博士論文

A study on the population viability of small cetaceans in coastal waters
（沿岸性小型鯨類の個体群存続可能性に関する研究）

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Chapter I

General introduction

I-1   Human-induced impacts on small cetaceans in coastal waters

Cetaceans inhabiting coastal waters can be critically affected by the human activities such as bycatch (i.e., incidental capture during fishing activities) and ship strikes, and the habitat degradation and reduction due to dredging and pollution. Target species of cetaceans in this study are narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) and Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), among about 40 species of cetaceans distributed in the waters around Japan. Five cetaceans including these two species were noted as the threatened species due to human-induced impacts around East Asia by the scientific committee of the International Whaling Committee (IWC, 2013).

Narrow-ridged finless porpoise, inhabiting the coastal waters of northern China, Korea and Japan, and the Yangtze River, seems to be exposed to various human impacts (Jefferson and Hung 2004). In particular, bycatch can have a serious impact on the porpoise populations because they have a lethal direct effect and, thus, can threaten the viability of the porpoise populations (Reeves et al., 1997; IWC, 2006). Indeed, a rapid decline has been noted in some populations (Kasuya et al., 2002; Zhao et al., 2008; Mei et al., 2012). *N. asiaeorientalis* is listed in Appendix I of CITES. According to the IUCN Red List of Threatened Species, it is classified as "Vulnerable (VU)" c under Criterion A2 about the past reduction in population size (Wang and Reeves, 2012). Moreover, the subspecies in the Yangtze River (*N. asiaeorientalis asiaeorientalis*) is classified as "Critically Endangered (CR)", the most serious threat level, under Criteria A3 and A4 about the future reduction in population size (Wang et al., 2013).

Indo-Pacific bottlenose dolphin is widely distributed in coastal waters of the Indian and western Pacific oceans (Jefferson et al., 2008). Habitat destruction and incidental catches may have a significant impact on local dolphin populations. *T. aduncus* is listed in Appendix II of CITES. However, the assessment in IUCN red list is "Data Deficient" due to the lack of available information (Hammond et al., 2012).

I-2   Biology of the target species

Biological information of the target species, which is related with the present study, was reviewed below.

Narrow-ridged finless porpoise

The narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) is a small toothed whale whose body size is approximately 1.7m (Jefferson and Hung, 2004). The porpoise has a ridge on their back instead of a dorsal fin. The ridge is narrower than that of another species in the same genus (*N. phocaenoides*) inhabiting the coastal waters of the Northwest Pacific Ocean to the Indian Ocean.

Japanese waters are the northernmost range of *N. asiaeorientalis* (Kasuya, 1999; Amano et al., 2003). At least five distinct populations of this species are identified by mitochondrial DNA variability (Yoshida et al., 2001; Yoshida, 2002). They are distributed in (1) Tokyo Bay - Sendai Bay, (2) Ise Bay and Mikawa Bay, (3) Seto Inland Sea, (4) Ariake Sound and Tachibana Bay, and (5) Omura Bay (Fig I-1a).

The maximum ages reported for female porpoises were 23 years in western Kyushu (Shirakihara et al., 1993), 23 years in the Inland Sea (Kasuya, 1999), and 33 years off Southern China (Jefferson et al., 2002b). A mature female porpoise typically bears a single calf at each parturition event. Kasuya and Kureha (1979) suggested that a two-year cycle would be most common for the porpoises. The gestation period is 10.6–11.2 months (Kasuya et al., 1986). The age at sexual maturity is less than 4 years in the Inland Sea (Kasuya, 1999) and 5–9 years in Ariake Sound and Tachibana Bay (Shirakihara et al., 1993). These estimates were obtained from biological examinations of small numbers of incidentally captured or stranded individuals. Jefferson et al. (2002b) reported that the age at sexual maturity for females is approximately 5 years, and there are no significant differences between the porpoise populations.

Indo-Pacific bottlenose dolphin

The Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) is a small toothed whale whose body size is approximately 2.5m (Wang et al., 2000). Although the taxonomic structure of the bottlenose dolphin (*Tursiops* species) is still debated, *T. aduncus* can be distinguished from common bottlenose dolphin (*T. truncates*) by the presence of flecks on bellies of adult dolphins.

T. aduncus is widespread in the warm temperate to tropical Indo-Pacific (Wells and Scott,

2002). It usually appears in the waters around Islands located in the southern half of Japan such as Ogasawara Island, Amakusa-Shimoshima Island and Mikurajima in the Izu Seven Islands (IWC, 2013; Fig. I-1b).

It was recorded that the dolphins lived for 37 years in an aquarium and that the maximum age was estimated to be over 40 years (Miyahara, 2013). A mature female dolphin typically bears a single calf at each parturition event. For the dolphins around Mikurajima, the probability that an adult female breeds in a year is estimated to be 24% (Kogi et al., 2004). Moreover, the calving interval is 3.08 years and the age at first reproduction is 10.31 years (Kogi, 2013). For the dolphins in South Australia, the calving interval is estimated to be 1.7–3.8 years (Steiner and Bossley, 2008).

I-3 Importance of risk evaluation for the populations of the target species

Evaluation of these human-induced impacts on cetacean populations is essential for their conservation. Monitoring the change of abundance is a feasible approach. The abundances of the narrow-ridged finless porpoise populations in Japanese waters have been estimated to be from 187 individuals for the Omura Bay population, to 7572 individuals for the Inland Sea population (Yoshida et al., 1997, 1998; Amano et al., 2003; Shirakihara et al., 2007). For example, the estimations of abundance have been performed in some different years for the Ariake Sound and Tachibana Bay population (Yoshida et al., 1997; Shirakihara and Shirakihara, 2002; Yoshida et al., 2013). Figure I-2 shows the change in the abundance estimates. Although the coefficient of variation (CV) of the abundance estimates are not considered too low for marine mammals, the population trend cannot be clearly revealed. Wade and DeMaster (1999) indicated the possibility that a population had already decreased to a critical level when the decreasing trend of the population was detected from the abundance estimation. This suggests that an evaluation of past population trends is not always sufficient for conservation. Rather, projections of changes in population size are required to identify appropriate conservation measures before the population size decreases to a critically low level.

Potential biological removal (PBR) has been commonly used as an index for evaluating the impacts of bycatches on cetaceans (e.g., Caswell et al., 1998; Dans et al., 2003; Williams et al., 2008; Fruet et al., 2012; Mannocci et al., 2012; Shirakihara and Shirakihara, 2012, 2013a). The PBR level is defined as the maximum number of individuals that is allowed to be removed from a population in order to prevent the depletion of that population (Wade, 1998). Only three

parameters: (1) minimum population estimate (approximately the 20th percentile of the abundance estimate), (2) maximum productivity rate and (3) recovery factor, are needed to calculate the PBR. In most cases, only abundance estimate and its CV are required because the default maximum productivity rate is specified as 0.04 for cetaceans, and the default recovery factor is set at 0.5 for endangered species (Wade, 1998). Although the PBR level is useful for assessing the risk of the cetacean populations with limited biological data, it provides only the safe bycatch level, which is sufficient for maintaining a sustainable population size. If the reported number of bycaught cetaceans overly exceeds the PBR level, then further evaluation would be necessary to assess the potential impacts so that appropriate conservation measures could be devised.

I-4   Purpose of this study

Risk evaluation at a population level is desired as a step of species conservation. However, no quantitative analysis on future projection for the populations in Japanese waters has been conducted due to a lack of biological information. The purpose of this study is to predict the future population change and to evaluate the extinction risk by considering the uncertainty of the limited data.

1. Estimation of annual rate of natural increase for the narrow-ridged finless porpoises.

2. Future predictions for the porpoise populations in the Inland Sea, the population in Ariake Sound and Tachibana Bay and other populations whose biological information is limited.

3. Estimation of survival rate and future prediction for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island.

Population viability analysis (PVA) is a procedure used to recognize a crisis for a species or population and to evaluate the probability that the population can persist in the future. PVA is frequently applied in the context of the conservation and management of costal marine mammals facing various anthropogenic impacts (e.g., Caswell et al., 1998; Thompson et al., 2000; Dans et al., 2003; Heinsohn et al., 2004; Currey et al., 2009a; Slooten and Dawson, 2010; Huang et al., 2012; Mei et al., 2012). PVA can be based on individual-based models when the population is composed of individuals whose sex, age, and breeding statistics are known or when the population size is so small that the individual variation in demographic parameters such as survival and fertility rate cannot be ignored (e.g., Thompson et al., 2000; Galimberti et

al., 2001; Heinsohn et al., 2004). However, it is difficult, and sometimes even impossible, to acquire information about the individual variation in demographic parameters for most marine mammals. Therefore, many studies have been performed by population-based models such as age-classified or stage-classified models (e.g., Caswell et al., 1998; Dans et al., 2003; Currey et al., 2009a).

IUCN (2001) classifies the threatened species into three categories: Critically endangered (CR), Endangered (EN) or Vulnerable (VU), among all the nine categories (Appendix 1). Whether a target species meets a category is determined by the following five criteria.

A: Reduction in population size

B: Geographic range

C: The number of mature individuals and its reduction

D: The number of mature individuals (a stricter standard than Criterion C)

E: Probability of extinction

For quantitative risk evaluation, this study focuses on criteria of A4 (future reduction in population size over three generations) and E. Details for the categories and criteria are summarized in Table I-1.

I-5   Structure of the following chapters

In Chapter II, a PVA was conducted for the narrow-ridged finless porpoise populations. As the first step of PVA (Section II-1), survival rate for the porpoises was estimated using the knowledge for other cetaceans with similar life histories. From the estimates, the annual rate of natural increase was determined for this species. Next, risk evaluations of human-induced impacts on the Inland Sea population (Section II-2) and the Ariake Sound and Tachibana Bay population (Section II-3) were conducted. Moreover, a versatile method was proposed for evaluating the future risks of various porpoise populations, for which data on population size and human-induced mortality rates is available (Section II-4). A major part of Section II-1 and II-2 was published in Population Ecology (Hashimoto et al. (2013), < hyyp://link.springer.com/ article/10.1007%2Fs10144-013-0374-5>) and a part of Section II-3 was published in Endangered Species Research (Hashimoto et al. (2015), <http://www.int-res.com/articles/ esr2015/27/n027p087.pdf >).

In Chapter III, a PVA was conducted for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island in Japan. Survival rate was estimated using photo-identification data (Section III-1). Moreover, using the estimates, the impacts of bycatch mortality were evaluated (Section III-2).

In Chapter IV, as general discussion, the contribution and limitation of the quantitative analysis were discussed. Notation and abbreviation used in this study are summarized in Appendix 2.
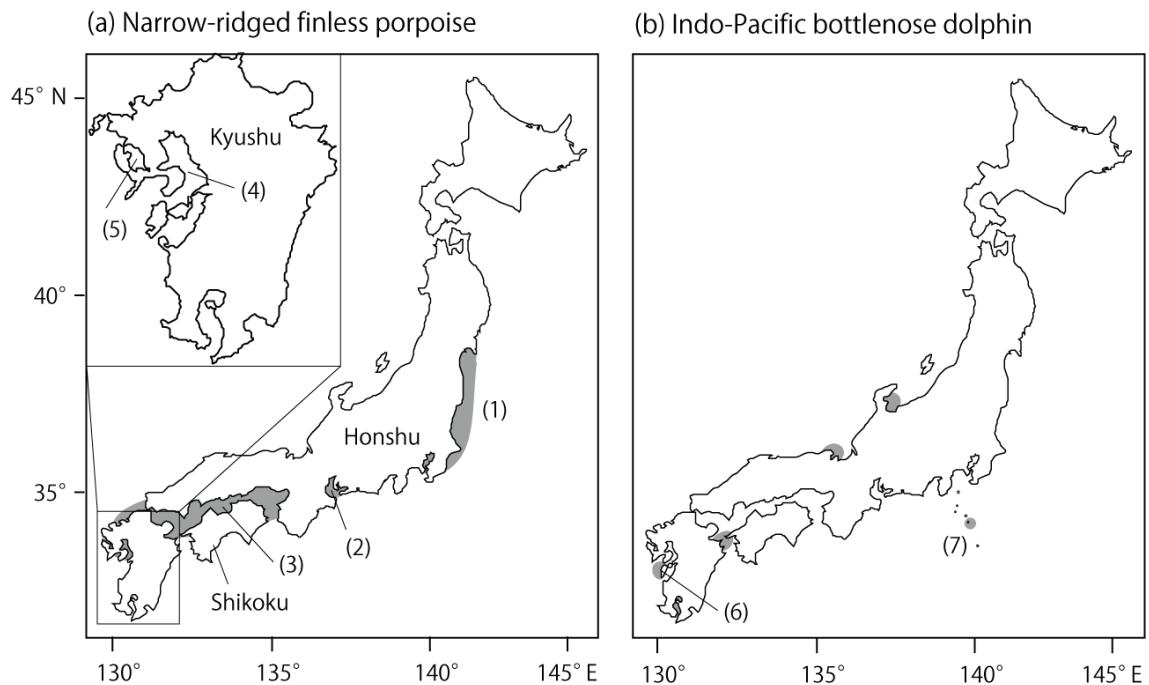
Fig. I-1 Distributions of **(a)** narrow-ridged finless porpoises (modified from Shirakihara et al. (1992)) and **(b)** Indo-Pacific bottlenose dolphins (modified from IWC(2013)) around Japanese waters. (1) Tokyo Bay - Sendai Bay, (2) Ise Bay and Mikawa Bay, (3) Seto Inland Sea, (4) Ariake Sound and Tachibana Bay, (5) Omura Bay, (6) Amakusa-Shimoshima Island and (7) Mikurajima.
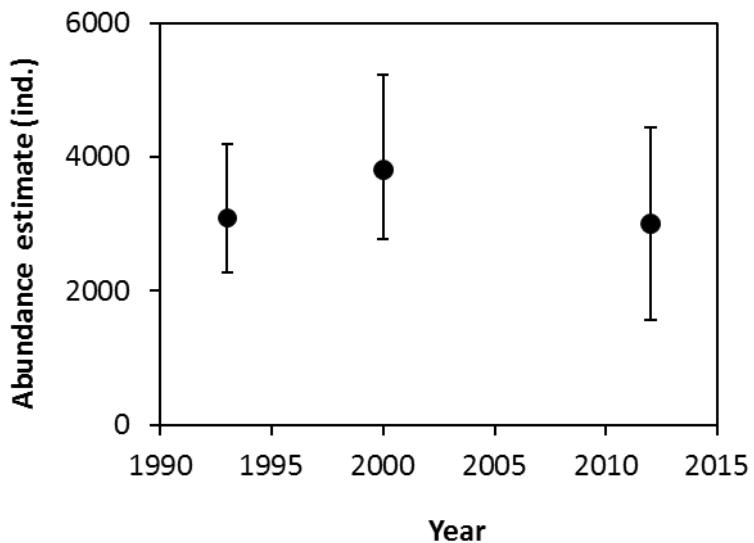
Fig. I-2 Estimates of the abundance for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay, modified from Yoshida et al. (1997), Shirakihara et al. (2001) and Yoshida et al. (2013).

Table I-1 Summary of the thresholds of three categories under criteria A4 and E defined in IUCN (2001).

Criterion	Category		
	Vulnerable (VU)	Endangered (EN)	Critically Endangered (CR)
(A4) Population size reduction over three generations	$\geq 30\%$	$\geq 50\%$	$\geq 80\%$
(E) Quantitative analysis showing the probability of extinction	$\geq 10\%$ within 100 years	$\geq 20\%$ within five generations	$\geq 50\%$ within three generations

Chapter II

Population viability analysis of the narrow-ridged finless porpoises

II-1   Estimation of the annual intrinsic rate of natural increase

II-1.1   Background

The intrinsic rate of natural increase (r) is a key parameter to express the population dynamics of wildlife species. The purpose of this section is to estimate the annual intrinsic rate of natural increase (λ_{natural}) for a narrow-ridged finless porpoise population. The relationship between r and λ_{natural} is defined as:

$$\lambda_{\text{natural}} = e^r, \tag{2-1-1}$$

where r (>0) is given by:

$$r = b - d, \tag{2-1-2}$$

where b is the instantaneous birth rate and d is the instantaneous natural death rate without human-induced mortality. Thus, λ_{natural} is also expressed as:

$$
\begin{aligned}
\lambda_{\text{natural}} &= e^{\,b} \times e^{-d} \\
&= (1 + B) \times P_{\text{natural}} \\
&= (1 + B) \times (1 - M_{\text{natural}}),
\end{aligned}
\tag{2-1-3}
$$

where B is the annual birth rate (number of newborn calves in a year / abundance at the beginning of the year), P_{natural} is the natural survival rate without human-induced mortality and M_{natural} is annual natural mortality rate.

II-1.2   Methods

II-1.2.1 Age-classified matrix model

An age-classified matrix model (Leslie, 1945; Caswell, 1989) was used to estimate the annual intrinsic rate of natural increase (λ_{natural}) for a narrow-ridged finless porpoise population, because

some information on fertility and survival is available for the porpoises (as shown in Section I-2). The dynamics of the age structure of the population is expressed as:

$$
\begin{pmatrix} n_{0,t+1} \\ n_{1,t+1} \\ n_{2,t+1} \\ \vdots \\ n_{k,t+1} \end{pmatrix} = A \begin{pmatrix} n_{0,t} \\ n_{1,t} \\ n_{2,t} \\ \vdots \\ n_{k,t} \end{pmatrix},
\tag{2-1-4}
$$

$$
A = \begin{pmatrix} F_0 & F_1 & \cdots & F_{k-1} & F_k \\ P_0 & 0 & \cdots & 0 & 0 \\ 0 & P_1 & \cdots & 0 & 0 \\ & & \vdots & & \\ 0 & 0 & \cdots & P_{k-1} & 0 \end{pmatrix},
\tag{2-1-5}
$$

where $n_{x,t}$ is the abundance (number of individuals) of age class x ($x = 0, 1,\ldots, k$; k is the maximum age class) at the beginning of year t, age class x denotes age x to $x+1$ and F_x is the per-capita fertility rate (referred as "fertility rate" below) of age class x. P_x is the survival rate from age x to $x+1$, where both natural and human-induced mortalities are included. The population will eventually show a stable age distribution regardless of the age structure in the first year if F_x and P_x do not change annually (Caswell, 1989). At that time, the annual change in population size N_t ($= \sum n_{x,t}$) can be expressed as:

$$
N_{t+1} = \lambda N_t,
\tag{2-1-6}
$$

where λ is the annual change rate of the population. When no human-induced mortality occurs ($P = P_{\text{natural}}$), λ can be replaced by λ_{natural}. An estimate of λ_{natural} is given as the maximum eigenvalue of the matrix A.

Assumptions in the estimation of λ_{natural} and the prediction of future population changes (Sections II-2 and II-3) were:

1. Demographic parameters are yearly unchanged (only for Section II-3).
2. There exists no density effect.
3. Sex ratio is 1:1 at any age.

Those were assumptions necessary for a basic form of the age-classified matrix model. The

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uncertainty of $\lambda_{natural}$ was estimated from stochastic variations in $P_{natural}$ (for details, see II-1.2.2). The model predicts an exponential change in population size after achieving a stable age distribution: an increase when $\lambda > 1$ and a decrease when $\lambda < 1$.

II-1.2.2 Demographic parameters

The values of life history parameter for narrow-ridged finless porpoises were obtained from the literature. Overview of demographic parameters is described in Section I-2 and the selected values are summarized in Table II-1-1. The estimates only for females were incorporated when there were estimates for both sexes.

Longevity

The baseline of maximum age class (k) was roughly given as 29 from the reported maximum ages. For sensitivity analysis concerning the effect of this parameter on $\lambda_{natural}$, the values between 24 and 29 were additionally considered.

Fertility

Estimates of the ages at first and last reproduction (AFR and ALR) are needed to specify F_x. AFR can be estimated by adding the gestation period (about one year) to the age at sexual maturity (about 5 years). Here, baseline of AFR was set at 6 years old and ALR was set at the maximum age class k. For sensitivity analysis, the AFR of 5 and 7 years were additionally considered.

Age-specific fertility is calculated as:

$$F_x = \begin{cases} 0 & \text{for } x < \text{AFR,} \\ 0.5 \times \frac{1}{\text{CI}} \times P_x & \text{for } x \geq \text{AFR,} \end{cases} \qquad (2\text{-}1\text{-}7)$$

where CI denotes the calving interval and 1/CI represents the annual pregnancy rate (Dans et al., 2003). Here, according to Kasuya and Kureha (1979), CI was set to be 2 years, which means half of all mature females breed ever year.

Survival

Direct observations of the survival process are usually difficult or impossible for many cetaceans, including the narrow-ridged finless porpoises. Therefore, modeling procedures have been developed to estimate survival rates. One approach is to establish adequate upper and lower limits for the survival rates of calves and adults (Reilly and Barlow, 1986; Slooten and Lad, 1991; Woodley and Read, 1991). A second approach is to construct a life table model for the species in question using the survival rate estimates for other species with similar life histories. Life tables have been described using Siler's competing risk model (Siler, 1979) and the random sampling from the possible distributions in order to quantify the uncertainty in $\lambda_{natural}$ (e.g., Barlow and Boveng, 1991; Slooten and Lad, 1991; Woodley and Read, 1991; Caswell et al., 1998; Dans et al., 2003).

In this section, the second approach was employed to estimate age-specific survival rates for narrow-ridged finless porpoises because there are no estimates for the porpoises. The estimates for four cetaceans that have AFR values similar to that of the porpoises, listed in Table II-1-2, were used. Here, it was expected that the age-specific natural survival rate ($P_{natural, x}$) for narrow-ridged finless porpoises would fall in the range of these estimates. Figure II-1-1a shows the survivorship curves for the four cetaceans. The following steps (i) to (iii) were conducted to estimate the $P_{natural, x}$ of an age class (Figure II-1-2).

(i) Select a species.

(ii) Randomly sample a value from the normal distribution defined by the mean and standard deviation of the survival rate estimate for the selected species. Repeat step (ii) if the sampled value did not fall in the range between 0 and 1. The effect of this treatment was disregarded because the upper limit of the 95% confidence interval of the survival rate estimate for four cetaceans did not exceed 1.

(iii) Set the sampled value as the survival rate for the narrow-ridged finless porpoise if the sampled value was ≤ 1.

The steps were repeated for all age classes in a trial and the trial was repeated 2000 times to generate the uncertainty in $P_{natural, x}$. The examples of the estimated survivorship curves for narrow-ridged finless porpoises are shown in Figure II-1-1b.

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II-1.3   Results

The estimates of the age-specific natural survival rate ($P_{natural, x}$) are shown in Figure II-1-3. The estimates for calves <1 year old and adults >10 years old were 0.87 and 0.96/year, respectively. The distributions of the estimates of the annual intrinsic rate of natural increase ($\widehat{\lambda_{natural}}$) are shown in Figure II-1-4. When AFR was assumed to be 5, 6, and 7 years, the medians of $\widehat{\lambda_{natural}}$ were 1.057 (2.5–97.5 percentile: 1.025–1.072), 1.048 (1.022–1.063), and 1.041 (1.015–1.055), respectively (Table II-1-3).

When the population was assumed to show a stable age distribution, the proportion of newborn calves in the whole population is 13% and, thus, the estimate of the annual birth rate ($\hat{B}$) was 0.13/year. The instantaneous birth rate (b) was estimated to be 0.052/year. In case of the AFR of 6 years, the annual natural mortality rate ($M_{natural}$) was estimated to be 7.1%/year from Eq. 2-1-3.

II-1.4   Discussion

Adequacy of the values of demographic parameters

The annual intrinsic rate of natural increase ($\lambda_{natural}$) is most sensitive to calving interval (CI) and adult survival rate (Reilly and Barlow 1986). As Bradford et al. (2008) indicated, the number of age class in the matrix model had relatively little effect on the estimate of $\lambda_{natural}$ (Fig. II-1-5a). Although Kasuya and Kureha (1979) suggested that a two-year cycle would be most common for narrow-ridged finless porpoises, if the porpoise population was to face extinction, its CI could become shorter than 2 years owing to a density effect that was not considered in this study. The values of $\lambda_{natural}$ remarkably increased in the case of CI = 1 year (Fig. II-1-5b). However, these increased values are unrealistic as long as current knowledge is considered, for example, Wade (1998) regards 1.04/year as $\lambda_{natural}$ for cetaceans.

Information regarding the survival process for most marine mammals is unclear. Caswell et al. (1998) translated life tables for other animals, including terrestrial mammals for which more accurate estimates have been obtained from direct observations, into a life table for harbor porpoises. When information from the other animals is used, the accuracy of the estimates depends on the selection of the model species and the time scaling procedure to adjust the differences in longevities among species. Although longevity is usually used as a scaling indicator, Caswell et al. (1998) rescaled time by AFR because there is not enough knowledge on the longevity of harbor porpoises. The AFR estimates for harbor porpoises ranged from 4 to 5

years, and the difference between the maximum and minimum was <1 year. However, the range for narrow-ridged finless porpoises was too large to rescale in the same manner as Caswell et al. (1998) did. Therefore, The age-specific survival rate estimates of other cetaceans that have AFR similar to that of the narrow-ridged finless porpoise was used without scaling time by AFR.

Comparison with the estimates in the previous studies

Among the previous analyses of $\lambda_{natural}$ using Monte Carlo methods, Caswell et al. (1998) estimated $\lambda_{natural}$ as 1.096/year for harbor porpoise populations for which calving interval (CI) was assumed to be 1 year. Dans et al. (2003) also estimated $\lambda_{natural}$ for dusky dolphin population to be 1.043/year (CI = 2 years) and 1.018/year (CI = 3 years). Comparing these estimates, the medians of $\lambda_{natural}$ obtained in the current study (Table II-1-3) seem to be plausible for a narrow-ridged finless porpoise population.
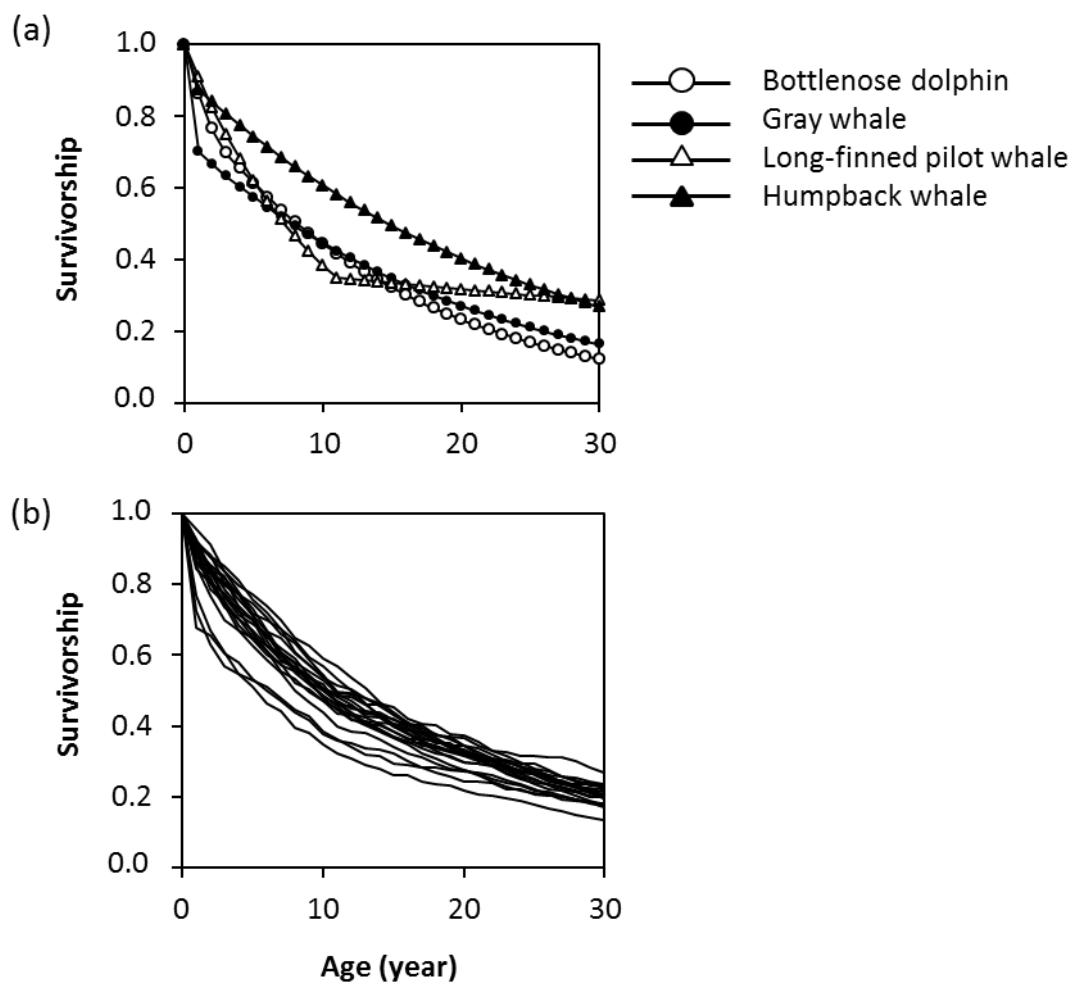
Fig. II-1-1 **(a)** Survivorship curves for four cetacean species. Survivorship at an age is defined as survival rate from birth to this age. References on survival rate of each species are listed in Table II-1-1. **(b)** Example of 20 estimated survivorship curves for a narrow-ridged finless porpoises.
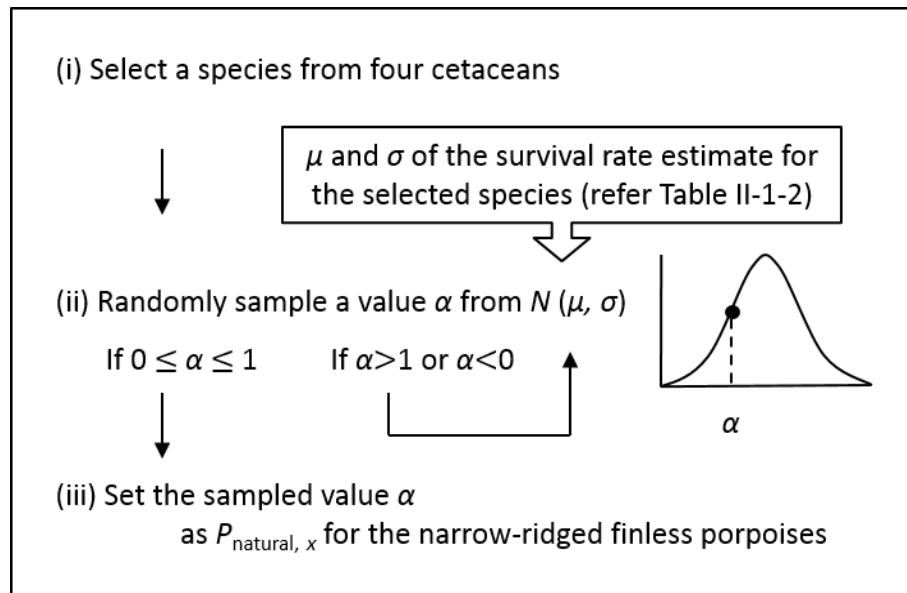
Fig. II-1-2 Flowchart to estimate the survival rate of an age class for the narrow-ridged finless porpoises. Symbols of μ, σ and $N(\mu, \sigma)$ indicate the average, the standard deviation, and the normal distribution defined by μ and σ, respectively.
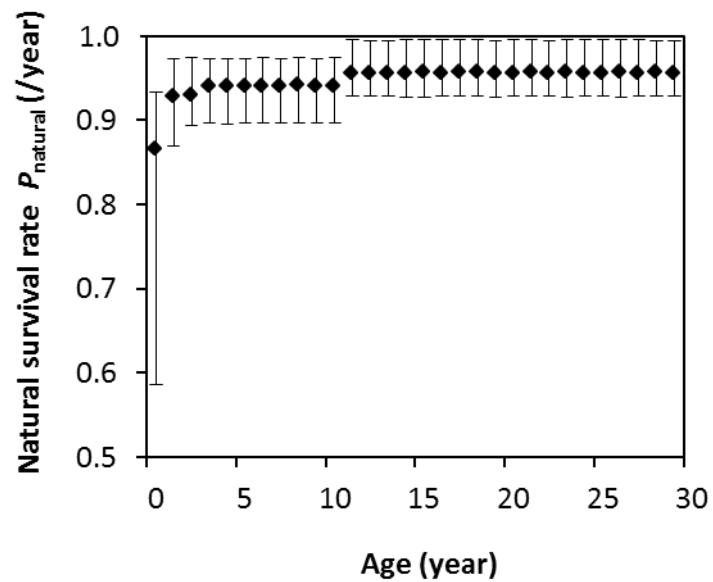
Fig. II-1-3 Median of 2000 estimates of natural survival rate ($P_{natural}$) from age x to $x+1$ for the narrow-ridged finless porpoises. Error bars are 2.5–97.5 percentiles of the estimates.
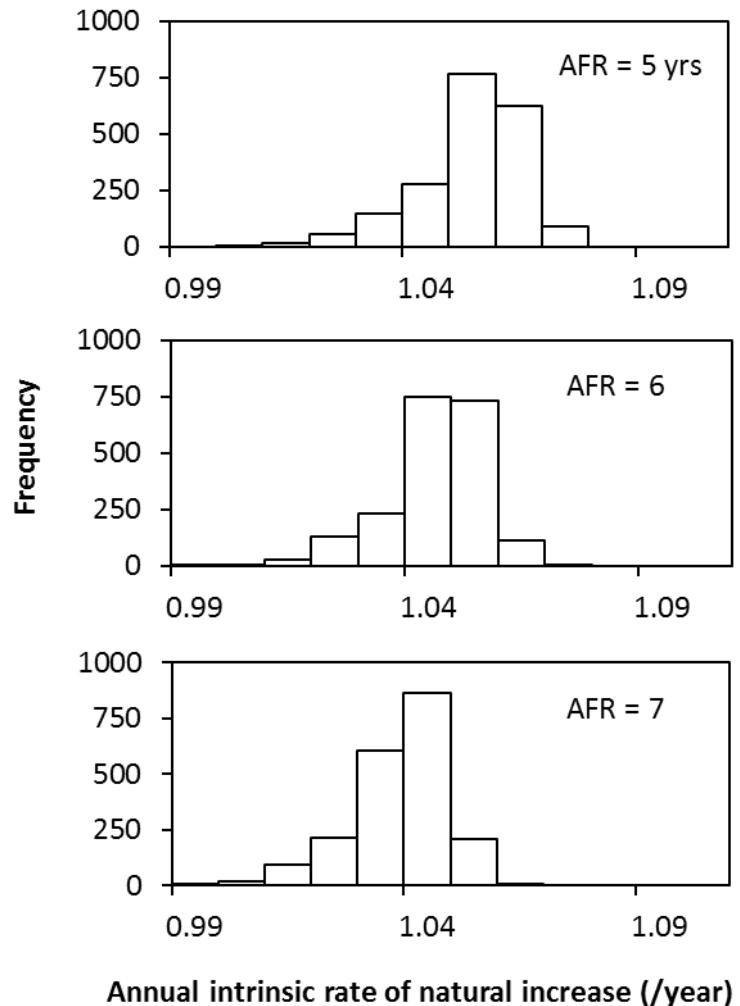
Fig. II-1-4 Distribution of the estimated annual intrinsic rate of natural increase ($\lambda_{natural}$) for a narrow-ridged finless porpoise population from 2000 simulation trials of random sampling on survival rate for age at first reproduction (AFR) of 5, 6, 7 years.
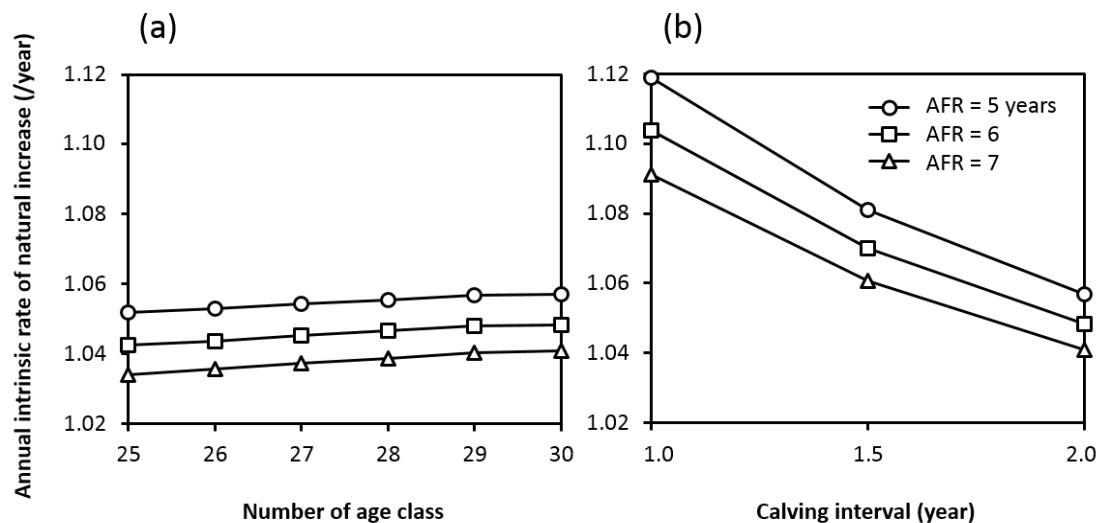
Fig. II-1-5 Sensitivity of the annual intrinsic rate of natural increase ($\lambda_{natural}$) for a narrow-ridged finless porpoise population to **(a)** number of age class in the matrix model (= 1+ maximum age class k) and **(b)** calving interval. Plots indicates the median from 2000 trials.

Table II-1-1　Summary of demographic parameters used as input data in a population viability analysis for narrow-ridged finless porpoises

Parameter	Value	Values for sensitivity analysis	Reference
Maximum age class (k)	29	24–29	Shirakihara et al. (1993) Kasuya (1999)
Age of first reproduction (AFR)	6 years	5, 6, 7 years	Jefferson et al. (2002b)
Age at last reproduction (ALR)	30 years	Same with the number of age class ($k+1$)	-
Calving interval (CI)	2 years	1, 1.5, 2 years	Kasuya and Kureha (1979)

Table II-1-2   Summary of the age at first reproduction (AFR) and the survival rate P_x (from age x to $x+1$) for four cetacean species.

Species	AFR (year)	P_x (SD)	Reference
Bottlenose dolphin (*Turisips truncatus*)	9.0–11.0	$P_0 = 0.862\ (0.018)$ $P_1 = 0.887\ (0.014)$ $P_2 = 0.912\ (0.010)$ $P_{3\text{-}29} = 0.937\ (0.006)$	Currey et al. (2009b)
Gray whale (*Eschrichtius robustus*)	5.0–9.0	$P_0 = 0.701\ (0.094)$ $P_{1\text{–}29} = 0.951\ (0.014)$	Bradford et al. (2006)
Long-finned pilot whale (*Globicephala melas*)	8.9	$P_{0\text{–}10} = 0.909\ (0.010)$ $P_{11\text{–}29} = 0.990\ (0.005)$	Bloch et al. (1993)
Humpback whale (*Megaptera novaeangliae*)	5.5–8.5	$P_0 = 0.875\ (0.047)$ $P_{1\text{–}29} = 0.960\ (0.008)$	Barlow and Clapham (1997)

Table II-1-3 Median, range and coefficient of variation (CV) of the estimated annual rate of increase ($\widehat{\lambda_{natural}}$) for a narrow-ridged finless porpoise population, based on 2000 simulations. AFR is age at first reproduction.

AFR (year)	$\widehat{\lambda_{natural}}$ (/year)		
	Median	Ranges (2.5–97.5 percentiles)	CV (%)
5	1.057	1.025–1.072	1.093
6	1.048	1.022–1.063	0.977
7	1.041	1.015–1.055	0.938

II-2 Evaluation of human-induced mortality on the Inland Sea population

II-2.1 Background

Seto Inland Sea is surrounded by three of the main islands of Japan, namely, Honshu, Shikoku, and Kyushu (Fig. I-1) and covers the marine area of 14,300km^2. The sea is the largest of all five waters inhabited by the narrow-ridged finless porpoises in Japan. Moreover, it has favorable topographical conditions for the porpoises: the dominance of non-rocky bottoms and shallow depth <50m (Shirakihara, 2003a). Therefore, the porpoise population in this area is the largest of all the five populations (Shirakihara, 2002). However, Kasuya et al. (2002) indicated that the abundance of the population had heavily decreased. The possible causes of the decline suggested by these authors were mortality due to bycatch, ship strikes, pollution and habitat degradation.

In this section, a population viability analysis was conducted for the narrow-ridged finless porpoise population in the Inland Sea, using two data sources for expressing the population dynamics: the abundance estimate and the past decreasing rate during 22 years. The purpose is to quantitatively analyze the impacts of human-induced mortality on future population size by assuming possible levels of human-induced mortality given from a Bayesian analysis.

II-2.2 Methods

II-2.2.1 Dynamics model

Under the presence of human-induced mortality, Eq. (2-1-6) is modified as:

$$N_{t+1} = \lambda_{\text{natural}} (1 - M_{\text{human}})N_t, \tag{2-2-1}$$

where λ_{natural} is the annual intrinsic rate of natural increase (estimated in previous section II-1) and M_{human} is the annual human-induced mortality rate. According to Eq. (2-1-3), the annual change rate (λ) is described as:

$$\begin{aligned}
\lambda &= (1+B) \times (1 - M_{\text{natural}}) \times (1 - M_{\text{human}}) \\
&= (1+B) \times \{1 - (M_{\text{natural}} + M_{\text{human}}) - M_{\text{natural}} \times M_{\text{human}}\} \\
&\approx (1+B) \times \{1 - (M_{\text{natural}} + M_{\text{human}})\}, \tag{2-2-2}
\end{aligned}$$

where the sum of M_{natural} and M_{human} means total annual mortality rate. The population size was simply approximated by a continuous value although it is an integer.

II-2.2.2 Bayesian analysis for estimating abundance and human-induced mortality

The abundance of this population was estimated to be 7572 individuals (95% confidence intervals: 5411–10596 individuals）in 2000 from an aerial sighting survey (Shirakihara et al., 2007). This estimate is negatively biased because the detection probability on the track line, $g(0)$, was assumed to be 1. Jefferson et al. (2002a) estimated $g(0)$ as 0.65 for finless porpoises from a helicopter whose flight speed and height were similar to Cessna used in the aerial sighting survey. Using this $g(0)$ estimate, an unbiased estimate of abundance is 11649 individuals. The population size reduction of 69.8% over 22 years was estimated by comparing the abundance indices for two time periods (1976-78 and 1999-2000). The indices were calculated by averaging the sighting rate (number of sighted individuals per 100 km during a shipboard sighting survey) weighted by the sea area over all 6 strata shown in Table 3 of Kasuya et al. (2002).

For assessing variability of the parameters of the population dynamics model, a Bayesian analysis was attempted. This analysis has been applied to a PVA for a harbor porpoise population (Moore and Read, 2008). Here, in order to utilize the limited information shown above, an abundance index was defined as:

$$I_t \ = \ N_t \ / \ q \qquad \text{for } t = 1978 \text{ and } 2000, \tag{2-2-3}$$

where q is the proportionality coefficient between abundance and abundance index. The likelihood for the abundance in 2000 (N_{2000}) was based on the following normal distribution,

$$L(N_{2000}|\,\mu_N, \sigma_N) \ = \ \frac{1}{\sigma_N\sqrt{2\pi}} \exp\left[-\frac{(N_{2000}-\mu_N)^2}{2\sigma_N{}^2}\right], \tag{2-2-4}$$

$$\mu_N \ = \ N_{1978} \ \times \ \{\,\lambda_{\text{natural}}\,(1 \ - \ M_{\text{human}})\,\}^{\,22}, \tag{2-2-5}$$

$$\sigma_N \ = \ \mu_N \ \times \ 0.173, \tag{2-2-6}$$

where N_{1978} is the abundance in 1978 and 0.173 is coefficient of variation (CV) of abundance estimate in 2000 (Shirakihara et al., 2007). The initial value of N_{2000} was set as 11649

individuals. Additionally, the likelihoods for I_{1978} and I_{2000} were based on the following normal distribution,

$$L\big(I_t\big|\,\mu_{I_t},\sigma_{I_t}\big) \;=\; \frac{1}{\sigma_{I_t}\sqrt{2\pi}}\exp\!\left[-\frac{(I_t-\mu_{I_t})^2}{2\sigma_{I_t}{}^2}\right], \tag{2-2-7}$$

$$\mu_{I_t} \;=\; \begin{cases} N_{1978}\,/\,q & \text{for } t \;=\; 1978, \\ (N_{1978}\,/\,q)\times\{\lambda_{\text{natural}}\,(1-M_{\text{human}})\}^{\,22} & \text{for } t \;=\; 2000, \end{cases} \tag{2-2-8}$$

$$\sigma_{I_t} \;=\; \begin{cases} \mu_{I_t}\times 0.212 & \text{for } t \;=\; 1978, \\ \mu_{I_t}\times 0.281 & \text{for } t \;=\; 2000, \end{cases} \tag{2-2-9}$$

where 0.212 and 0.281 are CVs of the sighting rates in 1978 and 2000 which were given from Table 2 in Kasuya et al. (2002). The initial values of I_{1978} and I_{2000} were given as 100 and 30, respectively. These three likelihood components were included in the total likelihood function,

$$\begin{aligned} L(N_{2000}, &I_{1978}, I_{2000}\,|\,N_{1978}, q, \lambda_{\text{natural}}, M_{\text{human}}) \\ &= L(N_{2000}\,|\,\mu_N, \sigma_N)\times L\big(I_{1978}\big|\,\mu_{I_{1978}}, \sigma_{I_{1978}}\big)\times L\big(I_{2000}\big|\,\mu_{I_{2000}}, \sigma_{I_{2000}}\big), \end{aligned} \tag{2-2-10}$$

The prior distributions for N_{1978}, q, λ_{natural} and M_{human} are shown in Table II-2-1. The priors were given as uniform, except for λ_{natural} whose prior is a Weibull distribution with a good fit to the observed distribution from 2000 estimated values of λ_{natural} (Fig. II-1-4, AFR = 6 years). In this approach, the posteriors for λ_{natural} and M_{human} depend on AFR. However, it had checked that the outcomes of population prediction using the posteriors were not sensitive to AFR. Parameters were estimated by using WinBUGS 1.4.3, freely available software for performing Bayesian analysis using Markov Chain Monte Carlo (MCMC) methods. Sampling of a set of λ_{natural} and M_{human} from the posteriors was repeated 100,000 times and it was assumed that these values would continue in the future.

II-2.2.3 Procedures of PVA

The flowchart of a population viability analysis for the Inland Sea population is shown in Figure II-2-1. The input values of the demographic parameters for step (i) were same with the baseline value in the previous section (Table II-1-1). For step (ii), three scenarios were considered on the selection of the value of λ_{natural} and M_{human}.

Scenario 1: the annual change rate (λ) kept the median of the estimates of λ by the Bayesian analysis in all years and all simulation trials (the deterministic simulation).

Scenario 2: The stochastic simulation without yearly fluctuations in $\lambda_{natural}$ and M_{human}. A set of $\lambda_{natural}$ and M_{human} was randomly selected from 100,000 sets from the posteriors and was used during 200 years in each trial.

Scenario 3: The stochastic simulation with yearly fluctuations in $\lambda_{natural}$ and M_{human}. A set of $\lambda_{natural}$ and M_{human} was randomly selected from the posteriors in each year and each trial.

Although the target for the population prediction was Scenario 3, other scenarios were taken up for comparisons. For simplicity, no autocorrelations were incorporated among the estimates of $\lambda_{natural}$ and M_{human} in each year. A simulation trial of step (iii) and (iv) was conducted for the future changes in population size over 200 years, and was repeated 2000 times for Scenarios 2 and 3. The starting year for the population predictions was 2000. The abundance in the year was calculated with an estimate of N_{1978} which was randomly selected from its posterior in each trial.

For step (v), the risks due to human-induced impacts were quantitatively assessed from two perspectives: the population size reduction over three generations and the probability of extinction within 100 years, both of which are associated with IUCN Criteria A4 and E (Table I-1). The generation period for the narrow-ridged finless porpoise is estimated to be 16.5 years (Taylor et al., 2007). Therefore, 50 years was given as three-generation period. There are different definitions of population extinction. Heinsohn et al. (2004) defined "quasi-extinction" as a decrease to <10% of the original abundance within 200 years. Whereas, Currey et al. (2009b) regarded "quasi-extinction" as a reduction to less than one-quarter of present levels, and "extinction" as a reduction to zero within 50 years. Two definitions were adopted: "extinction" was defined as the decline to <2 individuals, 1 female and 1 male, and "quasi-extinction" was defined as the decrease to <100 individuals. "Extinction" was the most extreme case and was expected to provide the most optimistic values of extinction probability. "Quasi-extinction" also denoted a tragic case. A total of 100 individuals was given from the threshold of 50 adults which is part of criterion D for the Critically Endangered (CR) category on the IUCN Red List (IUCN, 2001). The probability of extinction was calculated as the proportion of the trials in which the population reached "extinction" or "quasi-extinction" in the 2000 trials.

II-2.3   Results

II-2.3.1 Population projection using the estimates by the Bayesian analysis

The median of the posterior distribution of annual human-induced mortality rate (M_{human}) was 10%/year (2.5–97.5 percentile: 6.3–12.8%/year). The posteriors of λ and N_{2000} calculated from 100,000 samples of λ_{natural}, M_{human} and N_{1978} are shown in Figure II-2-2. The medians of these posteriors were 0.942/year (0.916–0.974) and 11989 individuals (8873–18222), respectively.

Figure II-2-3 shows the future changes in population size for the narrow-ridged finless porpoise population in the Inland Sea. The population size will rapidly decline. This is because the population was assumed to continue to decrease at an annual rate with the mean of 5.8%/year (=1-0.942).

II-2.3.2   Risk evaluation

In the deterministic prediction with the constant rate of 5.8%/year, the population size after 50 years will be 5.04% of the starting population size. In the stochastic prediction without and with yearly fluctuations in λ_{natural} and M_{human} (Scenarios 2 and 3), the median of the population size after 50 years was estimated to be 6.43% (2.5–97.5 percentile: 1.71–20.0%) and 6.68% (5.42–7.78%) of the size in 2000, respectively. Introducing the yearly fluctuations in λ_{natural} and M_{human}, which was given by the Bayesian analysis, had little effect on the future predictions as to population projection, time to extinction and time to quasi-extinction (Table II-2-2).

The yearly changes in the probability of extinction for the Inland Sea population are shown in Figure II-2-4. In Scenario 2, the probability of extinction began to rise after 88 years and became 0.75% after 100 years. The probability of quasi-extinction began to rise after 48 years and became 66% after 100 years (Fig. II-2-4a). On the other hand, in Scenario 3, the probability of extinction after 100 years was 0% but began to rise after 132 years. The probability of quasi-extinction began to rise after 56 years and became 89% after 100 years (Fig. II-2-4b).

II-2.4   Discussion

Risk assessment of the Inland Sea population

The reduction in abundance reported by Kasuya et al. (2002) is undoubtedly critical for the finless porpoise population in the Inland Sea. The results suggest that the population size reduction after 50 years will overly exceed 80% and meet the category of Critically Endangered (CR) under criterion A4 of the IUCN Red List (IUCN 2001), while the probability of extinction

after 100 years is 0% and do not meet criterion E for even the VU category.

Adequacy of the future predictions

In this study, yearly fluctuations in $\lambda_{natural}$ and M_{human} were given from the posteriors of the Bayesian analysis because no sufficient data were available on yearly changes in abundance of this population. The variations in sets of $\lambda_{natural}$ and M_{human} had little effect on the future predictions of this population. However, the variations in $\lambda_{natural}$ are likely to be underestimated because they were generated only from the variations in natural survival rate ($P_{natural}$). For evaluating the extinction risks in depth, yearly fluctuations in $\lambda_{natural}$ and M_{human} due to demographic stochasticity and catastrophic events should be incorporated. According to interview surveys for fishermen, bycatch of narrow-ridged finless porpoises suddenly increased when monofilament type gillnets were newly introduced (K. Shirakihara, unpublished data); thus, modification of fishing gears may result in a higher value of M_{human}. Moreover, the minimum viable population size was not considered because of lack of available data. If it exists, more pessimistic prediction will be made and the status of the Inland Sea population may be more critical.

(i) Input of demographic parameters (k, AFR, CI, N_0) **and initial population structure**

Simulation trials for future changes in population size

(ii) Select a scenario on the demographic parameters
Scenario 1: Deterministic simulation
Scenario 2: Stochastic simulation
without yearly fluctuation of $\lambda_{natural}$ and M_{human}
Scenario 3: Stochastic simulation
with yearly fluctuation of $\lambda_{natural}$ and M_{human}

(iii) Select a set of values for demographic parameters ($\lambda_{natural}$, M_{human}, N_{1978}) from the posteriors given by Bayesian analysis

(iv) Simulate future changes
in population size over 200 years

N_{2000}

2000 repetitions

Year

(v) Risk evaluation
Population size reduction over three generations
Extinction and quasi-extinction probabilities within 100 years

Fig. II-2-1   Flowchart of a population viability analysis for the narrow-ridged finless porpoises in the Inland Sea. $\lambda_{natural}$ is the annual rate of natural increase, M_{human} is the annual human-induced mortality rate and N_t is the current population size in year t.
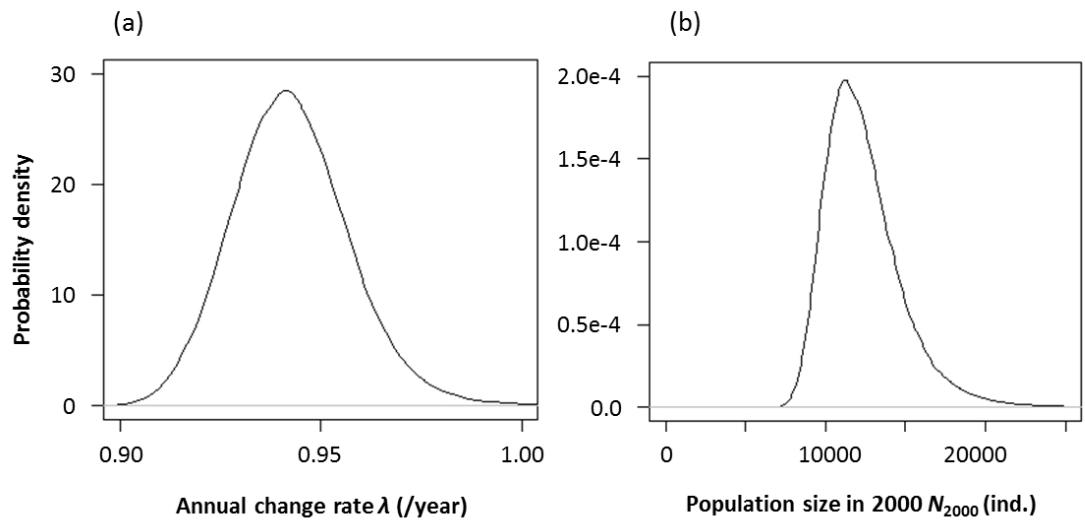
Fig. II-2-2 Posterior distributions of **(a)** annual change rate ($\lambda = \lambda_{natural}(1 - M_{human})$) and **(b)** population size in 2000 (N_{2000}), which was calculated from the posterior of annual intrinsic rate of natural increase ($\lambda_{natural}$), annual human-induced mortality rate (M_{human}) and populations size in 1978 (N_{1978}) by the Bayesian analysis for the narrow-ridged finless porpoise population in the Inland Sea.
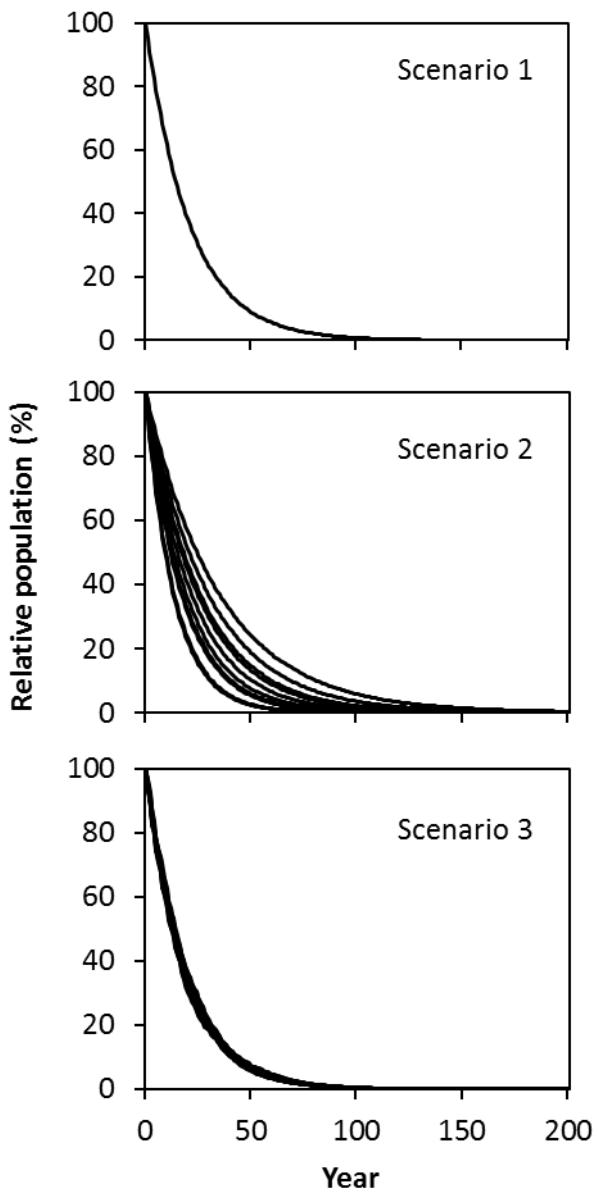
**Fig. II-2-3** Predicted future changes in population size for the narrow-ridged finless porpoise population in the Inland Sea. The population size in year 0 (year 2000) is 100%. Trajectories from 10 trials in the stochastic simulations are shown for Scenarios 2 and 3. For three scenarios, see Figure II-2-1.
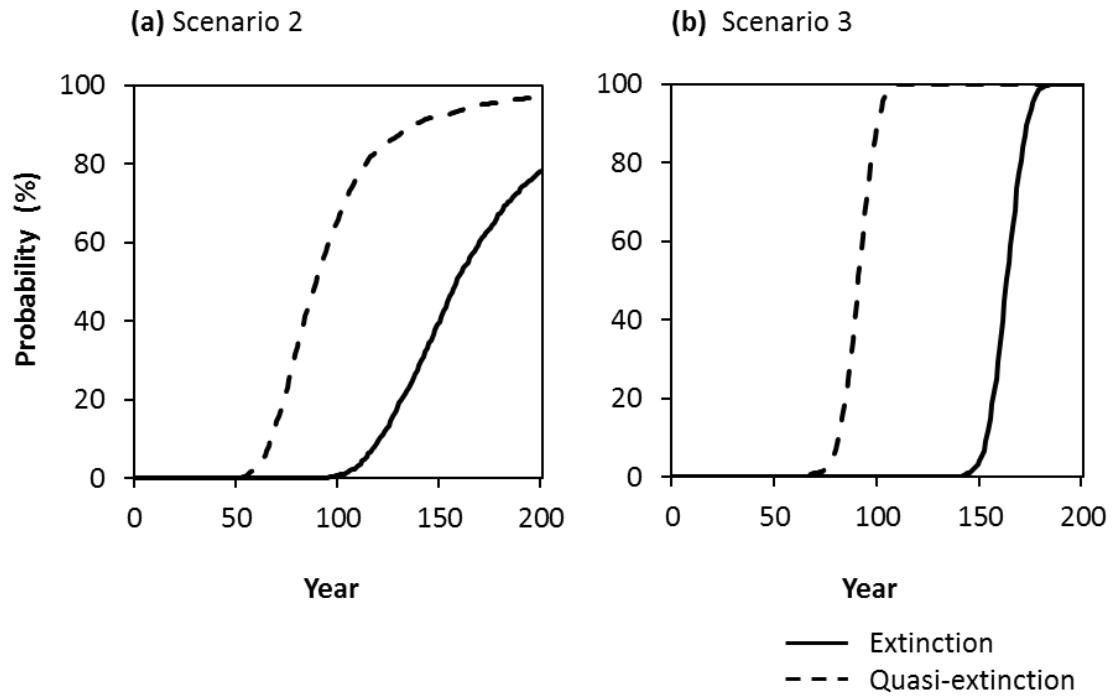
Fig. II-2-4 Yearly changes in the probability of extinction and quasi-extinction for the narrow-ridged finless porpoise population in the Inland Sea. "Extinction" is defined as the decrease to <2 individuals and "quasi-extinction" is defined as the decrease to <100 individuals. Year 0 is the year 2000. **(a)** Trajectories in Scenario 2, the stochastic simulation without yearly fluctuations in demographic parameters. **(b)** Trajectories in Scenario 3, the stochastic simulation with yearly fluctuations. The probabilities cannot be estimated for the deterministic Scenario 1.

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Table II-2-1   Summary of prior distributions used in the Bayesian analysis.

Parameter	Prior distribution	Interpretation
N_{1978}	uniform(0,100000)	The abundance in 1978
$\log_{10} q$	uniform(0,4)	Common logarithm of the proportionality coefficient between abundance and abundance index
$\lambda_{natural}$	Weibull(1.060,118.734)	Annual intrinsic rate of natural increase
M_{human}	uniform(0,1)	Annual human-induced mortality rate

Table II-2-2   Predicted population size, time to extinction, and time to quasi-extinction for the narrow-ridged finless porpoise population in the Inland Sea, from deterministic and stochastic simulations (see text for details of the scenarios). Numerals and those in parentheses are median and 2.5–97.5 percentiles, respectively.

	Scenario 1	Scenario 2	Scenario 3
Population size after 50 years / population size in 2000 (%)	5.04	6.43 (1.71–20.0)	6.68 (5.42–7.78)
Time to extinction (years)	146 (134–155)	162 (109–278)	164 (148–175)
Time to quasi-extinction (years)	81 (68–90)	90 (59–155)	91 (75–102)

II-3　Evaluation of bycatch impacts on the Ariake Sound and Tachibana Bay population

II-3.1　Background

Ariake Sound and Tachibana Bay (Fig. I-1a) is the southernmost of the waters inhabited by five populations of the narrow-ridged finless porpoises. Most parts of Ariake Sound and Tachibana Bay have topographical features that are favorable for the porpoises: a shallow depth (<50 m) and the predominance of non-rocky bottoms (Shirakihara et al., 1992). Ariake Sound has a rich biodiversity and is a fertile fishing ground. Tachibana Bay connects Ariake Sound to the open sea. The Ariake Sound and Tachibana Bay population is one of the most abundant, and has one of the highest population densities in Japanese waters (Yoshida et al., 1997, 1998; Yoshida, 2002; Amano et al., 2003; Shirakihara et al., 2007). Moreover, a distinct haplotype cluster is constructed from the population (Aizu et al., 2013). It therefore is a valuable resource for discovering the origin of Japanese narrow-ridged finless porpoises.

Bycatch is a major threat to the narrow-ridged finless porpoise populations. Shirakihara and Shirakihara (2013a) reported that bycatch impact was serious for the population in Ariake Sound and Tachibana Bay, located in the central region of western Kyushu, Japan. They indicated that the estimated annual number of porpoises killed due to bycatch was well over the PBR for this population.

Generally, individuals with different age classes do not necessarily experience a similar bycatch impact because there may be age-dependent habitat-use patterns and fishing-gear selectivity. Indeed, it was indicated that immature individuals (<1 year old) accounted for approximately half of the specimens collected around the waters of western Kyushu (Shirakihara, 2003b; Shirakihara and Shirakihara, 2013a). They also showed that the accidental capture of the porpoises in bottom-set gill nets mainly occurred between fall and winter, which is during the calving season for this population. It is possible that a significant number of adult females were bycaught with their calves, because it may be difficult for fishermen to carry heavier individuals back to port. The bias in age composition for bycaught individuals has been also recognized for other cetaceans (Fruet et al., 2012; Mannocci et al., 2012). Fruet et al. (2012) indicated that adults of the common bottlenose dolphins accounted for the majority of the bycatches in southern Brazil. Mannocci et al. (2012) reported that the age structure of common dolphins killed due to bycatch in the eastern North Atlantic was clearly different from the stable age structure. However, quantitative evaluations of the effects of age dependence in

bycatch on the viability of cetacean populations have not been performed, to date.

In this section, a population viability analysis was conducted for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay to evaluate the impacts of the reported level of bycatch mortality. Additionally, the impact of age dependence in bycatch on the viability of the population was evaluated.

II-3.2 Methods
II-3.2.1 Dynamics model and demographic parameters

Age-classified matrix model, as described in Section II-1-2, was used to incorporate the age-specific bycatch mortality rate ($M_{\text{bycatch, }x}$) and to express annual changes in the number of individuals of each age class. Presuming that only bycatch was the cause of human-induced mortality, age-specific "total" survival rate (P_x) in Eq. (2-1-5) was given as:

$$P_x = P_{natural,x} \left(1 - M_{bycatch,x}\right). \tag{2-3-1}$$

The value of age-specific natural survival rate ($P_{\text{natural, }x}$) was provided from the estimates for AFR of 6 years in previous section II-1.

To incorporate the age dependence in bycatch, it was presumed that one age class (referred as "target age class (x_{T})" below) had the highest bycatch mortality rate. Thus, $M_{\text{bycatch, }x}$ was given as

$$M_{bycatch,x} = \begin{cases} c \times \dfrac{M_{bycatch}}{1+(c-1)n_{x_{\text{T}}}/\sum n_x} & \text{for } x = x_{\text{T}}, \\[2ex] \dfrac{M_{bycatch}}{1+(c-1)n_{x_{\text{T}}}/\sum n_x} & \text{for } x \neq x_{\text{T}}, \end{cases} \tag{2-3-2}$$

where M_{bycatch} is the whole annual bycatch mortality rate of a population (usually, $<M_{\text{human}}$), which was constant regardless of age dependence in bycatch and was represented as:

$$M_{bycatch} = \frac{\sum M_{bycatch,x} \times n_x}{\sum n_x}, \tag{2-3-3}$$

where n_x is the number of individuals in age class x, which was given from the whole abundance under a stable age structure without any age dependence. The symbol c represents the scale of age dependence in bycatch ($c \geq 1$). $M_{\text{bycatch}, x}$ is equal to M_{bycatch} in the absence of a correlation with age ($c = 1$). When c increases, the effect of age also increases with a higher $M_{\text{bycatch}, x}$ in the target age class.

For the Ariake Sound and Tachibana Bay population, the most recent abundance estimate is 3093 individuals (CV = 15.7%) in 1993 and 1994 (Yoshida et al., 1997). For the population, 250 individuals (CV = 22.3%) were estimated to be bycaught annually during gill net fishing in 2007 and 2008 (Shirakihara and Shirakihara, 2013a). Assuming all bycaught individuals as dead, the default value of M_{bycatch} for this population is 8.1%/year (= 250/3093). Shirakihara and Shirakihara (2013a) suggested that this value might be an overestimation. The abundance estimate of 3093 individuals was calculated with the assumption that the detection probability on the track line in aerial sighting survey, $g(0)$, is equal to 1. If the abundance estimate is corrected by an available estimate of $g(0)$ (= 0.65; Jefferson et al., 2002a), the estimate of M_{bycatch} decreases to 5.3%/year (= 250/[3093/0.65]).

II-3.2.3 Procedure of PVA

The flowchart of population viability analysis for the Ariake Sound and Tachibana Bay population is shown in Figure III-3-1. In this section, a possible range of the annual bycatch mortality rate (M_{bycatch}) was not estimated by the Bayesian analysis. Alternatively, some scenarios on M_{bycatch} were set for considering the uncertainty in the estimate of M_{bycatch}.

The input values of the demographic parameters for step (i) were same with those in the previous sections (Table II-1-1). The population size in the first year (N_0) for all the simulation trials was set to be 3093 individuals and a stable age structure (without any bycatch mortality) was set as the age structure in the first year. This assumption would not significantly affect the predictions, because a new stable age structure would be conducted after a few decades so there was little effect on risk evaluation.

A simulation trial from step (ii) to (v) was conducted for the future change in population structure, and was repeated 2000 times. For step (iii), three scenarios were selected for incorporating the plausible values of the annual bycatch mortality rate (M_{bycatch}):

Scenario 1: The value of M_{bycatch} was fixed at 8.1%/year.

Scenario 2: The value of M_{bycatch} was fixed at 5.3%/year

Scenario 3: A new value of M_{bycatch} was randomly sampled from a distribution, given the uncertainty in the estimate of M_{bycatch}.

A possible distribution of M_{bycatch} was given as shown in Fig. II-3-2, assuming that the abundance estimate follows a log-normal distribution with a mean of 3093 and a CV of 15.7%. For step (v), the future change in population size was simulated over a 100-year period, starting from 1994, with the same survivorship curve and a fixed value of M_{bycatch}. The yearly variations in these parameters were not incorporated, because no useful data are available.

Moreover, five scenarios on the age dependence in bycatch were constructed by the combination of x_{T} and c (Table II-3-1). Scenario I (same as Scenario 1) is the baseline (i.e., the absence of age-dependent effects). In Scenarios II, it was assumed that almost half of the bycaught porpoises were calves <1 year old, according to Shirakihara and Shirakihara (2013a). The value of c was determined as an integer assuming that the bycatch ratios for age class 0 were approximately 25 and 50% in Scenarios II and III, respectively. Scenarios IV and V were determined on the basis of Fisher's reproductive value. The reproductive value (v) is defined as the present value of the future offspring of an individual in an age class (Fisher, 1930) and is calculated as:

$$v_x = \sum_{i=x}^{\text{ALR}} l_t\, m_t / l_x, \tag{2-3-4}$$
$$l_x = \prod_{j=0}^{x} P_{\text{natural},j}, \tag{2-3-5}$$

where l_x is age-specific survival rate from 0 year, m_x is age-specific number of newborn calves ($=F_x/P_{\text{natural},x}$) and ALR is age at last reproduction. Figure II-3-3 shows the estimated reproductive value for each age class. Age class 6 had the highest reproductive value. On the other hand, age class 0 had a relatively small reproductive value because $P_{\text{natural, 0}}$ was also small (Fig. II-1-2) and the chance of surviving to sexually maturity was low.

II-3.3   Results

II-3.3.1 Population projection

If bycatch mortality remained at the reported level, the medians of $\hat{\lambda}$ in all Scenarios 1-3 were less than 1 (Table II-3-2), and the population size would continue to decrease over the next 100 years (Fig. II-3-4). As an index of population decline, estimates of the annual rate of decrease were introduced as:

$$\widehat{D} = 1 - \hat{\lambda}. \tag{2-3-6}$$

The estimates were 3.64%/year (2.5–97.5 percentiles: 2.33–6.09) in Scenario 1, 0.671%/year (-0.677–3.20) in Scenario 2, and 3.87%/year (1.08–7.72) in Scenario 3 (Table II-3-2). In only 15% of all the simulation trials even in the most optimistic case (Scenario 2), the $\widehat{D}$ was below 0%/year, which means the population increased.

II-3.3.2 Risk evaluation

If bycatch mortality remains at the reported level, the median of the population size reduction estimates over three generations (i.e., 50 years) is 84.5% (2.5–97.5 percentiles: 69.9–95.7) in Scenario 1, 29.6% (-37.2–80.3) in Scenario 2, and 86.3% (42.6–98.2) in Scenario 3 (Table II-3-3). A population size reduction of ≥80% over three generations, which qualifies for the "Critically endangered (CR)" category according to Criterion A4 (Table I-1), occurred in almost 70% of the simulation trials in Scenarios 1 and 3 (Fig. II-3-5). Moreover, in almost all of the trials in Scenarios 1 and 3, and in almost 50% of the trials in Scenario 2, the population size was predicted to decline by ≥30% over three generations.

The predicted probability of extinction (<2 individuals) within 100 years was <10% in all Scenarios 1-3 (Table II-3-3). This suggests that the population does not meet any categories of Criterion E (Table I-1). However, with regard to the probability of quasi-extinction (<100 individuals), much worse estimates were given (64.6% and 61.8% for Scenarios 1 and 3, respectively).

II-3.3.3 Effects of age dependence in bycatch

The estimated rate ($\hat{\lambda}$) was <1 regardless of Scenarios I-V as long as M_{bycatch} >5%/year. (Fig. II-3-6). If the M_{bycatch} of 8.1%/year remains constant, then the population size will rapidly decrease over the next 100 years, as indicated in all scenarios (Fig. II-3-7). Figure II-3-8 shows the medians of $\widehat{D}$ over the possible ranges of x_T and c. The results for all scenarios are also plotted. The estimated medians were within the passible range of 2.0–4.5%, thus indicating that the selected scenarios did not illustrate extreme cases. Age dependence had a great effect on $\widehat{D}$ (Table II-3-4): 2.4%/year in Scenario III and 4.3%/year in Scenario V. Bycatches of adults approaching AFR had more adverse effects on population viability than those of other age classes.

Extinction risks were also sensitive to the target age class in bycatch (Table II-3-4). Among the five scenarios, the probability of extinction was zero only in Scenario III (i.e., the most optimistic scenario). With regard to the probability of quasi-extinction, serious estimates were given as follows: from 13% in Scenario III to 91% in Scenario V (i.e., the most pessimistic scenario).

II-3.4   Discussion

Risk assessment of the Ariake Sound and Tachibana Bay population

Bycatch mortality poses a serious threat to the viability of the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. A decreasing trend in population size was not clearly detected from past sighting surveys (Figure I-2). Therefore, no assessments of the population size reduction could be made from these surveys. However, our predictions suggest that the population size will dramatically decrease if bycatch mortality remains at the reported level. In more than half the simulation trials, population size declined by ≥80% over a three-generation period, including both the past and the future, which meets the requirements of the CR category according to Criterion A4 (Fig. II-3-5). Moreover, a population size reduction of ≥30%, which meets the requirements of the VU category according to Criterion A4, was predicted in more than half of the trials, even in the most optimistic case (Scenario II). These results suggest that the Ariake Sound and Tachibana Bay population should be classified at least as the VU category (Table II-3-4).

Uncertainty in the future predictions

Uncertainty in the value for the annual bycatch mortality rate ($M_{bycatch}$) is influenced by the accuracy in the estimated number of bycaught porpoises and the abundance estimate. The estimated bycatech mortality rate may be overestimated if the interview-based surveys for gillnetters were conducted during the active fishing period, as referred in Shirakihara and Shirakihara (2013a). The sampling bias in the surveys to estimate the number of bycaught porpoises was not incorporated in this study. The most recent available abundance estimate in Ariake Sound and Tachibana Bay was provided from observations taken in 1993 and 1994 (Yoshida et al., 1997), and it may be too old to estimate the bycatch mortality rate in 2007 and 2008, or to use as the current population size. Therefore, abundance and bycatch mortality estimates should be updated in order to conduct adequate risk assessments.

The uncertainty of these predictions may be underestimated, because they were only based on natural survival rates and bycatch mortality rates. Although the AFR and the calving interval were fixed at 6 years old and 2 years, respectively, they may be lower in a depleted species. Shirakihara and Shirakihara (2013a) showed that there are yearly variations in the number of the bycaught porpoises during gill net fishing (238 and 270 individuals in 2007 and 2008, respectively). However, additional accurate data are needed to estimate the uncertainty in these life history parameters, and the yearly variations in demographic parameters.

Effects of age dependence in bycatch

The predicted extinction risk was sensitive to target age classes with higher bycatch mortality rates. Bycatches of adults approaching AFR had the greatest effect on population viability. On the other hand, bycatches of calves yielded more optimistic predictions. Therefore, our results suggest that the age composition of bycaught porpoises should be considered when evaluating the possible impacts on population viability and recommending appropriate conservation measures before populations are reduced to critical levels. If age dependence in bycatch is identified, it would be appropriate to refer to a similar scenario in Figure II-3-6. In particular, minimizing bycatches of adults approaching AFR may be an effective approach for maintaining the viability of a population. Therefore, encouraging the collection of bycaught porpoises and investigating their age composition is necessary to provide additional information on the current bycatch status, and to plan for the future.

(i) Input of demographic parameters (k, AFR, CI, N_0) and initial population structure

Simulation trials for future changes in population structure

(ii) Sample a survivorship from survivorships of other species

Age

(iii) Select a bycatch mortality rate ($M_{bycatch}$) scenario
Scenario 1: Fixed $M_{bycatch}$ of 8.1%
Scenario 2: Fixed $M_{bycatch}$ of 5.3%
Scenario 3: A sample of $M_{bycatch}$ from a possible distribution in Fig.II-3-2

2000 repetitions

(iv) Build a Leslie matrix

N_0

Year

(v) Simulate future changes in population size over 100 years

(vi) Risk evaluation
Population size reduction over three generations
Extinction and quasi-extinction probabilities within 100 years

Fig. II-3-1 Flowchart of a population viability analysis for the narrow-ridged finless porpoises in Ariake Sound and Tachibana Bay. k is longevity, AFR is age at first reproduction, CI is calving interval and N_0 is current population size (=3093 individuals).
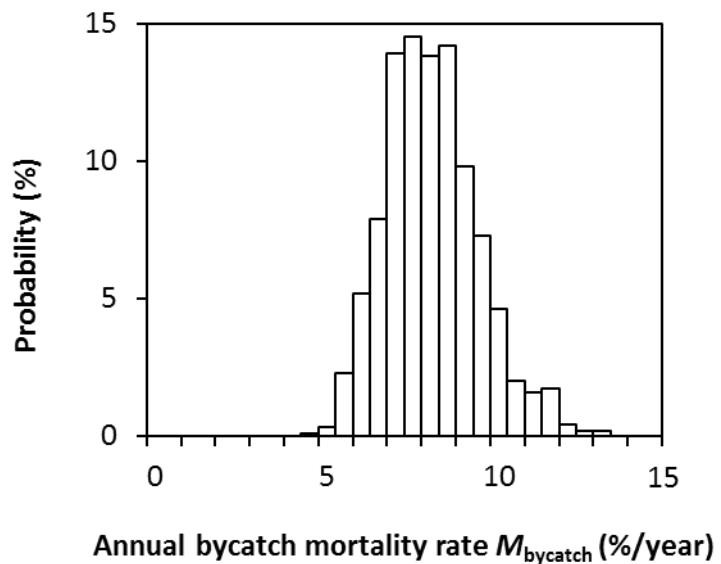
Fig. II-3-2 A possible distribution of annual bycatch mortality rates ($M_{bycatch}$) of the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. $M_{bycatch}$ was given as number of bycaught porpoises / abundance. The abundance estimate was assumed to follow a log-normal distribution.

Fig. II-3-3 Reproductive value of each age class for narrow-ridged finless porpoises when no bycatch mortality is added.
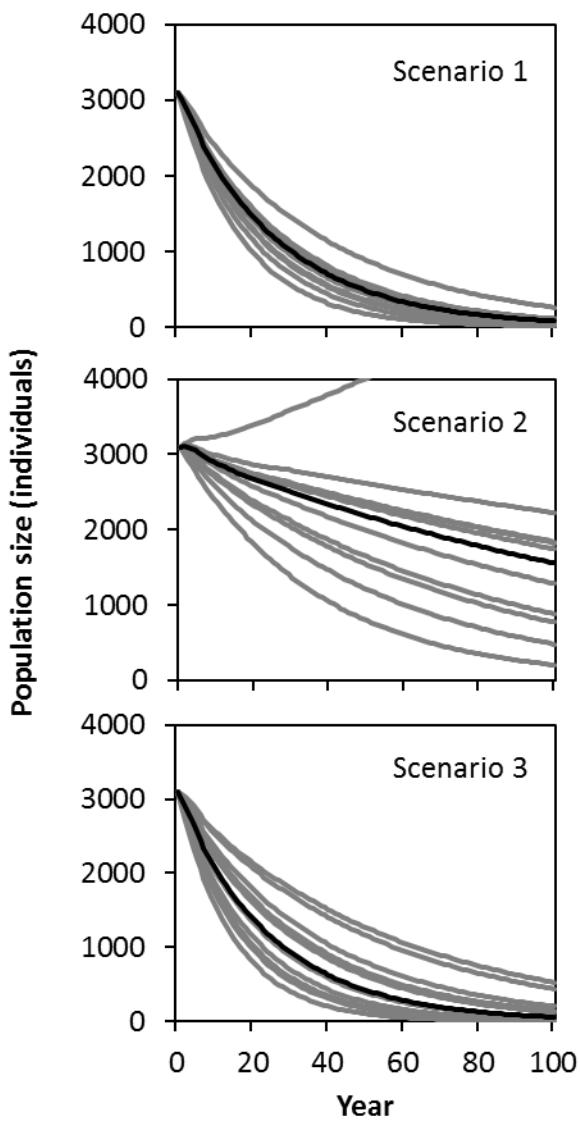
Fig. II-3-4 Future changes in population size over a 100-year period (starting from 1993) for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. Black and gray lines indicate the medians and 10 examples from 2000 simulation trials, respectively. For three scenarios, see Figure II-3-1.
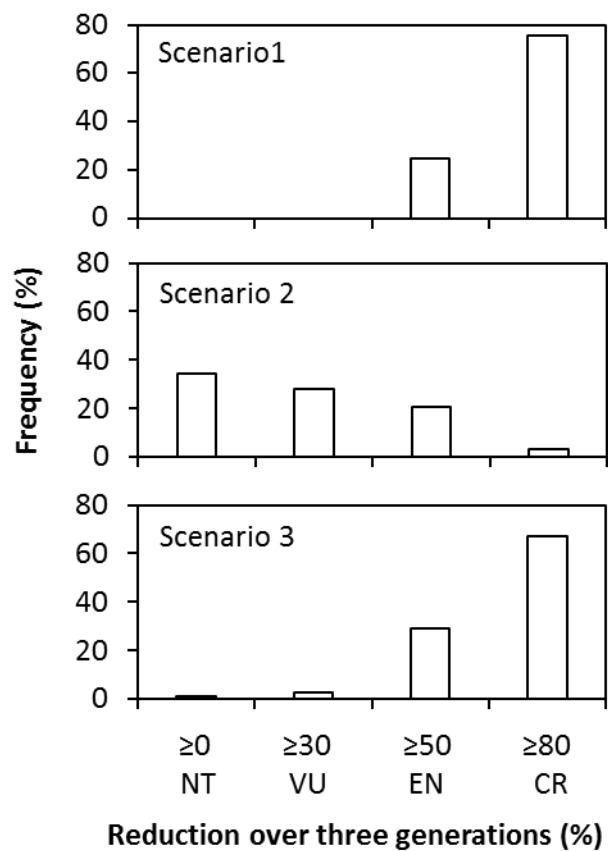
Fig. II-3-5 Frequency distributions of the predicted population size reduction over three generations of the narrow-ridged finless porpoises in Ariake Sound and Tachibana Bay, from 2000 trials based on risk categories according to Criterion A4 defined by the IUCN (2001): Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). For three scenarios, see Figure II-3-1.
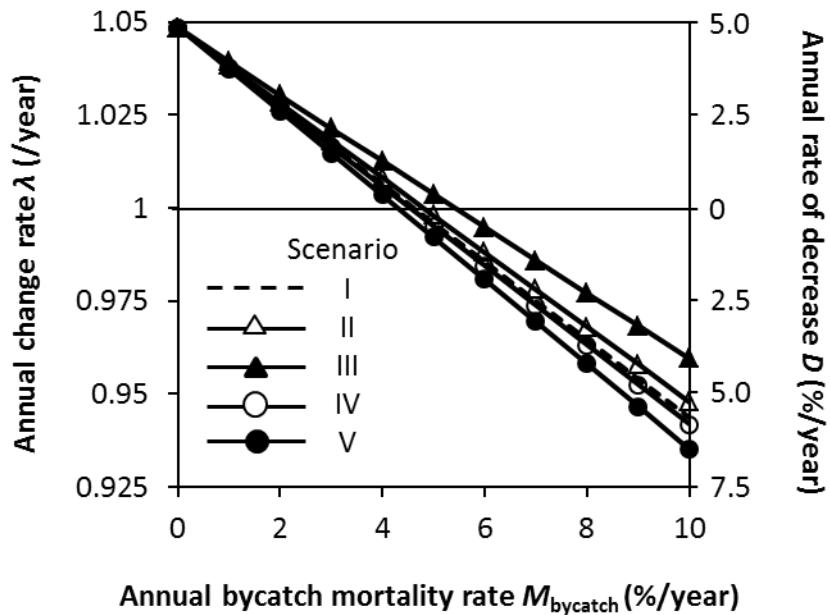
Fig. II-3-6 Medians of the estimated annual change rate ($\hat{\lambda}$) and the estimated annual rate of decrease ($\hat{D} = \hat{\lambda} - 1$) with changes in bycatch mortality rate of whole population (M_{bycatch}) for narrow-ridged finless porpoise populations. Details of each scenario are described in Table II-3-1.
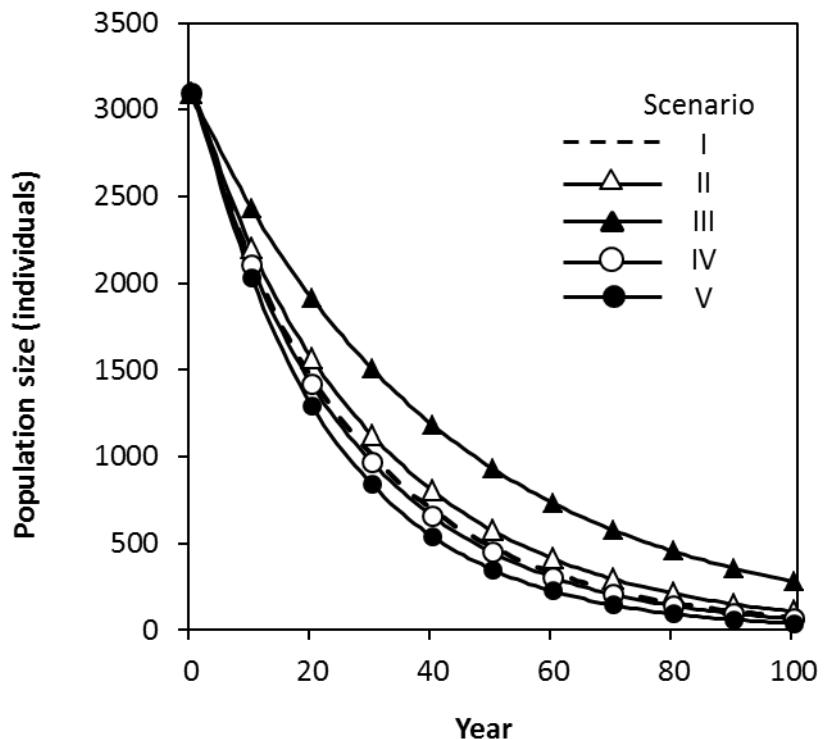
Fig. II-3-7 Future changes in the median of the population size for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay over a 100-year period (starting from the current year). Details of each scenario are described in Table II-3-1.
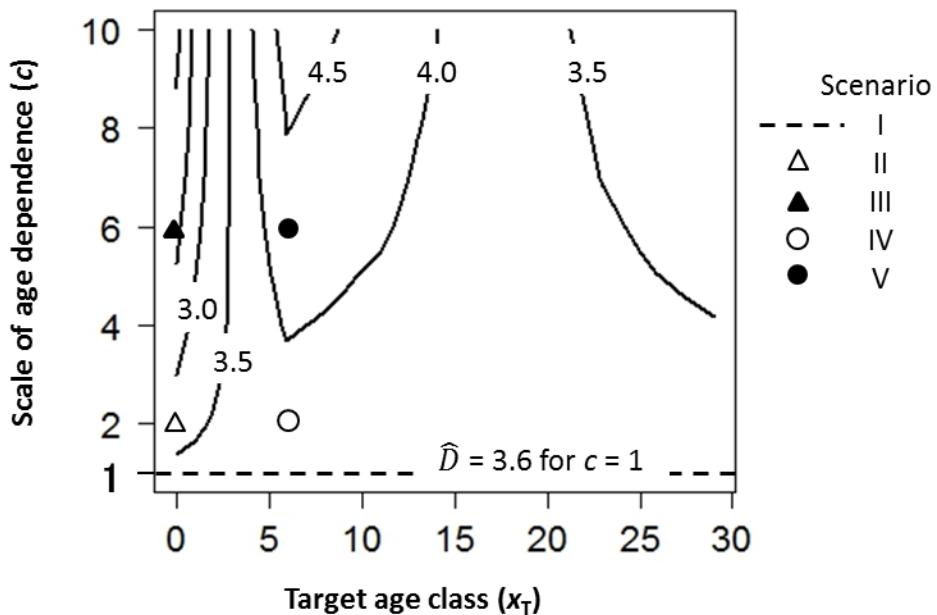
Fig. II-3-8 Medians of the estimated annual rate of decrease ($\widehat{D}$) for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay when the bycatch mortality rate of the target age class (x_T) was c times higher than the others. The population size was set at 3093 individuals and the annual bycatch mortality rate was set at 8.1%/year. The broken line ($c = 1$) and four symbols indicate the results of Scenarios I and II–V, respectively.

Table II-3-1 Summary of five scenarios representing age dependence in bycatch under the annual bycatch mortality rate of 8.1%/year. The symbols x_T and c are the target age class (e.g., x_T of 0 indicates ages 0–1), which has the highest bycatch mortality rate, and the scale of age dependence, respectively. The ratio of the target age class among all bycaught porpoises is also shown.

Scenario	x_T (years)	c	Ratio (%)
I	-	1	-
II	0	2	23.2
III	0	6	49.2
IV	6	2	9.46
V	6	6	25.8

Table II-3-2 Medians of the estimated annual rate of increase ($\hat{\lambda}$) and the estimated annual rate of decrease ($\widehat{D}$) for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. Values in parentheses represent the 2.5–97.5 percentiles. For three scenarios, see Figure II-3-1.

	Scenario 1	Scenario 2	Scenario 3
$\hat{\lambda}$ (/year)	0.964 (0.939–0.977)	0.993 (0.968–1.01)	0.961 (0.923–0.989)
$\widehat{D}$ (%/year)	3.64 (2.33–6.09)	0.671 (-0.677–3.20)	3.87 (1.08–7.72)

Table II-3-3 Future risk evaluations (medians) of the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. Values in parentheses represent the 2.5–97.5 percentiles. For three scenarios, see Figure II-3-1.

	Scenario 1	Scenario 2	Scenario 3
Population size reduction over three generations (%)	84.5 (69.9–95.7)	29.6 (-37.2–80.3)	86.3 (42.6–98.2)
Extinction probability within 100 years (%)	0.350	0	5.00
Quasi-extinction probability within 100 years (%)	64.6	1.90	61.8

Table II-3-4 Estimates of the annual rate of decrease (D), the population size reduction over three generations (N_{red}), the probability of extinction (PE) and the probability of quasi-extinction (PE_q) for the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay as illustrated by five scenarios based on the age dependence in bycatch (details of each scenario are described in Table II-3-1). Numerals and those in parentheses for D and N_{red} indicate the medians and 2.5–97.5 percentiles, respectively.

Scenario	D (%/year)	N_{red} (%)	PE (%)	PE_q (%)
I	3.64 (2.33–6.09)	84.5 (69.9–95.7)	0.35	65
II	3.29 (2.01–5.61)	81.4 (64.3–94.3)	0.10	46
III	2.37 (1.14–4.41)	69.9 (44.2–89.3)	0	13
IV	3.77 (2.47–6.21)	85.5 (71.9–95.9)	0.50	71
V	4.29 (2.99–6.73)	88.7 (78.1–96.8)	1.5	91

II-4　A method for risk evaluation of various narrow-ridged finless porpoise populations

II-4.1　Background

In the previous sections, the future impacts of the human activities were evaluated for two populations of narrow-ridged finless porpoises. Considering abundance estimate is available for all the recognized population around Japanese waters, the risk evaluation method developed in the previous sections can be applied to other populations.

The purpose of this section is to propose a versatile method for evaluating the future risks of various narrow-ridged finless porpoise populations.

II-4.2　Methods

II-4.2.1　Assumptions

Two assumptions are set for the risk evaluation of the porpoise population with limited data.

1. The values of life history parameters summarized in Table II-1 are common for all porpoise populations.
2. The annual human-induced mortality rate (M_{human}) does not depend on ages.

As for assumption 1, no information on the differences in demographic parameters among the genetically independent population is available. Indeed, Jefferson et al. (2002b) indicated that there was no difference in age at sexual maturity of females, although it was reported that the body length and the calving season were different between the populations (Shirakihara, 2003b). As for assumption 2, no quantitative data has been reported although age dependence in bycatch mortality is likely to exist. From assumption 2, the annual change in population size was described using Eq. (2-2-1).

II-4.2.2　Information necessary for application

In this section, the IUCN Criteria A4 and E were also focused on (Table I-1). For estimating the population size reduction over three generations (Criterion A4) and the probability of extinction (Criterion E), the absolute estimates of abundance in different year is not always required. However, as for the populations around Japanese waters, even the rate of decrease has not been reported except for the Inland Sea population. Furthermore, as introduced in Figure I-2, estimation of the rate is almost unlikely to be feasible. Therefore, the case that the rate of decrease was known was not considered. Instead, the annual human-induced mortality (M_{human})

was introduced. Because annual birth rate (B) and annual natural mortality rate ($M_{natural}$) was estimated in Section II-1, the annual change rate (the rate of decrease for the threatened populations) can be estimated from M_{human} using Eq. (2-2-2).

Therefore, only two estimates are needed for applying the risk evaluation to a population.

(1) An estimate or the rough range of the annual human-induced mortality rate (M_{human}) for applying both of Criteria A4 and E

(2) An estimate of current population size (N_0) for applying Criterion E

The estimate of M_{human} for the Inland Sea population was estimated to be 10%/year in Section II-2. The bycatch mortality rates for the Ariake Sound and Tachibana Bay population and the population in South Korean waters were reported as 8.1%/year (Shirakihara and Shirakihara, 2013a) and 7.4%/year (IWC, 2006), respectively. Therefore, a possible range of the estimates of M_{human} was set between 5 and 10%/year. On the other hand, a possible range of the estimates of N_0 was set between 0 and 8000 individuals to account for the abundance estimates of most porpoise populations around Japanese waters (Yoshida et al., 1997, 1998; Yoshida, 2002; Amano et al., 2003; Shirakihara et al., 2007).

II-4.2.3 Risk evaluation

Criterion A4

Relationship between the population size reduction after three generations (50 years) and the annual human-induced mortality rate (M_{human}) is shown in Figure II-4-1. The reduction estimate is sensitive to M_{human} when M_{human} is between 5 and 8%/year. The thresholds of M_{human} were 5.3, 6.0 and 7.7%/year for the Vulnerable (VU), Endangered (EN) and   Critically endangered (CR) categories, respectively.

Criterion E

The contour plot of the probability of extinction (<2 individuals) and quasi-extinction (<100 individuals) within 100 years over the possible ranges of M_{human} and N_0 are shown in Figure II-4-2. The probability dramatically increases (decreases) following an increase (decline) in M_{human} when N_0 >1000 individuals. On the other hand, the estimates also become sensitive to N_0 when N_0 <1000 individuals. If M_{human} of 8.1%/year remains constant as assumed for the Ariake Sound and Tachibana Bay population, the probability of extinction will exceed 10% (the threshold for the VU category) for a small population <400 individuals (Fig. II-4-2a). If M_{human}

of 8.1%/year remains constant, the probability of quasi-extinction will be always 100% for a population <540 individuals (Fig. II-4-2b).

Examples of the relationship between the probability of extinction (or quasi-extinction) and M_{human} under fixed N_0 are shown in Figure II-4-3. If N_0 is as large as 3093 individuals like the Ariake Sound and Tachibana Bay population (Yoshida et al., 1997) , the probability of extinction will exceed 10%, namely, the population will meet the VU category when M_{human} is >10%/year. On the other hand, if N_0 is as small as 187 individuals like the Omura Bay population (Yoshida et al., 1998) , the population will meet the VU category when M_{human} is >7.3%/year.

II-4.3　Discussion

Benefit of the risk evaluation

The proposed method shows both the population size reduction and the probability of quasi-extinction were more sensitive to estimates of the annual human-induced mortality rate (M_{human}) between 5 and 9%/year. The high sensitivity indicates that even a minor reduction in M_{human} can lead to a major reduction in the extinction risk of the population. Here, the M_{human} <5%/year is recommended, so that the population does not meet the IUCN Red List criteria. The PBR, another index of allowable human-induced mortality, is <1% of abundance estimates (Wade, 1998). The level of 1% is generally used as the sustainable level for small cetacean populations (IWC, 1995). This index is more conservative than the estimated threshold of M_{human}.

Moreover, it suggests that the probability of extinction within 100 years can easily exceed 10% when the current population size is small. Thus, we should pay careful attention to small porpoise populations, including the Omura Bay population.

Applicability of the proposed method

The proposed approach can be used to assess the future risks of various narrow-ridged finless porpoise populations in order to develop effective conservation programs. If the value of a demographic parameter is different from that shown in Table II-1, or, if there is age dependence in M_{human} as incorporated in Section II-3, a few adjustments is needed to risk evaluation. The adjustment can simply conducted using the results of sensitivity analysis for the annual intrinsic rate of natural increase in Figure II-1-5 or the annual change rate in Figure II-3-6.

Although the estimates of the current population size and the human-induced mortality rate are only required for the proposed approach, data on human-induced impacts is not usually reported for most populations. The human-induced mortality rate is calculated with the population size reduction in past, as described in Section II-2 (10%/yaer for the Inland Sea population). Alternatively, a part of human-induced mortality (in particular, bycatch mortality) can be available, as inferred in Section II-3 (8.1%/year for the Ariake Sound and Tachibana Bay population). A preliminary estimate of annual bycatch mortality rate ($M_{bycatch}$) can be obtained as:

$$M_{byctach} = 0.25 \times \text{number of gillnetters in target area,}$$

where 0.25 is a mean number of bycaught porpoises per year by a single gillnetter in Ariake Sound and Tachibana Bay (Shirakihara and Shirakihara, 2013a).

Future works for conservation

The most realistic measure is to repeat the abundance estimations for estimating the population size reduction. Although it may be difficult to detect the statistical decreasing trend (Wade and DeMaster, 1999), values or a possible rage of the past reduction can be estimated from the abundance estimates in at least two continuing observations. The information is useful for evaluating the risk by the proposed method in this section. Additionally, when more details on the age-specific features or sex-based bias in human-induced mortality are incorporated, the future risk of human-induced impacts can be evaluated more accurately.
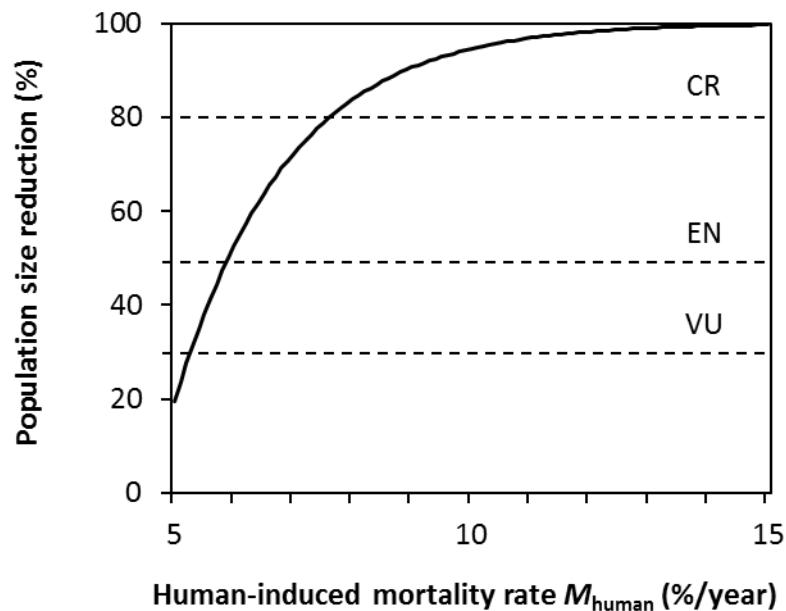
Fig. II-4-1 Relationship between population size reduction after three generations and the human-induced mortality rate of a narrow-ridged finless porpoise population. The medians from 2000 simulation trials are given. The divided zones indicate the risk categories according to Criterion A4 defined by the IUCN (2001): Vulnerable (VU), Endangered (EN), and Critically Endangered (CR).
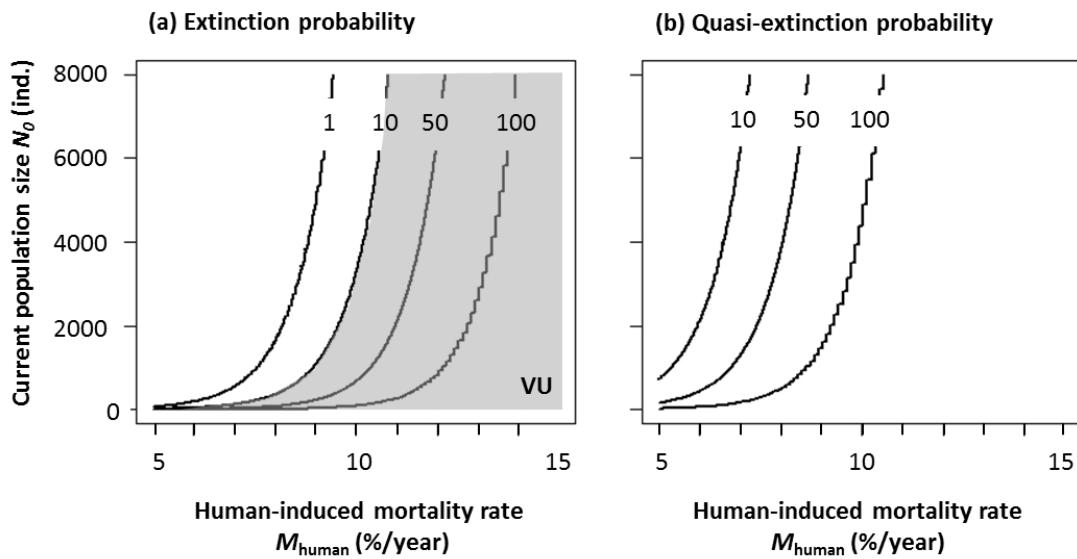
Fig. II-4-2 Contour plot of the probability of **(a)** extinction (<2 ind.) and **(b)** quasi-extinction (<100 ind.) within 100 years, associated with the annual human-induced mortality rate (M_{human}) and current population size (N_0) of a narrow-ridged finless porpoise population. Gray zone >10% indicates the Vulnerable (VU) category according to Criterion E defined by the IUCN (2001).

(a) Ariake Sound and Tachibana Bay population (N_0 = 3093 ind.)
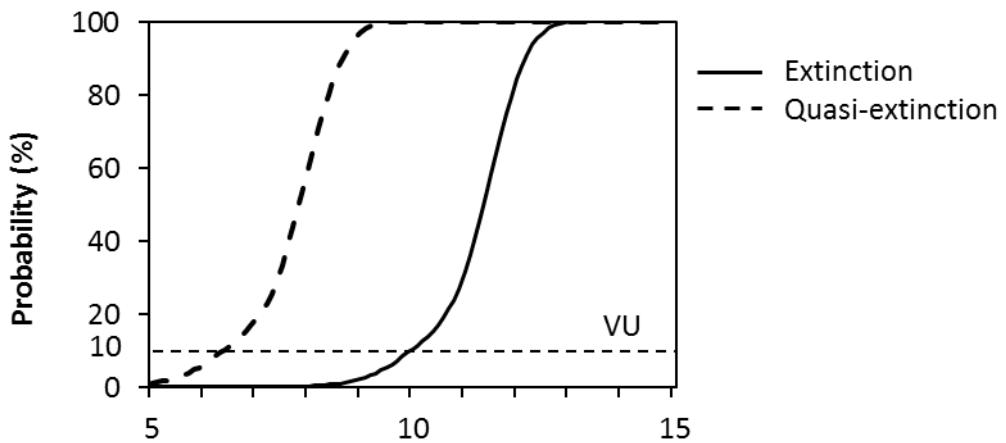
(b) Omura Bay population (N_0 = 187 ind.)

Human-induced mortality rate M_{human} (%/year)
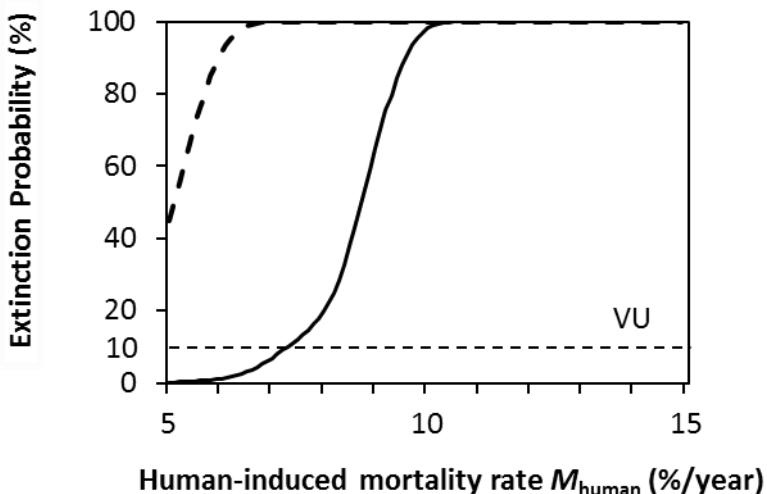
Fig. II-4-3 Relationship between the probability of extinction (<2 ind.) or quasi-extinction (<100 ind.) within 100 years, and the human-induced mortality rate of the narrow-ridged finless porpoise population, inhabiting **(a)** Ariake Sound and Tachibana Bay and **(b)** Omura Bay. Probability of extinction >10% meets the Vulnerable (VU) category according to Criterion E defined by the IUCN (2001).

Chapter III
Population viability analysis for Indo-Pacific bottlenose dolphins

III-1   Estimation of survival rate using photo-identification data for the Indo-pacific bottlenose dolphins off Amakusa-Shimoshima Island

III-1.1   Background

For some cetaceans, notches on their bodies (in particular, dorsal and caudal fins) are used as natural mark to identify individuals. The long-term observations of identified individuals can trace the survival and reproduction process of the target cetaceans. This photo-identification approach has been applied to the estimation of survival rates for multiple populations (e.g., Nicholson et al., 2012; Kogi, 2013; Pusineri et al., 2014).

A year-round resident population of Indo-Pacific bottlenose dolphins inhabits the coastal waters of Amakusa-Shimoshima Island in western Kyushu, Japan (Shirakihara et al., 2002), which is shown in Figure III-1-1. Many individuals in this area have notable notches on their dorsal fins after birth (Fig. III-1-2) and often allow the approach of research boats. Therefore, it is expected that estimation of survival rate is possible with high precision by taking many high-quality pictures of the fins over the long term. Photo-identification observation has been carried out every year since 1994 and revealed the abundance of about 200 individuals (Shirakihara et al., 2002; Shirakihara and Shirakihara, 2012).

The purpose of this section is to estimate survival rate of the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island by using the photo-identification data collected from the long-term observation.

III-1.2   Methods
III-1.2.1   Data set

The photo-identification data for the Amakusa population were used by permission of Miki Shirakihara, Toho University, who took the data together with students of Nagasaki University and the University of Tokyo. Details of the observation are described in Shirakihara and Shirakihara (2012). They noted that this population consisted of a northern and southern community, groups in different stable daytime habitats (Fig. III-1-1). Because the movement of dolphins between two areas is frequent, thus, these communities are dealt as a population.

The data collected in July and August of every year between 2000 and 2012 was used in this study. The observation effort was high in these months (48 and 11% of the total observation occasions during 2000-2012), taking into account that the calving season for this population is from summer to autumn (Shirakihara and Shirakihara, 2013b).

III-1.2.2   Cormack-Jolly-Seber model

The Cormack-Jolly-Seber (CJS) model (Lebreton et al., 1992) was used to estimate survival rates of identified individuals. The model allows year-specific estimates of survival rate (P) and capture probability (ψ), from the data collected by repeating mark (first take of an individual) and recapture (retake of the identified individual). The P_i is the probability that a marked (photo-identified) individual in a population in year i survives until year $i+1$ and remains in the observation area (dose not emigrate) and, thus, the emigration was assumed to be the death in terms of conservation. The ψ_i is the probability that an individual is captured in year i.

The basic data structure is shown in Figure III-1-3. The capture history is described by the sequence of 0 and 1, namely, 1 if the individual is seen on observation occasion and 0 otherwise. For example, when there are three occasions, 7 capture histories are possible. Each of them is replaced by a general form of XXX. Then, the probability of the history XXX ($\text{Pr}_{(\text{xxx})}$) can be described using P_i and ψ_i and the likelihood function L was given as:

$$L = \prod (\text{Pr}_{(\text{XXX})})^{n_{\text{xxx}}}, \qquad\qquad\qquad (3\text{-}1\text{-}1)$$

where n_{XXX} is the number of individuals with capture history XXX. The set of P_i and ψ_i that maximize the likelihood function L was estimated. In this study, the sighting of an individual in a year was determined by whether the dolphin was seen on at least one observation occasion in July or August of the year and, thus, it was regarded that time interval of the observation in every year was approximately one year.

Estimation of survival rate with the CJS models was performed by the MARK program (White and Burnham, 1999) for four models with the combinations of P and ψ:

Model 1: P: yearly fluctuated, ψ: yearly fluctuated.

Model 2: P: yearly constant, ψ: yearly fluctuated.

Model 3: P: yearly fluctuated, ψ: yearly constant.

Model 4: P: yearly constant, ψ: yearly constant.

Model selection was performed using the Akaike's Information Criterion adjusted for small samples (AIC_c, Burnham and Anderson, 2002). Survival rate was estimated for following four groups of the identified dolphins:

(G1) Whole identified individuals

(G2) Males

(G3) Mature females

(G4) Individuals whose sexes were completely unknown

In the photo-identification observations around Amakusa-Shimoshima Island, it is possible to distinguish newborn calves from the other individuals. Therefore, the sex is given by whether the individual has been seen with its newborn calve. Definitions of G2 to G4 were given, according to Miki Shirakihara (pers. comm.).

III-1.3   Results

The number of identified dolphins and the estimates of survival rate (*P*) for four groups are shown in Table III-1-1. For three groups of G1, G2 and G3, Model 2 was selected. Thus, estimates for all groups were basically selected from Model 2. The estimate for G1 was 0.957/year, which means annual mortality rate of 4.3%/year. The estimate of 0.933/year for G2 (males) was significantly lower than that for G3 (mature females) (*p*<0.05). For G4, Model 3 was selected and the estimated survival rates yearly fluctuated during 12 years. The *P* was estimated to be 0.923/year in case of Model 2.

III-1.4   Discussion

Comparison with the estimates in the previous studies

The survival rate was estimated to be 0.95/year (SE = 0.020) and 0.94/year (SE = 0.059) for the Indo-Pacific bottlenose dolphin population in Shark Bay of Australia and the Mayotte Island of western Africa, respectively (Nicholson et al., 2012; Pusineri et al., 2014). Comparing with these estimates for other populations, the estimates in this section seemed to be a plausible value and the CVs were sufficiently low (Table III-1-1).

Reason for the sexual difference in survival rate

The high mortality rate of males may be caused by emigration and bycatch. The emigrations of the dolphins to various areas around Japanese waters have been reported. Nearly half of the

population moved from the northern coast to the southern coast of Amakusa-Shimoshima Island in 2000 (Miki Shirakihara, pers. comm.). The emigrations of a few dolphin to other areas which were far from western coast of Kyushu have been reported (Mori, 2013; Morisaka et al., 2013). Moreover, there would be a bycatch impact on this population (Shirakihara and Shirakihara, 2012). Males may be more vulnerable to bycatch than females, although clarifying presence or absence of sex-dependent bycatch mortality rate in the Amakusa population is a future study.
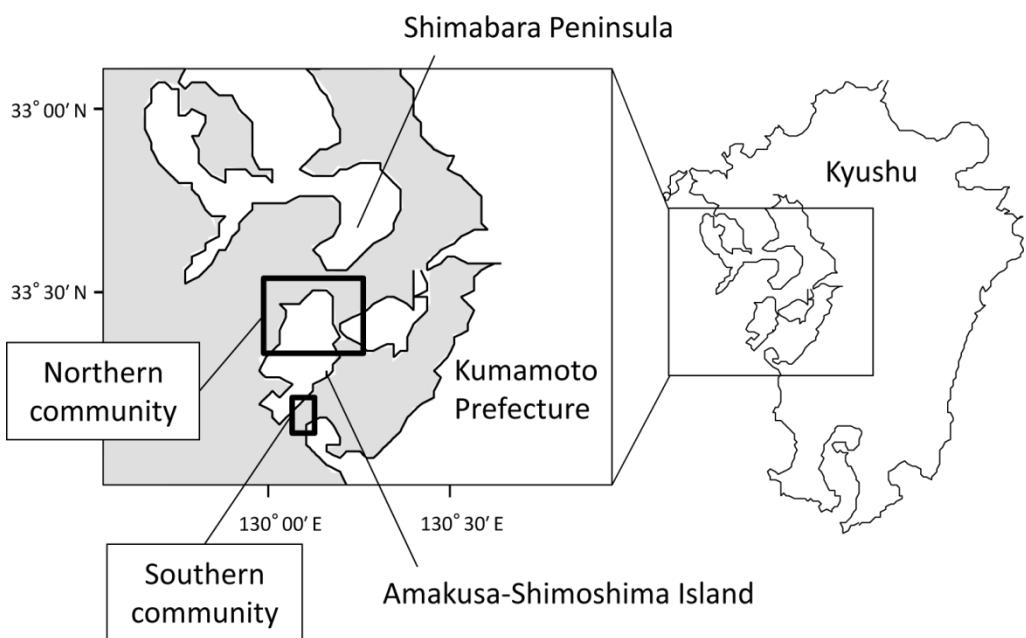
Fig. III-1-1 Map of the waters around Amakusa-Shimoshima Island. Boxes indicate rough positions of the stable daytime habitats for the northern and southern communities of the Indo-Pacific bottlenose dolphins.

Fig. III-1-2 Photograph of notches on the dorsal fins for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island (Photograph taken by the author).

Occasion 1	Occasion 2	Occasion 3	Capture history (XXX format)	Number of dolphins (ind.)	Probability ($Pr_{(XXX)}$)
$\psi_{i=1}$ $P_{i=1}$ Capture	ψ_2 P_2 Capture	ψ_3 Capture	111	n_{111}	$\psi_1 P_1 \psi_2 P_2 \psi_3$
		No capture	110	n_{110}	$\psi_1 P_1 \psi_2 (1-P_2\psi_3)$
	No capture	Capture	101	n_{101}	$\psi_1 P_1 (1-\psi_2) P_2 \psi_3$
		No capture	100	n_{100}	$\psi_1 \{1-P_1\psi_2-P_1(1-\psi_2) P_2\psi_3\}$
$1-\psi_1$ No capture	Capture	Capture	011	n_{011}	$(1-\psi_1) P_1 \psi_2 (1-P_2\psi_3)$
		No capture	010	n_{010}	$(1-\psi_1) P_1 \psi_2 (1-P_2\psi_3)$
	No capture	Capture	001	n_{001}	$(1-\psi_1) P_1 (1-\psi_2) P_2 \psi_3$

Fig. III-1-3   Basic data structure for three observation occasions. ψ_i is the capture probability and P_i is the survival rate for occasion i. Occasion i indicates i-th year in this study.

Table III-1-1 Estimates of the survival rate for four groups of the identified Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island. P_i indicates the survival rate in i-th year. SE is standard error and CV is coefficient of variation. See text for details of models.

Group	Model 1		Model 2		Model 3		Model 4	
	AIC_c	min.–max. of $\hat{P}_i$	AIC_c	$\hat{P}$	AIC_c	min.–max. of $\hat{P}_i$	AIC_c	$\hat{P}$
(G1) whole identified dolphins (230 ind.)	1595	0.93–0.99	1584	0.957 (SE=0.0052, CV=0.54%)	1833	0.92–1.0	1827	0.960 (SE=0.0049, CV=0.51%)
(G2) Male (69 ind.)	285	0.90–0.99	281	0.933 (SE=0.015, CV=1.6%)	290	0.89–0.98	284	0.934 (SE=0.014, CV=1.5%)
(G3) Mature female (81 ind.)	583	0.93–1.0	567	0.967 (SE=0.0076, CV=0.79%)	686	0.93–1.0	672	0.971 (SE=0.0071, CV=0.73%)
(G4) Sex-unknown dolphins (56 ind.)	158	0.14–1.0	185	0.923 (SE=0.019, CV=2.0%)	155	0.25–1.0	192	0.922 (SE=0.020, CV=2.1%)

III-2   Evaluation of bycatch impacts on the Amakusa population

III-2.1   Background

Bycatch is the major threat for the Indo-Pacific bottlenose dolphins inhabiting the waters around Amakusa-Shimoshima Island. Shirakihara and Shirakihara (2012) stated that the minimum number (reported number) of bycaught dolphins was 12 and 14 individuals in 2007 and 2008, respectively. However, the potential biological removal (PBR) level (referred in Section I-3) for this population was estimated to be two individuals (Shirakihara and Shirakihara, 2012). It is therefore obvious that the estimated bycatch level in these years is serious for the population viability. Moreover, the impact of watching boats has been threatened in this area (Matsuda et al., 2011).

In this section, a population viability analysis was conducted for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island. The purpose is to quantitatively evaluate the human-induced impact on this dolphin population using the values of survival rate estimated in the previous section III-1.

III-2.2   Methods
III-2.2.1   Overview of individual-based model

An individual-based model (IBM) was constructed to simulate the fate of individual dolphins and predict the annual change in population size. In this model, the survival and reproductive process for an individual is determined by its biological attribution such as sex, age and breeding status, as shown in Figure III-2-1. The IBM was employed because the Amakusa population might be so small that the individual variation in demographic parameters such as survival and fertility rate could not be ignored.

The simulations with the IBM were performed using VORTEX (version 10.0.7.1), which permits a Monte Carlo simulation with demographic and environmental stochasticity (Lacy, 1993; Lacy and Pollak, 2014). This software is useful for analyzing the risk of long-lived species, or populations with biased sex ratio or <500 individuals (Lacy et al., 2014). It has been widely used for the PVAs of various marine mammals (e.g., Thompson et al., 2000; Galimberti et al., 2001; Heinsohn et al., 2004; Chilvers, 2012; Castelblanco-Martinez et al., 2012; Araujo et al., 2014).

III-2.2.2 Demographic parameters

Knowledge of life history parameters is limited for the Amakusa population. The values of survival rate for three groups (immature individuals and, mature male and female) were given from the estimates in the previous section III-1. The values of the other parameters were provided from the literatures for other populations of the Indo-Pacific bottlenose dolphin. Overview of demographic parameters is described in Section I-2 and the input values of each parameter are summarized in Table III-2-1.

According to Lacy et al. (2014), the variance across the data can be made from the combination of demographic stochasticity (DS) and environmental variability (EV). When a parameter β represents a probability that a demographic event such as birth and survival occurs (Fig. III-2-1), as the input value for the analysis using VORTEX, the standard deviation due to EV for parameter β was given by:

$$\sigma_{EV} = \sqrt{\sigma_{TOT}^2 - \overline{\sigma_{DS}^2}}. \tag{3-2-1}$$

σ_{TOT}^2 is the total variance across the data and was given from the literatures. For example, the variance for survival rate was calculated from the standard error of the estimated survival rate shown in Table III-1-1. $\overline{\sigma_{DS}^2}$ is the mean sampling (binomial) variance across the individual rates of parameter β and was estimated by:

$$\overline{\sigma_{DS}^2} = \hat{\beta}\left(1 - \hat{\beta}\right)/(n - 1), \tag{3-2-2}$$

where $\hat{\beta}$ is the estimates of parameter β ($0 \leq \hat{\beta} \leq 1$) and n is the number of the concerned individuals.

Longevity

Longevity was set to be 40 years for baseline scenario and it was given between 40 and 50 years for sensitivity analysis.

Fertility

The age at first reproduction (AFR) was set to be 10 years. The reproduction was assumed to

last in the lifetime. The probability that an adult female breeds in a year ($Pr_{breeding}$) was set at 24% with SD of 8%, using estimates for the dolphins around Mikurajima (Kogi et al., 2004). The probability was also estimated to be approximately 30% from the calving interval (CI) estimate of 3 years. It was thus set to be 24% for baseline and the range between 24 and 30% was given for sensitivity analysis. Additionally, no bias in sex ratio at birth was incorporated in this study.

Survival

Different values of the mortality rate (=1 − survival rate) were given for following five groups:

(1) Calves <1 year old

(2) Calves from 1 to 2 years old

(3) Immature individuals from 2 to 9 years old

(4) Mature males ≥10 years old

(5) Mature females ≥10 years old

The range of ages for each group was given on the basis of Miki Shirakihara (pers. comm.) and literatures. The input values of morality rate for each group and the related literature are shown in Table III-2-1. The values for Groups (3) to (5) were given from the survival rate estimates in the previous section III-1. These values include the impacts of bycatch mortality.

Survival rate for calves has not been revealed for the Amakusa population. Because there is usually no notable notches on calf's dorsal fin, a calf can be identified only when the adult female who is always along with the calf is identified. The age-specific mortality rates of calves <1 year old and calves from 1 to 2 years old were set to be 29 and 18%/year, respectively, from the estimates of natural survival rate ($P_{natural} > P$) for the bottlenose dolphin population inhabiting Shark Bay in Australia (Mann et al., 2000). Because the values of the total mortality rate (=1−P) seem to be higher than these values, the possible range of values between 30 and 50%/year was set for sensitivity analysis of the mortality rate of calves <1 year old.

III-2.2.3   Procedure of PVA

The flowchart of population viability analysis for the Amakusa population is shown in Figure III-2-2. For step (i), the latest abundance estimate of 216 individuals by Shirakihara and Shirakihara (2012) was given as the population size in the first year (N_0) for all the simulation trials. A stable age structure was set as the age structure in the first year

A simulation trial of step (ii) was conducted for the future change in population size over a 100-year period, and was repeated 1000 times. Because even high mortality rate of mature male did not explain the reported level of bycatch mortality in Shirakihara and Shirakihara (2012), two scenarios were taken up for describing the scale of the bycatch mortality of calves <2 years (Groups (1) and (2)).

 Scenario 1: No calf is bycaught. Namely, the values of mortality rate for Groups (1) and (2) are 29 and 18%, respectively (Baseline scenario).

 Scenario 2: Annual bycatch mortality rate of calves remains at 30%/year. Namely, the values of mortality rate for Groups (1) and (2) are 59 and 48%, respectively. Here, it is assumed that nearly half of bycaught dolphins are calves.

For step (iii), the risks of the bycatch impacts were quantitatively assessed from two perspectives: the population size reduction over three generations and the probability of quasi-extinction within 100 years (PE_q). The generation period for the Indo-Pacific bottlenose dolphin is estimated to be 21.1 years (Taylor et al., 2007), therefore, 60 years was given as three-generation period. The PE_q was defined as the percentage of trials in which only one sex remained.

III-2.3 Results

III-2.3.1 Population projection

Figure III-2-3 shows 10 trajectories of the annual change in population size for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island. The population size will decrease even when no bycatch mortality of calves was assumed (Scenario 1).The estimate of annual rate of decrease ($\widehat{D}$) was 1.4 and 5.3%/year for Scenario 1 and 2, respectively (Table III-2-2).

III-2.3.2 Risk evaluation

The future risks were shown in Table III-2-2. In Scenario 1, the population size reduction after 60 years was approximately 60%. Although the PE_q was 0%, the population decreased to <100 individuals over 100 years in almost of all the simulation trials. On the other hand, when the possible value of the bycatch mortality rate was incorporated for calves (Scenario II), the population size reduction overly exceeded 80% and the population reached quasi-extinction in almost of all the simulation trials.

III-2.4   Discussion

Risk assessment of the Amakusa populaion

Our results suggest that the population size declined by ≥80% over a three-generation period when the possible bycatch mortality of calves was assumed. It indicates that the Amakusa population may meet the Critically Endangered (CR) category under Criterion A4 in IUCN (2001).

Sensitivity analysis to the demographic parameters

The sensitivity of the annual rate of decrease (D) and the population size reduction after 60 years to three parameters, the lifespan, the probability of adult females breeding ($Pr_{breeding}$), and mortality rate of calves <1 year old, were shown in Figure III-2-4. The lifespan had relatively little effect on the results. The risk was sensitive to the value of m (approximately inverse of calving interval). Steiner and Bossley (2008) pointed out that the calving interval became shorter when the previous calf died before weaning. This will make the higher value of m and result in more optimistic predictions. The mortality rate of newborn calves was estimated to be about 20 and 30%/year for the Indo-pacific bottlenose dolphin populations around Mikurajima and South Australia, respectively (Kogi, 2013; Steiner and Bossley, 2008). Even if the similar level of mortality for calves to the other populations was assumed (Scenario 1), the population would decrease by a considerable rate. It is thus clear that further observation on the demographic parameters is necessary for more accurate risk evaluation.
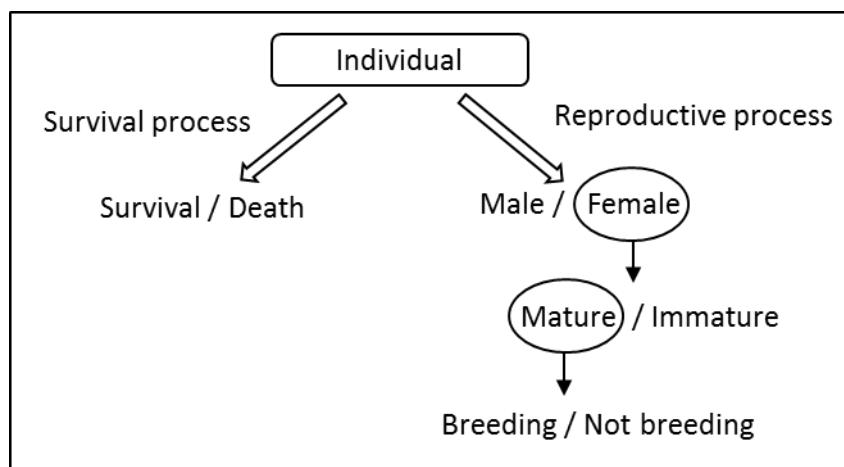
**Fig. III-2-1**   Basic concept of an individual-based model (IBM).
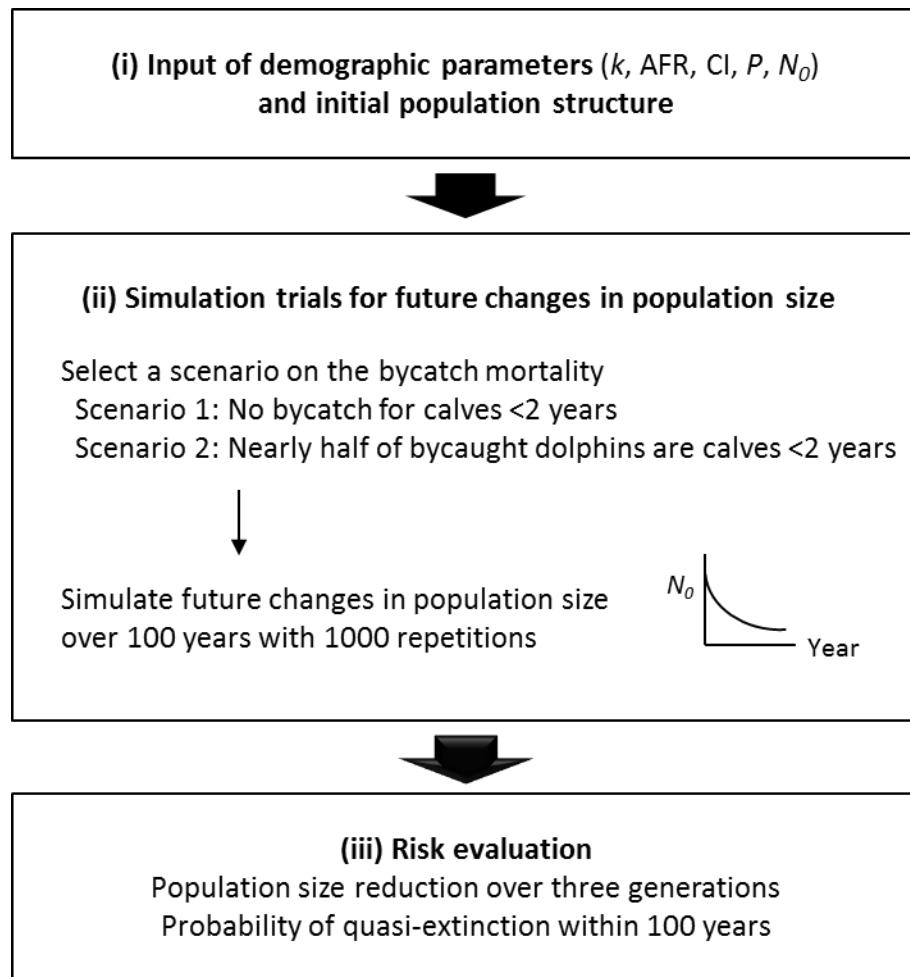
Fig. III-2-2 Flowchart of a population viability analysis for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island. k is longevity, AFR is age at first reproduction, CI is calving interval, P is survival rate and N_0 is current population size.
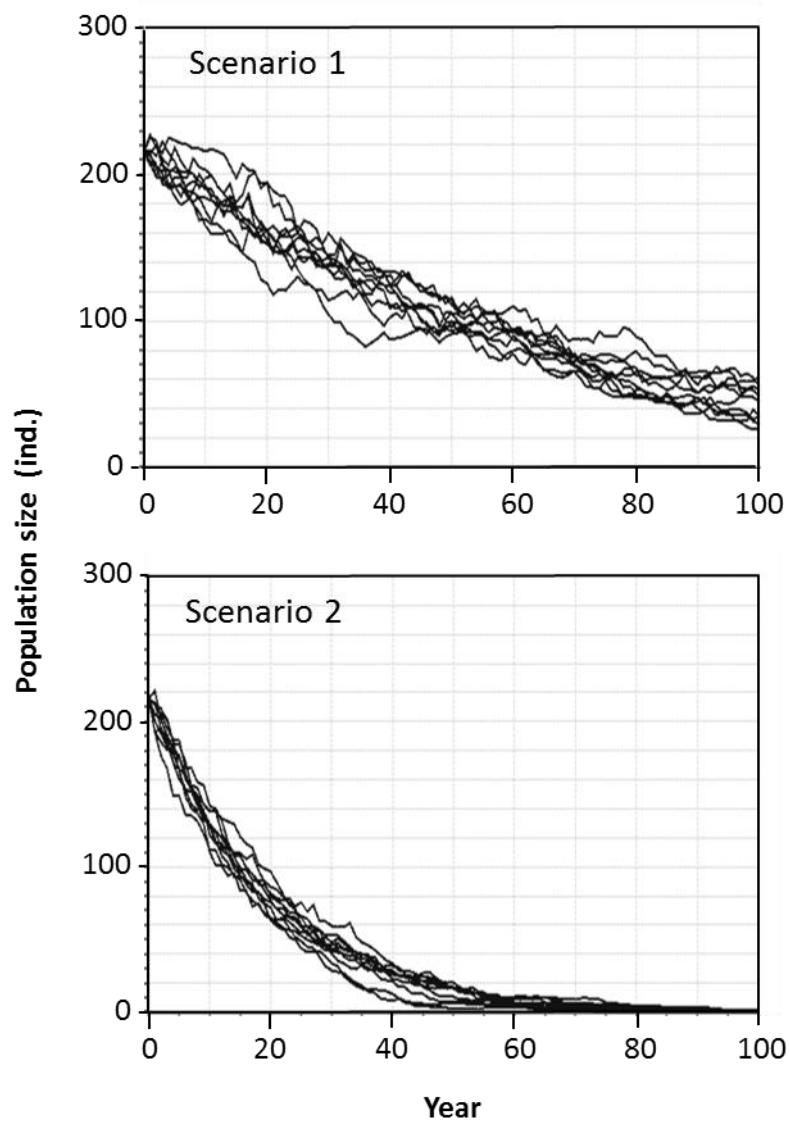
Fig. III-2-3 Examples of 10 trajectories of future changes in population size for the Indo-Pacific bottlenose dolphin population off Amakusa-Shimoshima Island over a 100-year period (starting from 2008). Details of each scenario are described in Table III-2-2.
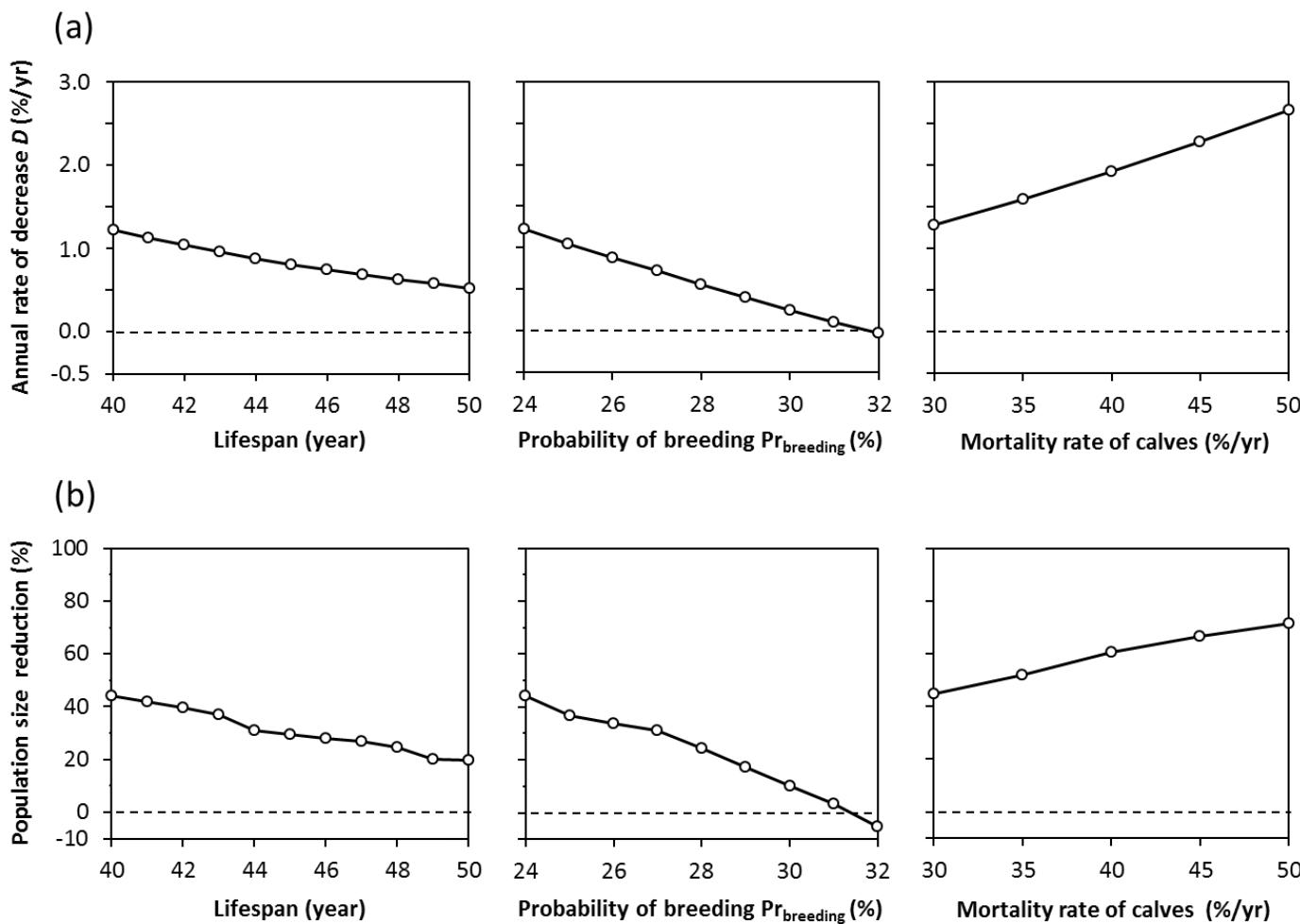
Fig. III-2-4 Sensitivity of **(a)** annual rate of decrease and **(b)** population size reduction after three generations to three demographic parameters (longevity, probability that an adult female breeds in a year ($Pr_{breeding}$), and annual mortality rate of calves <1 year old).

Table III-2-1 Summary of demographic parameters used as input data in the population viability analysis for the Indo-Pacific bottlenose dolphins off Amakusa-Shimoshima Island. Standard deviation due to environmental variation (EV) is shown in parenthesis (See text for details of EV).

Parameter	Input value	Range of values for sensitivity analysis	Reference
Maximum age	40 years	40–50	Miyahara (2013)
Reproductive system	Monogamous	-	-
Age at first reproduction	10 years	-	Kogi (2013)
Age at last reproduction	40 years	Same with maximum age	-
Probability of adult females breeding	24% (8)	24–30	Kogi et al. (2004) Kogi (2013)
Sex ratio at birth (% males)	50%	-	-
Mortality rate			
Calf <1 year old	29% (0.14)	30–50	Mann et al. (2000)
Calf from 1 to 2 years old	18% (0.14)	-	Mann et al. (2000)
Immature individual from 2 to 9 years old	7.7% (0.14)	-	Present study (section III-1)
Mature male	6.7% (0.12)	-	Present study
Mature female	3.3% (0.065)	-	Present study

Table III-2-2 Estimates of the annual change rate ($\hat{\lambda}$), mean of the population size reduction after 60 years ($\pm$SE), and the probability quasi-extinction within 100 years (PE$_q$), predicted from 1000 simulation trials for the Indo-Pacific bottlenose dolphin population off Amakusa-Shimoshima Island. For the scenarios, see Figure III-2-2.

	Scenario 1	Scenario 2
$\hat{\lambda}$ (/year)	0.986	0.947
Population size reduction (%)	58.9 ($\pm$ 0.33)	96.6 ($\pm$ 0.06)
PE$_q$ (%)	0	97

Chapter IV
General discussion

IV-1 Contribution of quantitative risk evaluation

Our quantitative analysis for future change in population size enabled the risk evaluation at a population level for the cetacean populations threatened by human-induced impacts. The analysis additionally revealed a significant factor which is sensitive to the risk evaluations. Updating of the estimates of calving interval and age at first reproduction is especially efficient for more accurate risk evaluations of two target species in this study.

This study contributes to highlight that just a little effort for reducing the human-induced mortality can be effective in maintaining persistence of the cetacean populations. For example, an absolute ban on fisheries to remove the risk of incidental capture is not always required. The development of fishing gears, the setting of "pinger", an acoustic device to prevent the approach to fishing gears and the protection of a part of the sea where high level of bycatch has been recognized will be useful to reduce the bycatch. These partial approaches may be enough to mitigate the risk of population extinction. This result is expected to promote conservation actions.

IV-2 Limitation of the risk evaluation in this study

The risk evaluated in this study may be underestimated because only a part of human-induced impacts were incorporated. In Sections II-3 and III-2, bycatch mortality was regarded as a major threat to the cetacean populations. Moreover, the bycatch mortality rate was given from information only for gillnet fisheries. Because bycatches by other fishing methods might occur (Shirakihara et al., 1993), and other human-induced effects may exist, our predicted risk is an underestimate in terms of the conservation of the cetacean populations. We should point out that the incorporation of other factors will result in more pessimistic predictions.

Stochastic variations of life history parameters were not completely incorporated in this study. In particular, in the analysis for the narrow-ridged finless porpoises (Chapter II), the uncertainty of the estimated risks was evaluated only from the stochastic variation in survival rates. Traill et al. (2007) indicated that minimum viable population (MVP) size, a key measure in conservation biology, for both of marine and terrestrial mammals is 3876 individuals. The abundance of most populations focused on in this study was less than this MVP level. It should

be noted that the populations can dramatically decrease by the impact of a catastrophic event such as a great amount of stranding and a spread of endemic disease.

IV-3   Future prospects for conservation of the target species

For the future, it is desired to update the knowledge on population size, life history parameters, human-induced impacts and their uncertainties. As described in the analysis for the Indo-Pacific bottlenose dolphins (Chapter III), the continued observations for a long period is necessary to reveal the survival and reproduction process for a long lived cetacean. Improvement of system for continuing the long-term observations is essential for conservation. When the identification of individuals in the wild is difficult, like the narrow-ridged finless porpoise, collections of stranded or bycaught specimen are useful to acquire not only the biological data but the information on human-induced impacts. At this time, close cooperation with the related people in fisheries would be a powerful weapon for efficient access to these specimens and the knowledge of a target coastal area.

Recently, the idea of adaptive management that presupposes the existence of the uncertainty is widely introduced for the environmental impact assessment (Walters, 1997). Doing nothing due to the limitation of biological data is undesired in the field of conservation ecology. Repeating the acquisition of latest information and the risk evaluation are expected to act as a stepping stone to conservation of even the cetacean populations whose biological information is limited.

Summary

Importance of risk evaluation for cetaceans threatened by human-induced impacts

Cetaceans inhabiting coastal waters can be critically affected by the impacts of human activities such as bycatch (i.e., incidental capture during fishing activities), ship strikes, and the degradation and reduction of habitats. The target species of cetaceans in this study are narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) and Indo-Pacific bottlenose dolphin (*Tursiops aduncus*). Risk evaluations of these two cetaceans have been conducted at a species level. Although genetically independent populations are identified for these target species, no evaluation has been done at a population level due to the lack of information on population dynamics. For conservation of the populations that may be endangered, assessment under uncertainty should be made. The purpose of this study is to attempt the prediction of future population change and the evaluation of extinction risk by using available data of other species and populations, and considering the uncertainty of the data.

Population viability analysis for the narrow-ridged finless porpoises

In Section II-1, the annual intrinsic rate of natural increase was estimated by using an age-classified matrix model for expressing the population dynamics. Because there is no information on survival for the porpoises, age-specific survival rates were estimated by randomly sampling from the estimates for other four cetaceans with the similar age at first reproduction (AFR). The annual intrinsic rate of natural increase was estimated to be 1.048/year (2.5–97.5 percentile: 1.021–1.063/year) for the AFR of 6 years.

In Section II-2, the impact of human-induced mortality for the Inland Sea population was evaluated. The rapid reduction in population size was reported during the period between 1978 and 2000 for the population. The annual human-induced mortality rate was estimated to be 10%/year (2.5–97.5 percentile: 6.3–12.8%/year) by a Bayesian analysis. This study indicated that the population size reduction after three generations (50 years) would overly exceed 80% when the rate remains in future. It was therefore suggested that the population meets the critically endangered (CR) category according to Criter ion A4 in the IUCN Red List.

In Section II-3, the impact of bycatch mortality for the Ariake Sound and Tachibana Bay population was evaluated. Bycatch seems to be a major threat for the population, and the annual bycatch mortality rate in 2007 and 2008 was reported to be 8.1%/year. When the bycatch mortality remains at the reported level, the population size willcontinue to decrease over the next 100 years. The predictions indicated that the population size reduction after three generations will exceed 30% even if the bycatch mortality rate remains at a minimum estimate of 5.3%/year. It was therefore suggested that the population meets at least the vulnerable (VU) category according to Criterion A4. The effect of age dependence in bycatch was additionally evaluated. The predicted extinction risk was sensitive to target age classes with higher bycatch mortality rates. In particular, bycatches of adults approaching AFR had the pessimistic effect on population viability. It was suggested that the age composition of bycaught porpoises should be considered when evaluating the possible impacts of bycatch mortality.

In Section II-4, a versatile method was proposed for evaluating the future risks of various narrow-ridged finless porpoise populations. Abundance estimation has been conducted for all the recognized populations around Japanese waters and then it seems possible to apply the risk evaluation method developed in the previous sections to the populations. A simple procedure was shown for predicting the population size reduction after three generations and the probability of extinction within 100 years from the estimates of the annual human-induced mortality rate and the abundance.

Population viability analysis for the Indo-pacific bottlenose dolphins

Photo-identification observation has been carried out every year since 1994 for the dolphin population inhabiting the waters off Amakusa-Shimoshima Island. In Section III-1, the survival rates for four groups of all the identified individuals, males, mature females and immature individuals were estimated from the photo-identification data during the period between 2000 and 2012 by the Cormack-Jolly-Seber (CJS) model, which is a kind of mark-recapture approaches. In Section III-2, the change in population size was predicted by an individual-based model using the survival rate estimates. The population size would dramatically decrease when the reported mortality rate is attributed to bycatches of calves <2 years old. This study indicated that the population size reduction after three generations (60 years) would overly exceed 80%. It was therefore suggested that the population meets the critically endangered (CR) category according to Criterion A4 in the IUCN Red List.

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Contributions of this study and future prospects for conservation

This study developed a method for a quantitative analysis on future change in population size. The analysis enabled the risk evaluation at a population level for the cetaceans threatened by human-induced impacts. It also revealed a significant factor which is sensitive to the risk evaluations. This study contributes to highlight that just a little effort for reducing the human-induced mortality can be effective in maintaining persistence of the cetacean populations. The risk evaluated in this study may be underestimated because only a part of human-induced impacts were incorporated. We should point out that the incorporation of other factors will result in more pessimistic predictions. Stochastic variations of life history parameters were not completely incorporated. Therefore, it should be noted that the populations can dramatically decrease by the impact of a catastrophic event such as a great amount of stranding and a spread of endemic disease. As a future work to improve the reliability of analysis, it is desired to update the knowledge on population size, life history parameters, human-induced impacts and their uncertainties. Adaptive managements by repeating the acquisition of latest information and the risk evaluation are expected to act as a stepping stone to conservation of the cetacean populations whose biological information is limited.

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Appendix 1   **Structure of the categories in the IUCN Red List**

Categories in the IUCN Red List are given below (modified from Figure 1 in IUCU (2001)).
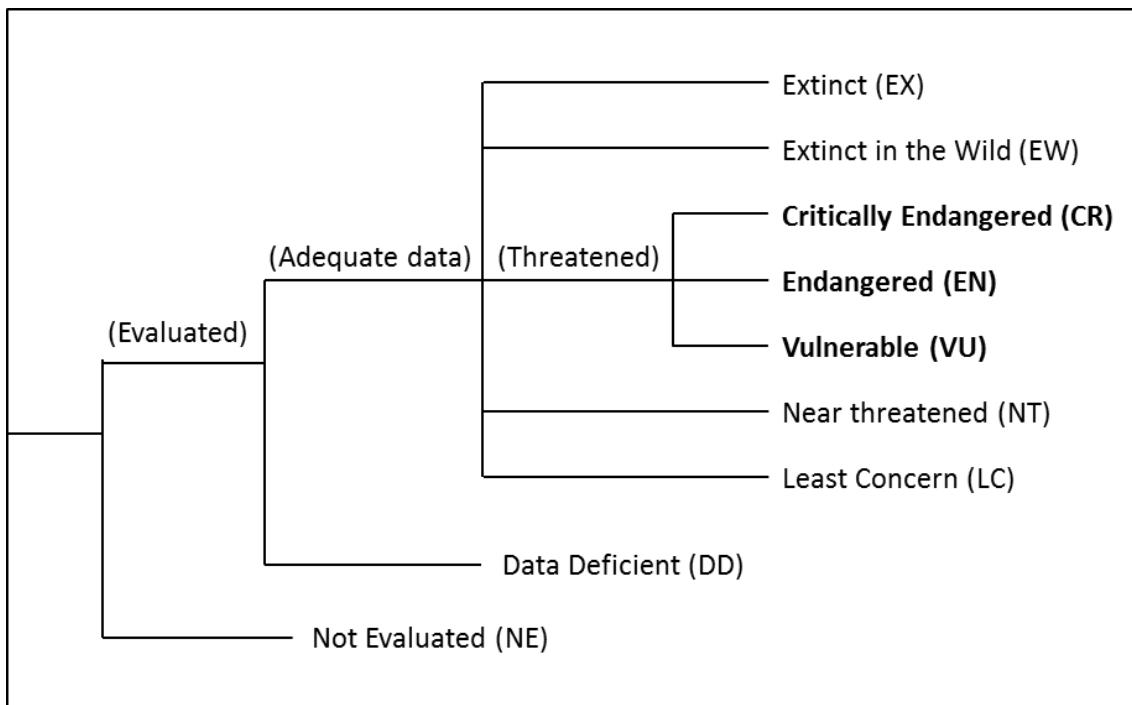
Appendix 2   Glossary of notation and abbreviations

Notation and abbreviations used in this thesis are given below.

λ annual change rate of a population ($= \lambda_{natural}(1 - M_{human})$).

$\lambda_{natural}$ annual intrinsic rate of natural increase ($= e^r$).

μ mean of a probability distribution.

σ standard deviation of a probability distribution. σ^2 indicates variance.

ψ capture probability in photo-identified observations.

AFR   age at first reproduction

AIC_c second-order Akaike's Information Criterion adjusted for small samples

ALR   age at last reproduction

b instantaneous birth rate.

B annual birth rate = number of newborn calves in a year/ abundance at the beginning of the year ($= e^b - 1$).

c the scale of age dependence in bycatch (≥ 1).

CI   calving interval

CITES   Convention on International Trade in Endangered Species of Wild Fauna and Flora

CV   coefficient of variation (= standard error / estimate).

d instantaneous death rate.

D annual rate of decrease ($= 1 - \lambda$).

F per-capita fertility rate (referred as "fertility rate" through the text).

g(0)   the detection probability on the track line.

I_t abundance index in year t ($= N_t / q$).

IBM   individual-based model

IUCN   International Union for Conservation of Nature and Natural Resources

IWC   International Whaling Commission

k maximum age class ($\cong$ longevity).

K   carrying capacity.

L the likelihood function.

m number of newborn calves

M_{human} annual human-induced mortality rate of a population.

M_{bycatch} annual bycatch mortality rate = number of individuals killed by bycatch / abundance ($\leq M_{\text{human}}$).

M_{natural} annual natural mortality rate ($= 1 - e^{-d}$).

MVP   minimum viable population

$n_{x,t}$ abundance (number of individuals) of age class x at the beginning of year t.

N_t abundance (total number of individuals) at the beginning of year t ($= \sum n_{x,t}$). Only N_0 indicates current population size (initial total number of individuals for simulation trials).

P total survival rate.

P_{natural} natural survival rate without human-induced mortality.

PVA   population viability analysis

PBR   potential biological removal

PE   probability of extinction.

PE_q probability of quasi-extinction.

Pr_{breeding} probability that an adult female breeds in a year ($\cong 1/CI$).

$Pr_{(XXX)}$ probability of the capture history XXX.

q proportionality coefficient between abundance and abundance index. For details, see II-2.2.

r intrinsic rate of natural increase ($= b - d$).

SE   standard error.

t year

x age class

x_T target age class with the highest bycatch mortality rate. For details, see Section II-3.2.1.