100
	Mature male	4,900	600	3,200	7,100
	Mature female	6,500	900	3,800	7,900
Sei	Immature male	13,700	3,200	4,300	20,000
	Immature female	15,400	3,300	6,300	21,400
	Mature male	19,900	2,400	13,700	25,900
	Mature female	24,800	3,600	16,700	34,400
Bryde's	Immature male	9,600	2,400	4,000	14,800
	Immature female	9,300	3,000	2,800	14,700
	Mature male	15,500	2,200	11,300	21,400
	Mature female	17,800	2,900	11,100	24,900

Table 7. The relationship between values of the ratio of low feeding/high feeding intake (*r*), feeding index of high feeding season (*H index*) and the days of high feeding season (*HD*)

(a) *r*

HD	Proportion per year		
	90%	80%	70%
120		0.11	0.18
130		0.12	0.21
140		0.14	0.24
150		0.16	0.27
160		0.17	0.30
170		0.20	0.33
180	0.10	0.22	0.37
190	0.11	0.24	0.42
200	0.12	0.27	0.47
210	0.13	0.30	0.52
220	0.15	0.34	0.58
230	0.17	0.38	0.65
240	0.19	0.43	

(b) *H index*

HD	Proportion per year		
	90%	80%	70%
120	2.74	2.43	2.13
130	2.53	2.25	1.97
140	2.35	2.09	1.83
150	2.19	1.95	1.70
160	2.05	1.83	1.60
170	1.93	1.72	1.50
180	1.80	1.60	1.40
190	1.73	1.54	1.34
200	1.64	1.46	1.28
210	1.54	1.36	1.19
220	1.49	1.33	1.16
230	1.43	1.27	1.11
240	1.35	1.20	1.05

Table 8. The seasonal estimated numbers distributed of whales in each sex and reproductive status in each sub area and season

Early season

Area 7

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	1,202	0.93	255	5,677
	Immature female	3,179	0.93	673	15,011
	Mature male	374	0.93	79	1,766
	Mature female	214	0.93	45	1,009
Sei	Immature male	167	0.53	63	442
	Immature female	167	0.53	63	442
	Mature male	334	0.53	126	884
	Mature female	0	0.53	0	0
Bryde's	Immature male	146	1.59	16	1,323
	Immature female	73	1.59	8	662
	Mature male	207	1.59	23	1,875
	Mature female	378	1.59	42	3,419

Area 8

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	102	0.60	34	301
	Immature female	584	0.60	198	1725
	Mature male	56	0.60	19	164
	Mature female	28	0.60	9	82
Sei	Immature male	353	0.33	186	668
	Immature female	641	0.33	339	1215
	Mature male	192	0.33	102	364
	Mature female	1,154	0.33	610	2,186
Bryde's	Immature male	110	1.30	16	771
	Immature female	110	1.30	16	771
	Mature male	79	1.30	11	551
	Mature female	236	1.30	34	1,652

Area 9

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	211	0.58	74	602
	Immature female	1,179	0.58	412	3,371
	Mature male	84	0.58	29	241
	Mature female	126	0.58	44	361
Sei	Immature male	728	0.37	360	1,473
	Immature female	1,530	0.37	757	3,092
	Mature male	692	0.37	342	1,399
	Mature female	1,785	0.37	883	3,608
Bryde's	Immature male	37	0.73	10	133
	Immature female	81	0.73	22	292
	Mature male	73	0.73	20	265
	Mature female	147	0.73	41	531

Late season

Area 7

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	131	0.67	40	430
	Immature female	408	0.67	124	1,341
	Mature male	68	0.67	21	224
	Mature female	58	0.67	18	189
Sei	Immature male	40	1.15	7	242
	Immature female	121	1.15	20	727
	Mature male	20	1.15	3	121
	Mature female	60	1.15	10	363
Bryde's	Immature male	773	0.46	330	1,811
	Immature female	826	0.46	352	1,936
	Mature male	586	0.46	250	1,374
	Mature female	906	0.46	386	2,123

Area 8

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	25	0.75	7	90
	Immature female	182	0.75	49	669
	Mature male	0	0.75	0	0
	Mature female	20	0.75	5	72
Sei	Immature male	145	0.54	54	391
	Immature female	459	0.54	170	1238
	Mature male	193	0.54	72	521
	Mature female	603	0.54	223	1629
Bryde's	Immature male	796	0.47	334	1897
	Immature female	720	0.47	302	1717
	Mature male	379	0.47	159	904
	Mature female	1,023	0.47	429	2439

Area 9

Species	Sexual maturity	Estimates	CV	95% CI LL	95% CI UL
Minke	Immature male	305	0.60	103	902
	Immature female	777	0.60	263	2,299
	Mature male	285	0.60	96	844
	Mature female	718	0.60	243	2,124
Sei	Immature male	551	0.35	282	1,074
	Immature female	1,403	0.35	719	2,738
	Mature male	515	0.35	264	1,005
	Mature female	1,296	0.35	664	2,530
Bryde's	Immature male	632	0.58	219	1,821
	Immature female	632	0.58	219	1,821
	Mature male	491	0.58	170	1,416
	Mature female	2,035	0.58	706	5,867

Table 9-1. The consumption estimates from two models (Equation 6)

$$FMR = 2529.2M^{0.524}$$

Minke whales

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	29.03	13.48	0.46	12.21	69.00
Immature female	26.71	12.72	0.48	11.01	64.77
Mature male	41.15	17.90	0.43	18.20	93.04
Mature female	47.81	20.70	0.43	21.22	107.73

Sei whale

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	74.92	32.40	0.43	33.28	168.69
Immature female	79.73	34.24	0.43	35.59	178.59
Mature male	90.78	37.55	0.41	41.66	197.81
Mature female	102.51	43.05	0.42	46.53	225.83

Bryde's whale

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	95.28	23.82	0.25	58.80	154.39
Immature female	92.24	25.97	0.28	53.68	158.50
Mature male	120.97	26.63	0.22	78.97	185.29
Mature female	132.32	30.15	0.23	85.14	205.65

Table 9-2. Continued (Equation 7)

$$FMR = 863.6M^{0.783}$$

Minke whales

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	77.45	39.51	0.51	30.18	198.80
Immature female	68.76	37.75	0.55	25.14	188.02
Mature male	126.79	55.21	0.44	56.03	286.94
Mature female	158.09	68.11	0.43	70.42	354.91

Sei whale

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	304.58	135.39	0.44	132.51	700.08
Immature female	336.32	146.92	0.44	148.26	762.95
Mature male	404.82	161.23	0.40	190.83	858.78
Mature female	491.18	205.89	0.42	223.24	1,080.70

Bryde's whale

Sex and reproductive status	Average	S.D	C.V	95%CI LL	95%CI UL
Immature male	354.36	103.37	0.29	202.40	620.43
Immature female	343.38	115.15	0.34	181.09	651.12
Mature male	513.26	121.70	0.24	324.54	811.72
Mature female	577.89	143.17	0.25	358.17	932.40

Table 10. The observed stomach contents weight (kg) in each sex and maturity status of each whale species

Species	Sex maturity	N	Average	S.D.	Max.	Min.
Minke	IM	10	28.47	16.78	53.96	3.80
	MM	86	67.85	40.43	196.19	17.35
	IF	10	40.14	36.60	105.60	9.97
	MF	11	85.10	48.96	197.60	21.45
Sei	IM	18	147.35	114.70	426.00	22.15
	MM	44	220.62	156.29	694.31	11.62
	IF	13	151.82	83.92	293.60	52.90
	MF	39	286.04	246.27	1,041.90	11.98
Bryde's	IM	24	144.21	78.44	290.00	5.55
	MM	13	184.89	103.39	463.86	76.27
	IF	14	156.31	93.94	272.55	7.25
	MF	26	263.31	191.19	810.45	1.25

Table 11. The total prey consumption of common minke whales in the research area

Equation 6.

	Area 7				Area 8				Area 9				Total
	IM	IF	MM	MF	IM	IF	MM	MF	IM	IF	MM	MF	
Apr.-Oct.													
Average	15,111	39,579	6,357	4,873	683	2,742	233	344	2,491	9,381	2,342	6,133	90,271
S.D	4,204	11,832	1,693	1,266	172	607	79	62	462	1,739	440	1,227	
C.V.	0.28	0.30	0.27	0.26	0.25	0.22	0.34	0.18	0.19	0.19	0.19	0.20	
95%CI+	8,849	22,306	3,805	2,953	420	1,786	122	242	1,737	6,544	1,626	4,160	54,551
95%CI-	25,806	70,226	10,620	8,043	1,110	4,209	445	489	3,572	13,449	3,375	9,042	150,386
Mar.-Oct.													
Average	19,888	54,290	8,091	6,228	912	3,578	350	410	2,950	12,035	2,577	6,537	117,846
S.D	5,115	13,808	1,898	1,477	201	709	94	70	512	2,002	425	1,270	
C.V.	0.26	0.25	0.23	0.24	0.22	0.20	0.27	0.17	0.17	0.17	0.16	0.19	
95%CI+	12,110	33,237	5,140	3,938	595	2,436	208	294	2,104	8,705	1,869	4,483	75,120
95%CI-	32,660	88,680	12,735	9,850	1,396	5,256	588	572	4,136	16,638	3,554	9,532	185,598

Equation 7.

	Area 7				Area 8				Area 9				Total
	IM	IF	MM	MF	IM	IF	MM	MF	IM	IF	MM	MF	
Apr.-Oct.													
Average	45,351	106,016	19,816	14,862	2,119	10,996	1,486	1,493	6,605	24,135	6,116	21,526	260,521
S.D	13,523	31,917	5,401	3,830	499	2,514	403	285	1,217	4,874	1,277	4,373	
C.V.	0.30	0.30	0.27	0.26	0.24	0.23	0.27	0.19	0.18	0.20	0.21	0.20	
95%CI+	25,595	59,518	11,727	9,041	1,343	7,065	881	1,031	4,617	16,310	4,080	14,514	155,723
95%CI-	80,356	188,840	33,486	24,431	3,342	17,115	2,504	2,163	9,449	35,714	9,167	31,925	438,492
Mar.-Oct.													
Average	59,708	137,831	26,020	18,508	2,760	14,360	2,065	1,837	7,682	29,893	6,852	23,388	330,904
S.D	15,874	35,367	6,266	4,376	577	2,986	497	346	1,304	5,737	1,285	4,367	
C.V.	0.27	0.26	0.24	0.24	0.21	0.21	0.24	0.19	0.17	0.19	0.19	0.19	
95%CI+	35,776	84,023	16,338	11,717	1,841	9,595	1,297	1,274	5,520	20,591	4,760	16,271	209,003
95%CI-	99,651	226,096	41,439	29,234	4,139	21,491	3,288	2,650	10,689	43,396	9,865	33,619	525,556

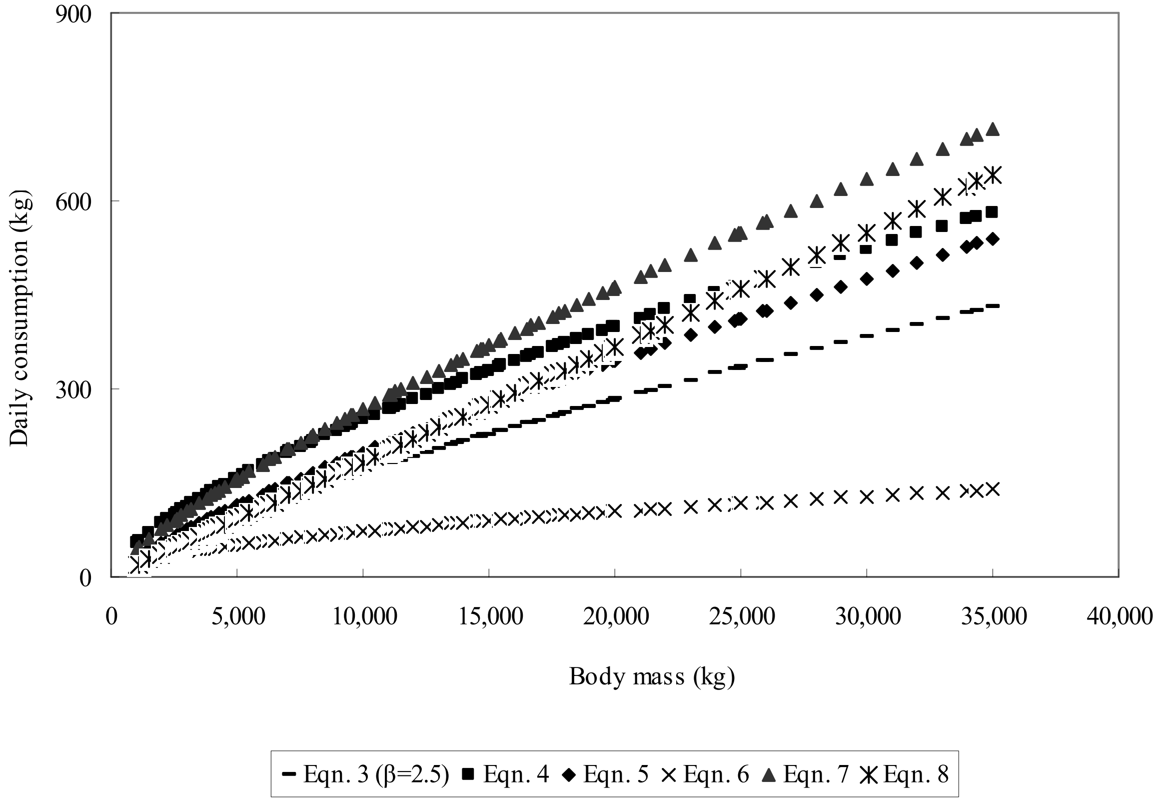


Fig.1. Daily prey consumption estimates of whales using several models.

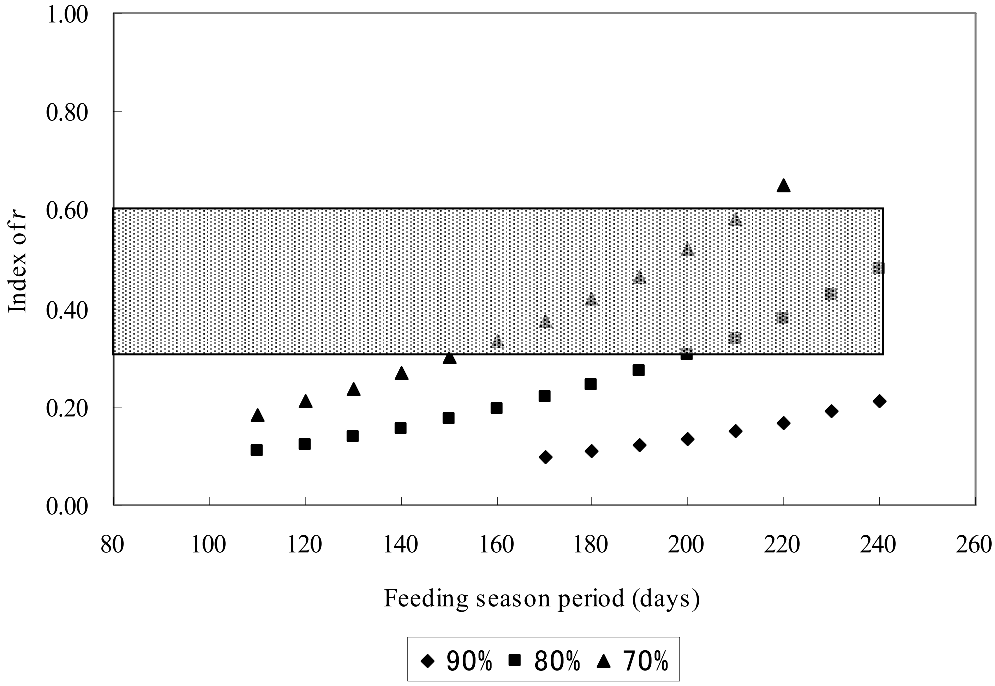


Fig.2. The relationship between values of ratio of feeding rate in high feeding season and feeding rate in low feeding season (r) and days of high feeding season (*HD*). Gray shade portion shows the estimated range of *r* in Antarctic minke whales and North Atlantic minke whales (Leaper and Lavigne, 2007).

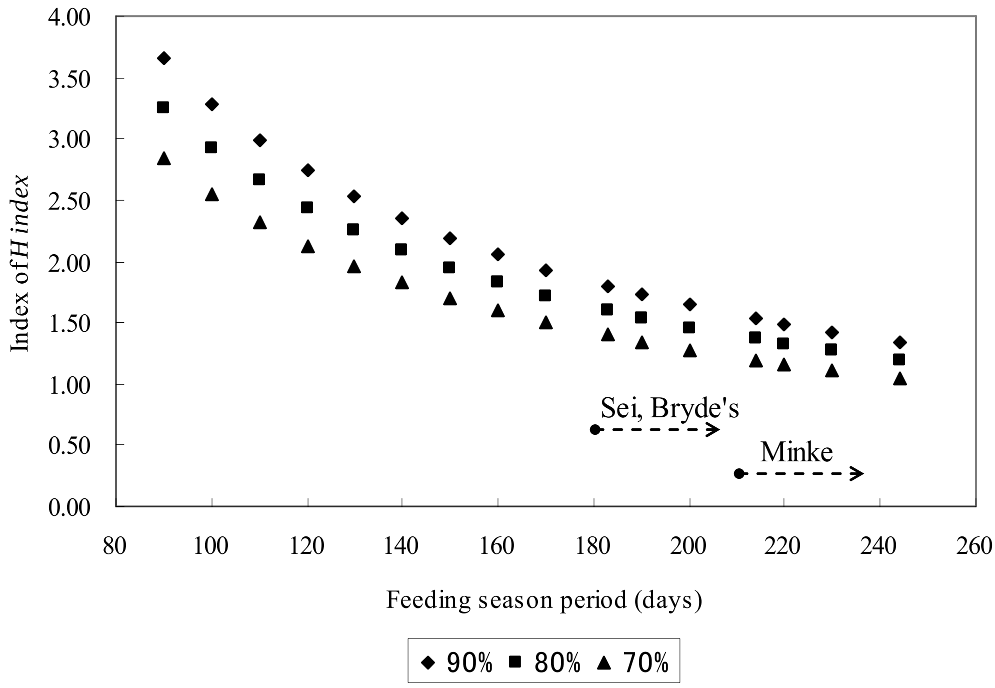
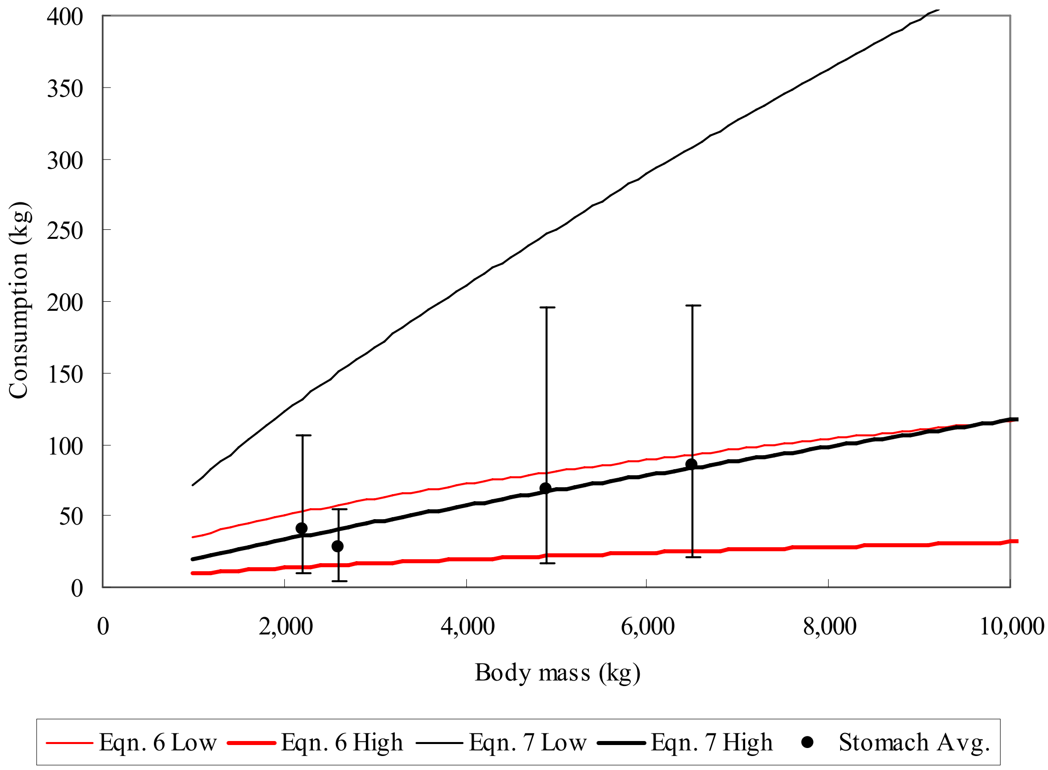


Fig.3. The relationship between values of *H index* and *HD* with assumed range of feeding season periods in each whale species.

H index = 1.05



H index = 1.54

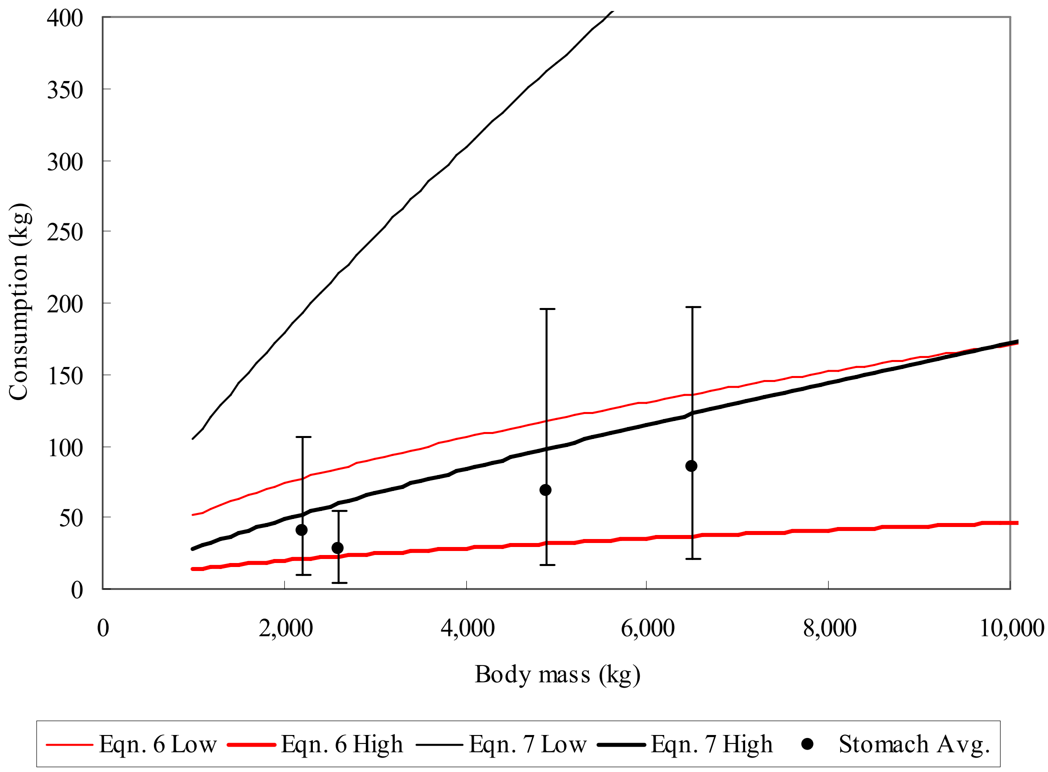
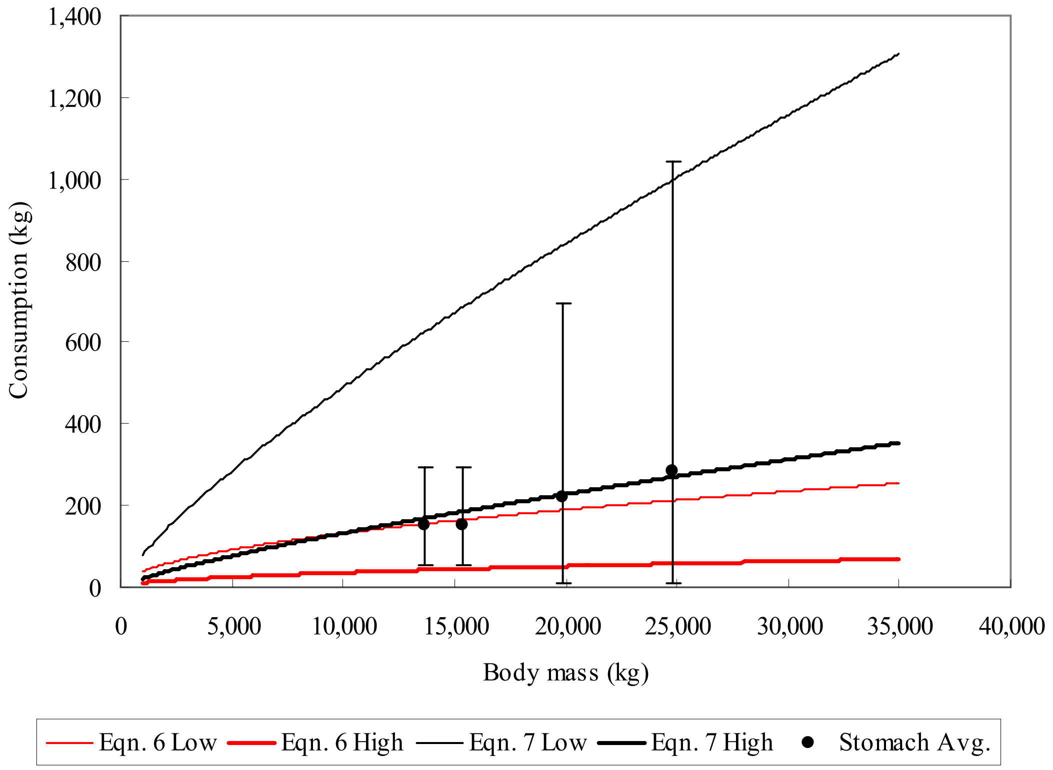


Fig.4-1. Comparison between estimates from models and observed stomach contents weight (common minke whales). Bar line shows the range between Maximum and Minimum values.

H index = 1.19



H index = 1.80

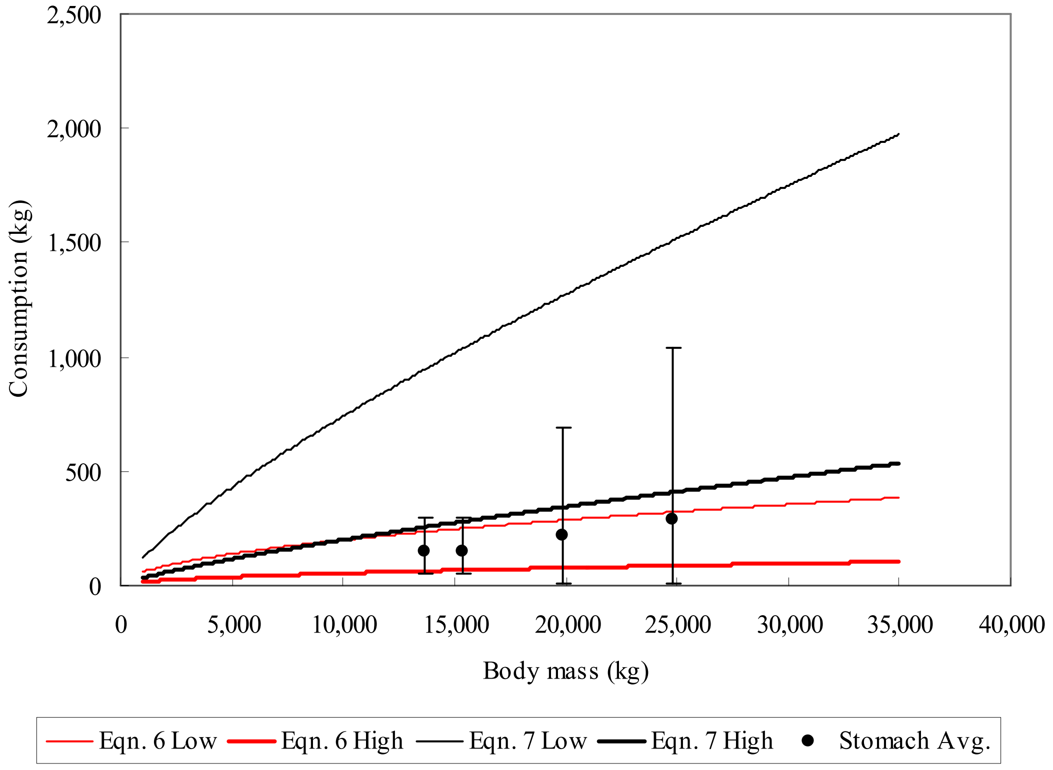
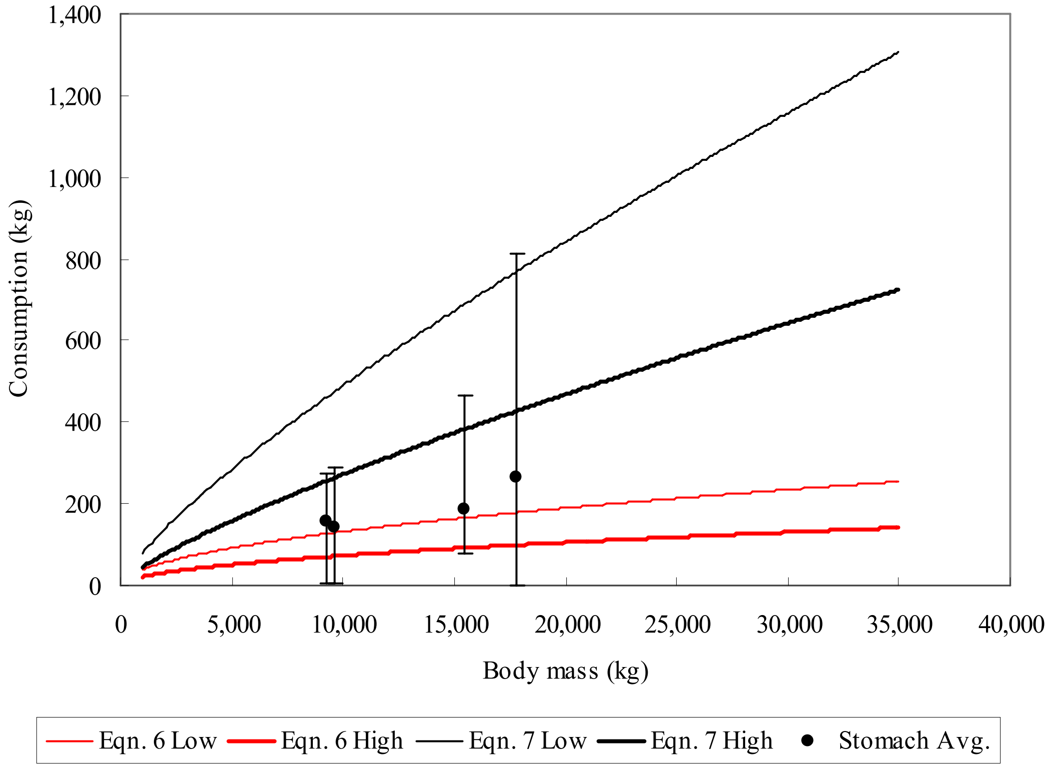


Fig.4-2. Comparison between estimates from models and observed stomach contents weight (sei whales). Bar line shows the range between Maximum and Minimum values.

H index = 1.19



H index = 1.80

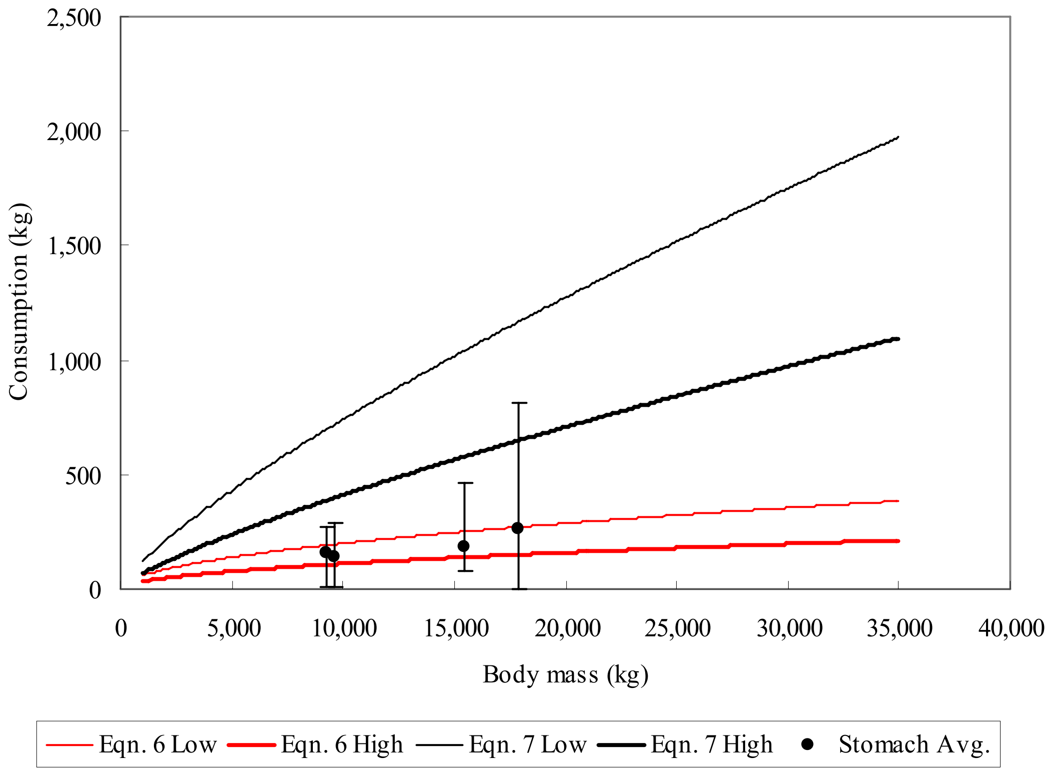


Fig.4-3. Comparison between estimates from models and observed stomach contents weight (Bryde'swhales). Bar line shows the range between Maximum and Minimum values.